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Impact of Curing Periods on the Evaluation of Thermal, Mechanical Properties, and Energy Consumption of Concrete Buildings

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Abstract
This study examines the impact of the curing period on the thermal and mechanical properties of concrete and its subsequent effect on building energy consumption. The research methodology is divided into two parts: experimental and simulation. In the experimental section, concrete specimens were created using regular concrete with a dosage of cement of 350 kg/m³, and curing periods were varied (without curing, 3, 7, 14, 21, and 28 days) to assess thermal conductivity, density, ultrasonic pulse velocity, and compressive strength age 28 days. The results indicated that compressive strength increased by 71% between uncured and 28-day cured specimens, ultrasound propagation speed increased by 15%, and thermal conductivity increased by 31% with longer curing periods. A simulation using TRNSYS software estimated the energy consumption of a reference building with varying concrete properties based on the curing period. The simulated building consisted of three rooms, a hall, and a kitchen, with double exterior walls of 25 cm thickness and interior walls of 10 cm thickness. The findings revealed that longer curing periods contributed to increased energy consumption in the building. This study provides valuable insights into the relationship between curing periods, concrete properties, and their effect on the energy efficiency of concrete buildings.
Keywords: Energy consumption of the building. Curing periods of concrete. Thermal and mechanical properties. TRNSYS software.

1. Introduction

Concrete is a more fundamental material in the construction sector due to its exceptional mechanical properties, which make it appropriate for a wide range of applications, including foundations, roads, buildings, and bridges. (Gagg, 2014; Moulay-Ali *et al*., 2021). Proper curing of concrete is essential to achieve its maximum strength and longevity (Guimarães & Silva, 2021).

Additionally, modern concrete design must focus on enhancing thermal properties to reduce CO_2 emissions and energy consumption, addressing current environmental concerns.

In Algeria, many construction sites and contractors often neglect proper concrete curing methods and periods due to factors such as lack of time, ignorance or lack of awareness, poor planning, unfavorable weather conditions, and inadequate quality control. This neglect can lead to several issues, including reduced strength, cracking, poor durability, increased permeability, and heightened sensitivity to environmental conditions (Wang *et al*., 2022; El-Hawary & Al-Sulily, 2020). Adequate concrete curing is essential for achieving optimal performance and long-lasting durability in concrete structures.

Various curing methods include natural curing, standard curing, combined curing (Ge *et al*., 2023), heat curing (Rajhans *et al*., 2019), ambient curing, solar curing, water curing (Haruna *et al*., 2020), and how the concrete is cured by steam (Liu *et al*., 2020). Significant improvements in the mechanical performance of the concrete have been observed with the introduction of high-performance and self-compacting concretes (Zouini *et al*., 2023; Rabehi *et al*., 2023), as well as by enhancing its physical and mechanical properties.

Concrete also possesses multiple thermal properties, which are crucial in various applications. Engineering and construction fields require an understanding of these thermal properties to consider factors such as thermal comfort, energy efficiency, and structural integrity, particularly given population growth and limited energy sources (DTR-32, Ministère de l'Habitat, 1997; DTR-32, CNERIB, 1998). Studies have shown that enhancing the thermal efficiency of the concrete can be achieved through several techniques, such as incorporating natural fibers (RAHEEM *et al*., 2021). These fibers can be added to cementitious compounds to create insulating materials for construction (Mahdi *et al*., 2019). Additionally, research has assessed the impact of aggregate substitution on the mechanical and thermal properties, as well as the alteration of the pore structure (Ying *et al*., 2024). However, while fibers can improve thermal characteristics, they may also weaken the mechanical characteristics of concrete (Abdellatief *et al*., 2024).

This investigation aims to establish the relationship between curing periods and the thermal properties of concrete to estimate the energy needs within buildings. The mechanical properties of concrete can be evaluated using both destructive and non-destructive techniques (Mohammed *et al*., 2021), while its thermal properties can be assessed through laboratory studies. The "Isomet 2104" device can measure factors such as thermal conductivity, thermal capacity, and thermal diffusivity (Omrane & Rabehi, 2020). These thermal properties are crucial for planning and constructing reinforced concrete structures to ensure maximum thermal efficiency.

The purpose of this investigation is to study the influence of the curing period of concrete on the thermal and mechanical properties of a building, as well as its energy consumption. The experiment involved subjecting samples to six different water-curing periods: 0, 3, 7, 14, 21, and 28 days. The mechanical and thermal properties were measured using experimental methods following recognized protocols. Additionally, the energy consumption of a structure in various Algerian climates was determined based on the experimental results.

2. Materials and methods

2.1 cement

The cement used in this experiment is Portland compound cement of type CEM II/A-LL 42, 5 N. The composition includes around 17% limestone, which is crushed together with Portland clinker. The CEM II/A-LL 42.5 N is in accordance with the SN EN 197-1 standard. The cement factory Sidi Moussa, situated in the Wilaya of Adrar, was responsible for its creation. The chemical composition is displayed in Table 1.

2.2 Water

The water used for mixing is tap water, specifically referred to as "potable water," which is obtained from the public network of the city. The Table 2 provides the information regarding the physico-chemical makeup.

2.3 Aggregate

The sand utilized is SD dune sand. Abundant amounts of sand are found in dry locations, and it encompasses over 60% of Algeria's desert area. The plant utilizes coarse crushed material with fractions G3/8 and G8/15. These aggregates were selected to evaluate their effect on the thermal and mechanical properties of concrete. Their physical, mechanical, and chemical properties are summarized in Table 3.

Table 1 – Chemicals properties of cement.

Compound	CaO	SiO2	Al2O3	FeO3	SO3	MgO	C2S	C3A	C4AF
Values	64.53	21.30	4.83	3.31	2.28	1.43	25.93	7.2	10.07

Table 2 - Physico-chemical parameters of water.

Physico-chemical parameters	Results	Drinking standards
PH	7.81	>6.5 et <9
Conductivity ms/cm	1.2800	2.80
Raw water turbidity NTU	0.09	5.00
Water turbidity dec. NTU	/	
Dry residue a 110°C mg/l	800	1500.00
Temperature °C	/	25.00

Table 3 - Physical properties of sand and gravel.

Properties measured	Dune sand	Gravel G3/8	Gravel G3/8	Standards
Absolute density (kg/m^3)	2.64	2.65	2.65	NF EN 12620
Apparent density (kg/m^3)	1.48	1.52	1.47	NF P 18-554 Déc 1990
Sand equivalent (%)	92.63 88.42	/	/	P 18-598 Oct 1991
Fineness modulus	2.03	/	/	NFP 18-540

2.4 Concrete formulation

In this study, the Dreux-Gorisse process was employed to produce ordinary concrete of class C30/35 with a slump of 8 cm (consistency class S2) in accordance with Standard P18-305, 2006. The mixture of concrete has a ratio of water-to-cement (w/c) of 0.55, as specified in Table 4.

Table 4 – Composition of Concrete.

Compounds	Cement	Water	Sand	Gravel G3/8	Gravel G8/15
Concrete dosage (kg/m^3)	350	193.46	645.46	277.59	925.29

2.5 Preparation of test specimens and conservation procedure

This study employed two types of test specimens: cylinders for measuring mechanical properties and parallelepipeds for thermal properties. To evaluate the impact of the curing period on concrete properties, six sets of specimens were prepared with varying curing durations: 0 days (no curing), 3, 7, 14, 21, and 28 days of curing.

The cured specimens were completely immersed in a water bath that was kept at a constant temperature of 23 °C. Under the "no curing" condition, the specimens were removed from the water and stored in a laboratory at a temperature of 23°C with a relative humidity of 15%.

The main emphasis of the assessment of mechanical properties was on compressive strength, tensile strength, density, and ultrasonic pulse velocity. These tests were conducted on all specimens at 28 days. Additionally, thermal conductivity measurements were performed on all specimens after reaching 28 days.

We conducted this study to examine the impact of the curing period on concrete under various curing conditions.

2.6 Standards and Equipment

This section details the standards and equipment employed for specimen preparation and property testing:

Specimen Preparation: Cylindrical specimens were prepared according to code NF EN P18-416.

Strength Testing: Compressive and tensile strengths were measured in accordance with code NF 12390-4.

Ultrasonic Pulse Velocity: Code NF EN 12504-2 guided the measurement of ultrasonic pulse velocity.

Thermal Conductivity: Thermal conductivity was directly measured using the ISOMET 2104 device, which adheres to the principles outlined in code ISO 8302.

Figure 1 – Thermal Conductivity Measurement with ISOMET 2104

3. Numerical simulation of a building's energy consumption

In this section, we are interested in evaluating the influence of the curing duration of ordinary concrete on the energy behavior of buildings in the several Algerian climatic zones. We used the TRNSYS program for the numerical simulation. We used the energy demands for heating and air conditioning as an indicator to display our numerical data. Energy needs for heating and cooling were calculated used on the specified temperature settings of 18°C for heating and 26°C for cooling according to the values recommended by DTR C 3-2 and DTR C3-4. Four cities were selected by our study: Bechar, Elbayadh,Oran and Adrar.

In this section, we are interested in evaluating the influence of the curing duration of ordinary concrete on the energy behavior of buildings in different Algerian climatic zones. The TRNSYS program was used for numerical simulation. The energy demands for heating and air conditioning were used as indicators to display our numerical data. Energy needs for heating and cooling were calculated based on the set temperature of 18°C for heating and 26°C for cooling, according to the values recommended by DTR C 3-2 and DTR C3-4.

For this study, four cities representative of Algeria's diverse climatic zones were selected. El Bayadh experiences a cold semi-arid climate, classified as BSk according to the Köppen system. Adrar, on the other hand, is characterized by a hot desert climate (BWh in the Köppen classification), typical of the hyper-arid Saharan region at the heart of the Sahara, with extremely long, scorching summers and short, warm winters. Oran enjoys a warm temperate climate, categorized as Csa by Köppen and Geiger. Finally, Bechar has a hot desert climate (BWh according to Köppen's climate classification), similar to that of Adrar.

Figure 2 illustrates the floor plan of the apartment under investigation. Occupancy conditions significantly affect comfort levels. The number of occupants in the accommodation varies irregularly. We have endeavored to anticipate potential scenarios and estimated an occupancy of seven individuals per room. Metabolic activity levels are set at 1.5 MET from 8:00 a.m. to 11:00 p.m. in the summer (8:00 a.m. to 9:00 p.m. in the winter) and 1 MET from 11:00 p.m. to 8:00 a.m. in summer (9:00 p.m. to 8:00 a.m. in the winter). Considering thermal resistance of clothing at 0.5 Clo (light summer clothing) in the summer and 1.5 Clo in the winter (Roulet, 2014), each occupant is considered a heat source with an assumed average power of 120 Watt. According to (Roulet, 2014), a person with low activity emits 65 Watt of sensible heat, comprising 40% convective and 60% radiative, and 55 Watt of latent heat. Additionally, from 2:00 p.m. to 11:00 p.m., we assumed the use of a 100-watt PC and a 150-watt TV. For illumination, we anticipate using light bulbs between 6:00 p.m. and 11:00 p.m.

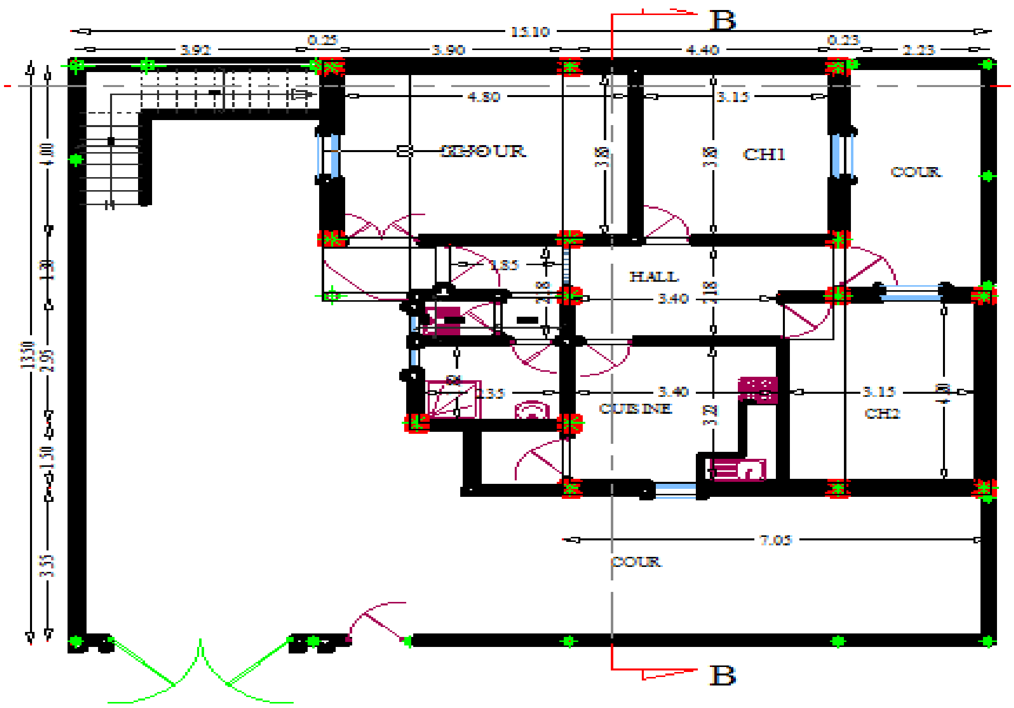

Figure 2 - Apartment Layout Used for Building Energy Simulation

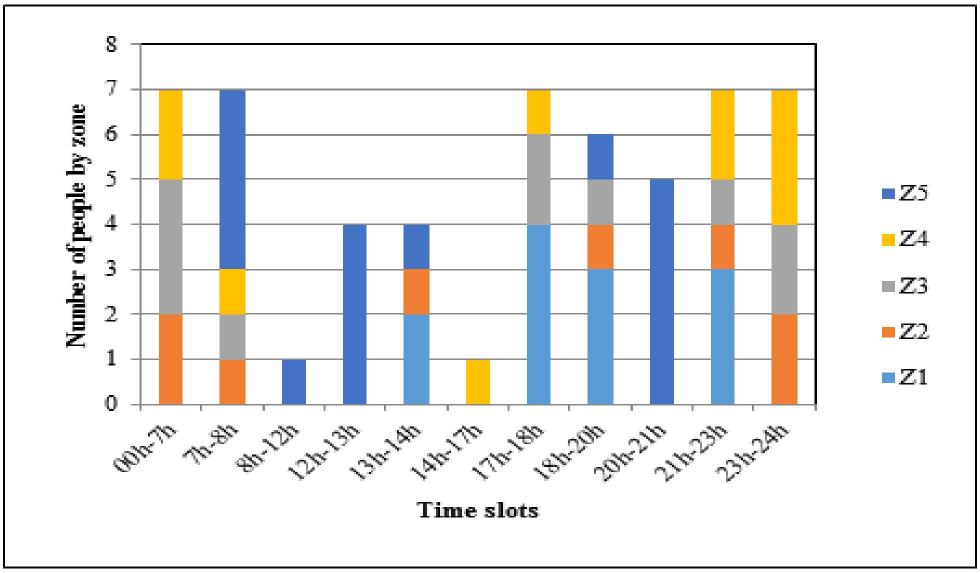

Figure 3 – Occupancy Scenarios in Different Apartment Zones

Table 5 shows the composition of the apartment envelope.

Table 5 - Composition of the Apartment Envelope

Designation	External walls	Internal walls	Low floor on a level ground	Roof
Material and thickness	Concrete 10 cm Air layer 5cm Concrete 10 cm	Concrete 10 cm	tile 2cm Cement mortar 2 cm Sand 1cm reinforced concrete 4cm Stone 20cm	Cement mortar 2 cm Slabs 16 cm reinforced concrete 4cm Waterproofing 1 cm

4. Results and discussion

4.1 Impact of curing period on the mechanical properties

The mechanical properties of concrete are an important factor. Evaluating its behavior can take different forms, including testing its compressive strength, tensile strength, density, and an ultrasonic test. Gaining a comprehensive understanding of these characteristics can assist us in conducting a more thorough analysis of the strength and dependability of concrete in various industries.

Figure 4 displays compressive strength of concrete. The curing period of concrete led to a significant rise in compressive strength, increasing from 22 to 38 MPa. Specimens exhibiting optimal formation demonstrated superior performance following a 28 days curing period. Typically, the length of curing has a more significant positive impact on the compressive strength of concrete. Consequently, a prolonged curing period can aid in preserving the uniformity and density of the concrete, leading to improved compressive strength.

Figure 5 shows the tensile strength of concrete. The period of curing for the concrete increase in tensile strength, rising from 1.93 to 2.88 MPa. The specimens exhibited the most superior performance after a curing period of 28 days, particularly in the concrete with the most optimal formation. Consequently, curing period aid in preserving the uniformity and density of the concrete, leading to improved tensile strength.

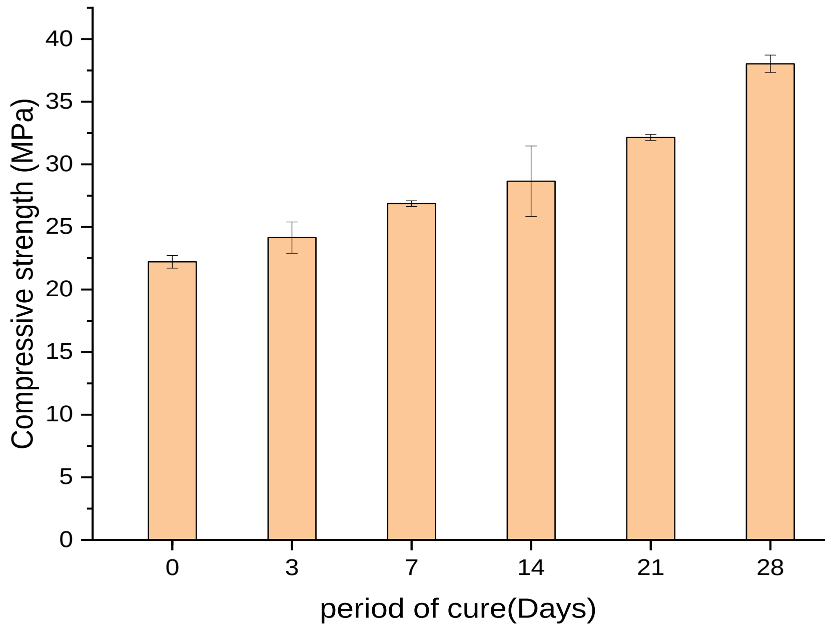

Figure 4 - Compressive strength depends on curing period

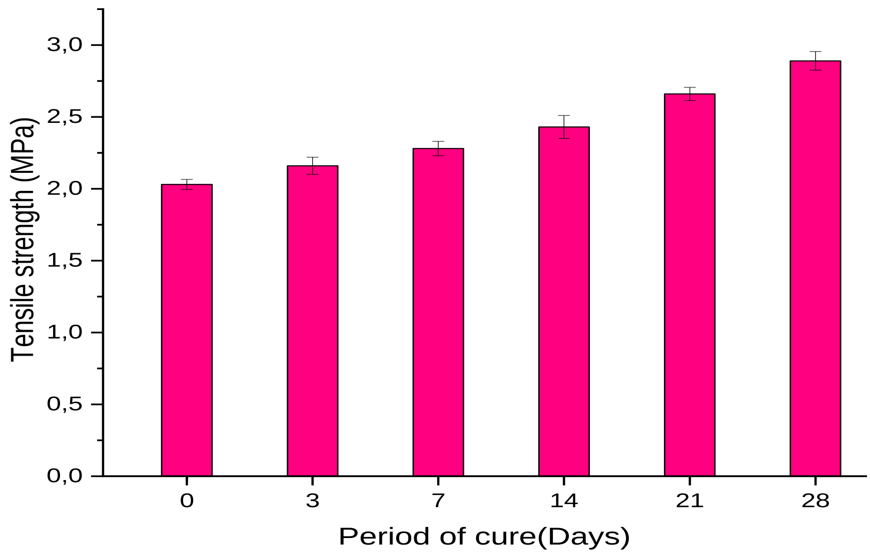

Figure 5 - Tensile strength depends on curing period

Furthermore, we have assessed the compressive and tensile strength of concrete by considering the period of curing, and we also analyzed its performance through the utilization of an ultrasonic test. Figure 6 illustrates the correlation between the cure time and the pulse velocity of ultrasonic waves. The sound speeds were determined to be acceptable, and the objects were classified as "good" based on the average results of the ultrasonic tests. The concrete with a curing period of 28 days exhibited the highest level of performance, indicating a low occurrence of cracks that could potentially disrupt the propagation of ultrasonic waves.

Figure 7 illustrates the calculation of the Young's modulus of concrete using the values obtained from ultrasonic pulse velocity testing. Its values range from 30 GPa to 38 GPa. The acceptable range for the Young's modulus in concrete typically falls between 30 and 40 GPa. This range represents the stiffness and elasticity of the concrete material, which is an important parameter in structural engineering and construction.

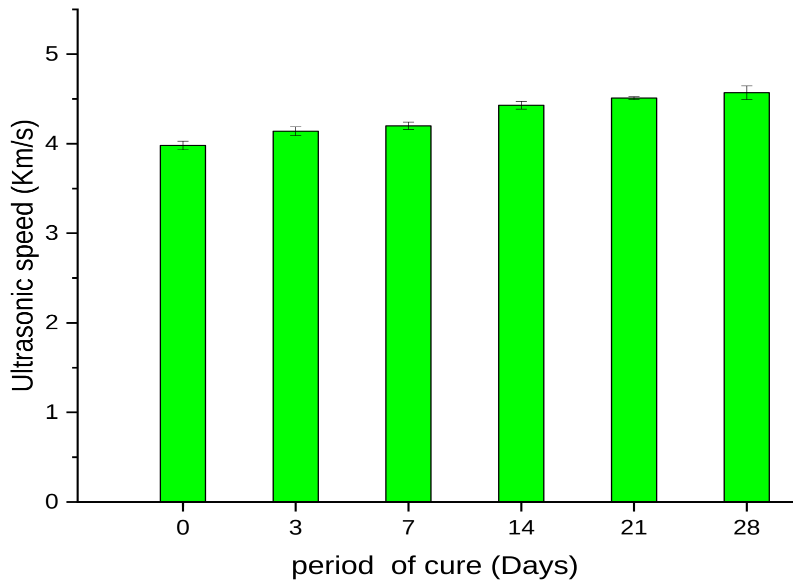

Figure 6 – Ultrasonic speed depends on curing period

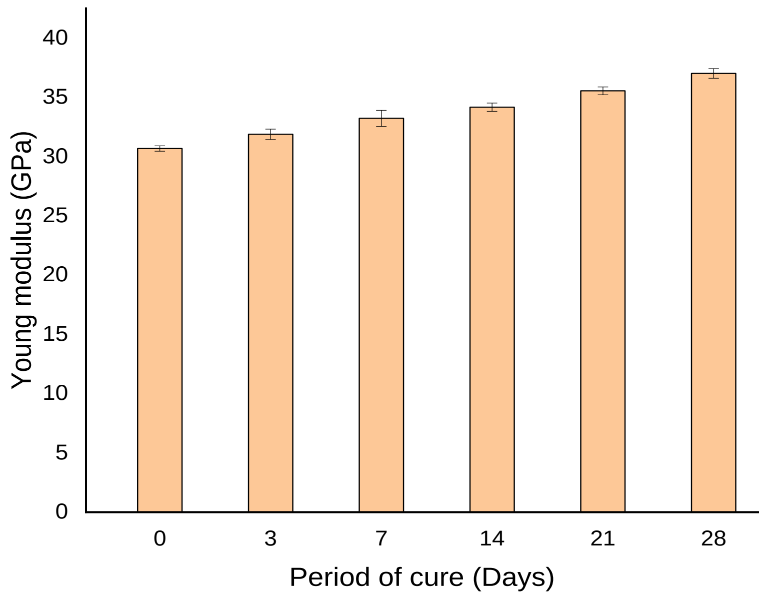

Figure 7 – Young's module depends on curing period

Figure 8 clearly demonstrates that the concrete's curing period increases its density. Notably, density reveals the porosity composition of this specific concrete arrangement. The curing period can have a significant effect on the density of concrete. Density is a key property of concrete that influences its strength, durability, and thermal properties. During the curing period, concrete undergoes a process of hydration, where cement particles react with water to form a hardened matrix. Proper curing helps to ensure that this hydration process proceeds efficiently, resulting in more densely packed and stronger concrete. As hydration progresses, the cementitious materials fill in the void spaces between the aggregate particles, reducing the overall porosity of the concrete. This leads to an increase in density. The curing conditions, such as temperature and moisture levels, can significantly affect the rate of hydration and, consequently, the density of the concrete. Proper curing is essential to achieving the desired density and strength. Concrete's strength closely correlates with its density. A higher density generally corresponds to higher strength and better performance in terms of load-bearing capacity and durability.

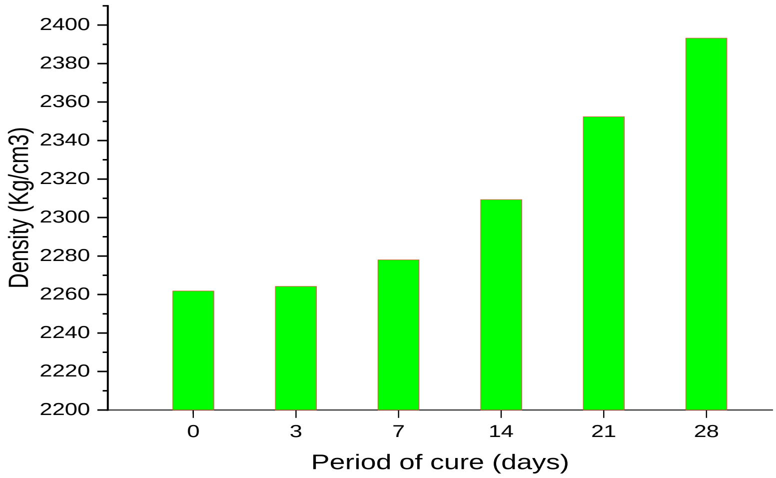

Figure 8 – Density depends on curing period

4.2 Effect of curing period on thermal properties

The period of the curing process has a notable impact on the thermal characteristics of concrete, particularly its ability to conduct heat. Concrete undergoes a chemical reaction known as hydration during the curing phase, where cement and water combine to form a durable substance. Furthermore, this hydration process has an impact on the concrete's mechanical and thermal properties. During the process of curing, the heat conductivity of the concrete changes. Concrete generally takes longer to cure and exhibits a higher heat conductivity compared to less cured concrete. The reason for this is that hydration results in the formation of a substance that has reduced porosity and increased density, leading to increase thermal conductivity.

Figure 9 displays the variation in thermal conductivity. During the curing process, the thermal conductivity of the concrete increases as its porosity increases, going from 1.81 w/m.k. to 2.38 w/m.k.

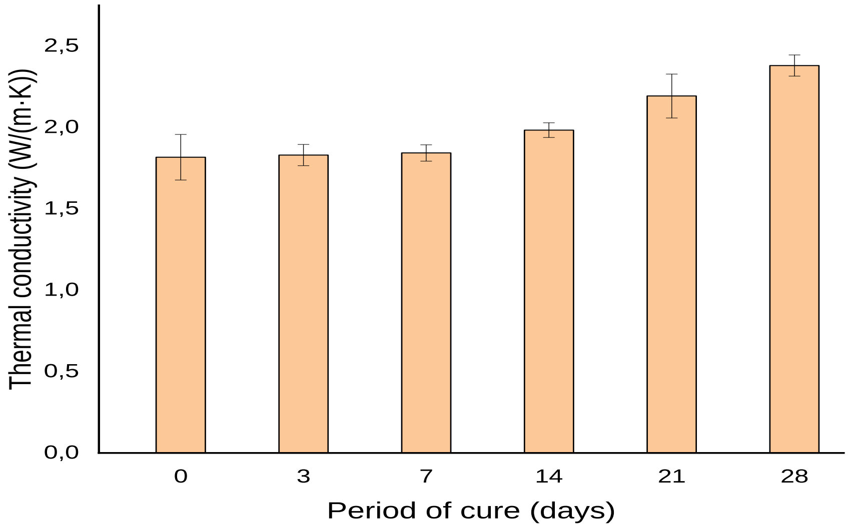

Figure 9 – Thermal conductivity depends on curing period

4.3 Energy consumption

Figure 10 displays the projected energy consumption for a basic concrete building in the city of Bechar, which ranges from 4000 to 4100 for cooling and 3500 to 3700 for heating. This is because the semi-desert area requires more cooling than heating due to its natural characteristics. Additionally, we observe that the longer the curing period, the more energy-intensive concrete buildings become. This is because the concrete's porosity decreases and its thermal conductivity increases with the curing time. The longer the curing period, the more significant the impact on cooling requirements.

Figure 11 shows the energy of annual use for cooling and heating a three-story apartment in the city of Adrar. Because Adrar is a desert region, there is a greater need for cooling than for heating. We see that cooling requires between 8275 and 8660 kWh, while heating uses far less energy roughly 1517–1613 kWh. The energy inside concrete buildings has increased. This is because the concrete's porosity decreases and its thermal conductivity increases with the curing time. The longer the curing period, the more significant the impact on cooling requirements.

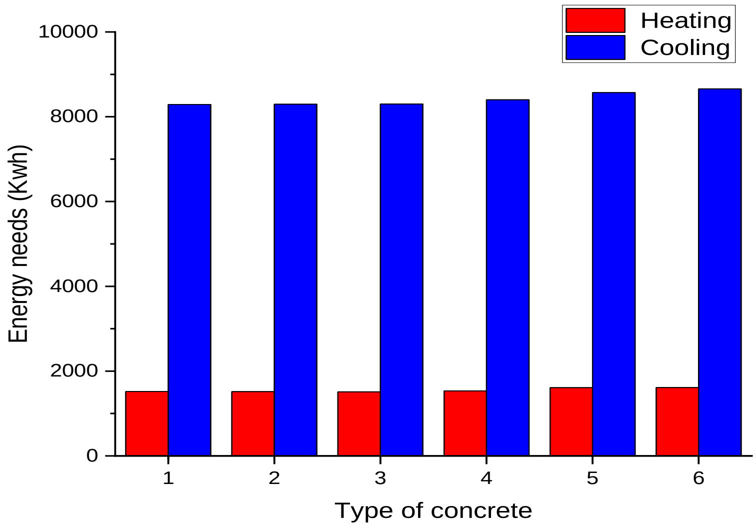

Figure 10 – Energy needs on Adrar depends on type of concrete

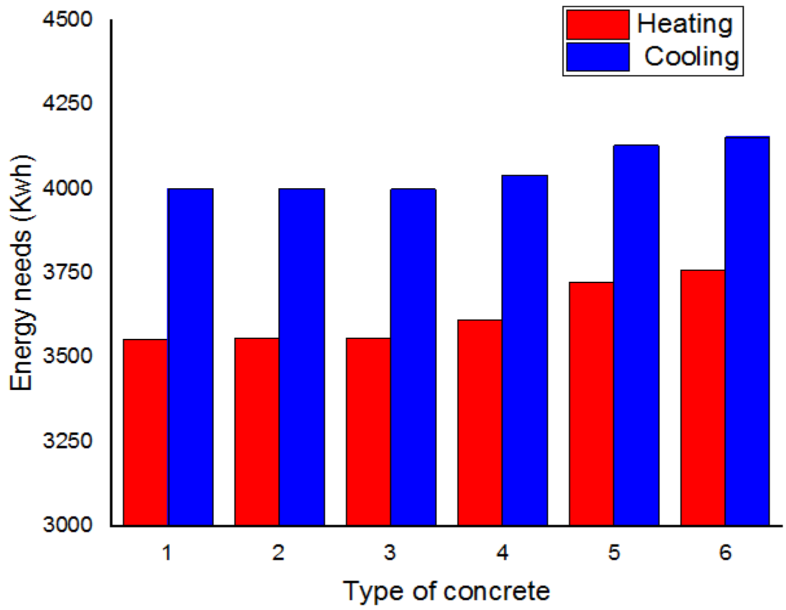

Figure 11 – Energy needs on Bechar depends on type of concrete

Figure 12 illustrates that the annual energy requirements for heating and cooling in the city of Oran are typically climate of Mediterranean. This climate classification suggests that the energy requirements for cooling would be lower compared to heating. The require of heating between 3650 to 3870 kwh and cooling around 1490 to 1535 Kwh. The energy needs increase with the curing period of concrete because thermal conductivity increases. The impact on heating requirements increases with the length of the curing period.

Figure 13 illustrates that the annual energy needs for heating and cooling in the city of El-Bayadh, has a climate, characterized by very cold winters and mild summers. This type of climate generally results in high energy requirements for heating and lower requirements for cooling. the annual consumption between 8540 and 9020 Kwh for heating and between 1630 and 1670 Kwh for cooling. The energy needs increase with the curing period of concrete because thermal conductivity increases. The impact on the amount of heating needed increases with the length of the curing period.

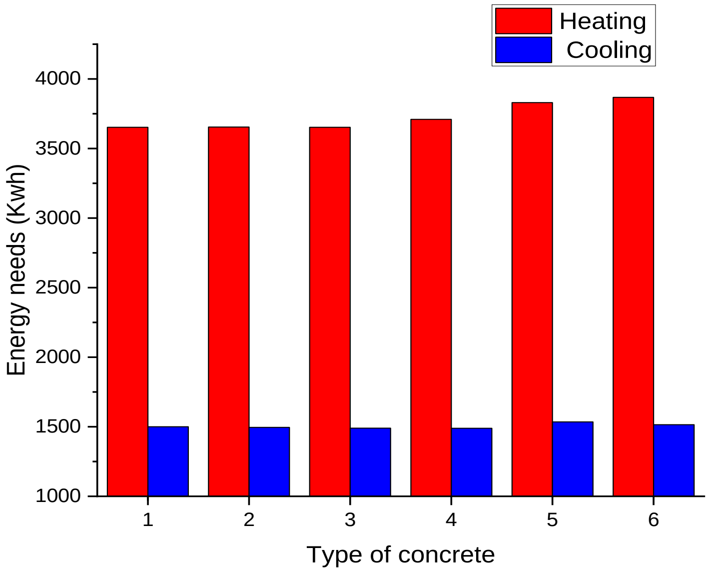

Figure 12 - Energy needs on Oran depends on type of concrete.

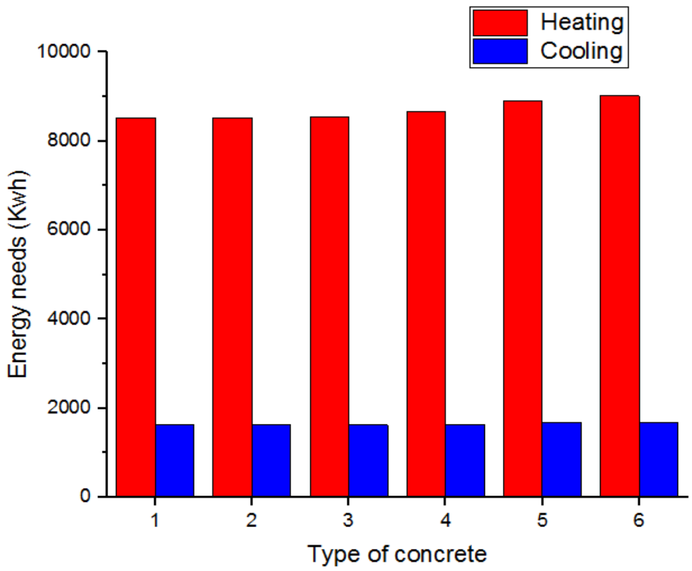

Figure 13 - Energy needs on Elbayad depends on curing period.

5. Conclusion

This investigation has been divided into two main sections: experimental and simulation. In the experimental phase, we focused on studying the mechanical and thermal properties of concrete based on varying curing periods. In the simulation part, we utilized the outcomes from the experimental phase to simulate the energy requirements within buildings over time, considering four distinct regions in Algeria within the same building (Adrar in the south-arid area, Bechar in the semi-arid area, Oran in the north-climate of the Mediterranean, and Elbayad in the center).

Our findings reveal several key insights: any alteration in the curing period impacts the density of concrete, resulting in improved mechanical behavior. Specifically, extending the curing period correlates with enhanced compressive strength, tensile strength, and ultrasound propagation speed. The data provided clearly illustrate a robust relationship between compressive resistance and ultrasonic pulse velocity testing for concrete. However, notable convergence was observed, indicating a strong correlation between compressive strength and ultrasonic pulse velocity under specific circumstances.

Conversely, prolonged curing periods lead to deteriorating thermal behavior, with increased thermal conductivity and diminished thermal comfort within buildings. Additionally, energy consumption escalates with longer curing periods, with heating demands being more significant in northern cities and cooling requirements prevailing in southern cities. Although acceptable thermal behavior can be achieved with shorter curing periods, it often compromises mechanical performance.

In conclusion, our investigation identifies a viable compromise between mechanical and thermal behavior, recommending curing periods of 7 to 14 days. Understanding the mechanical and thermal properties of concrete under various curing conditions enables us to comprehend its behavior and tailor its application accordingly to specific environments.

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