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Numerical simulation study of the effect of integrating hemp concrete and passive strategies on the energy consumption of a residential building in Al-Hoceima

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Abstract In this work, we present an energy efficiency study for a residential building located in the city of Al-Hoceima, Morocco. The aim is to bring the building into compliance with the technical requirements of the Moroccan Thermal Building Regulations (RTCM). To achieve this, several modifications and interventions were carried out, such as the use of hemp concrete for insulation and the integration of passive strategies to minimize energy loads. Similarly, this energy study is carried out as a simulation using TRNSYS software, so that the building is modeled as a multizone entity with an occupancy schedule. The simulation results show that the technical requirements of the RTCM are achieved using a construction containing hemp concrete with an optimum thickness of around 10cm, this thickness can be reduced to 4cm using double glazing, or to 1cm using controlled natural ventilation in summer and winter.

Keywords Energy efficiency, Residential building, Moroccan Thermal Building Regulations, Hemp concrete, passive strategies

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1. Introduction

*A*t the global level, estimates of population dynamics and demographic growth show a trend towards population growth [1]. This increase in population has a direct impact on energy demand, particularly for domestic needs such as heating, air conditioning, and lighting. The increase in this demand has major environmental implications. Human activities that consume energy are often the source of greenhouse gas emissions, contributing to global warming and temperature variations around the world.

The building sector in Morocco is the second largest consumer of energy, accounting for 33% of final energy consumption and more than 12% of national greenhouse gas emissions [2]. Electricity consumption in residential buildings alone increased by half over the period 2000-2020, so that by 2020, during the COVID-19 pandemic, consumption will have risen by between 5% and 6% [3]. To achieve this, Morocco has implemented an energy efficiency policy, such as the adoption of the Moroccan Thermal Construction Regulations (RTCM) in October 2014 [4].

To achieve high levels of energy efficiency in buildings, and reduce their energy consumption while preventing any kind of heat loss through the envelope, it is crucial to improve the building envelope by using various bio-sourced construction materials, especially as this choice will contribute to the energy recovery of these waste materials of organic origin known as biomass. In this context, some studies have been carried out, including the use

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of wood waste [5], cannabis waste [6], straw waste, date palm waste [7], walnut shell waste [8], and other natural waste materials.

In the same vein, it is worth highlighting the role of integrating passive strategies in improving the energy efficiency of the building, as well as in improving the comfort of its interior environment. At this stage, several studies have been carried out on the orientation and location of the building [9], shading [10, 11], stores [12], natural ventilation [13], etc.

An exhaustive study of a building's energy performance is highly complex and can only be achieved by modeling all the factors influencing energy efficiency [14]. Various simulation tools have been developed for this purpose [15]. In addition, some studies have looked at active measures and renewable energy solutions that can be integrated into buildings [16, 17].

Hemp represents one of the most promising alternatives in the building sector, given its insulating power and low thermal conductivity [18]. While the use of a hemp biocomposite such as hemp concrete in construction reduces, the greenhouse gas emissions caused by the manufacturing process of other conventional materials and enables the construction of buildings with high-energy performance envelopes. In addition, the optimal choice of glazing has a direct impact on the amount of solar radiation received by the building, in other words, load control for direct passive solar heating. In addition, the feasibility of incorporating a natural ventilation system as an alternative to forced mechanical ventilation systems is being assessed.

This article aims to evaluate the effect of integrating a bio-sourced insulating material such as hemp concrete into a wall envelope separately or in combination with passive strategies such as glazing and natural ventilation. The study concerns a residential building in Al-Hoceima, Morocco.

2. Methodology and Case Study

The present work focuses on a real case study of a residential building in a Mediterranean climate. Our study begins with the building design phase, followed by the physical and mathematical model and simulation assumptions, through to the results and their discussion. Finally, a summary of the work is presented in the form of a conclusion. Figure 1 illustrates the working methodology.

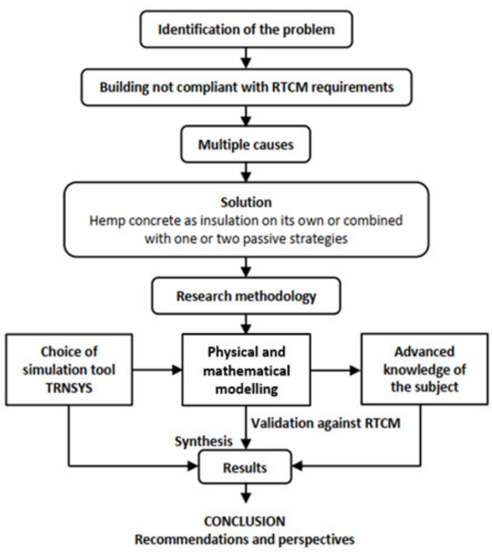

Figure 1. Working methodology.

2.1. Climate of the study region

Al-Hoceima is a Moroccan city on the Mediterranean coast, in the Rif region in the north of Morocco, 291 km west of Tangier and 205 km east of Saïdia. The region has a Mediterranean climate, with mild, relatively rainy winters and hot, sunny summers. Figure 2 shows that the temperature peaks at $27.1°$C in August, while the lowest temperature $9.5°$C is recorded in January. Over the year, rainfall is higher during winter compared to summer ($414mm$ on average).

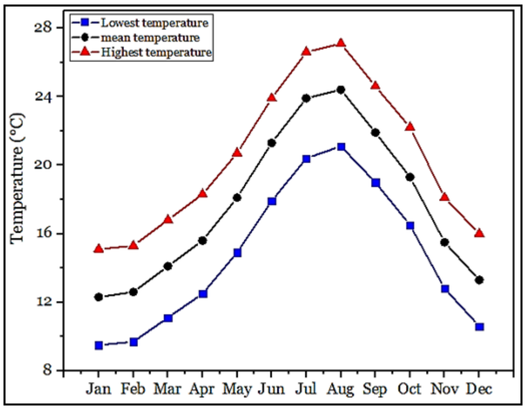

Figure 2. Temperature in Al-Hoceima Morocco (Data: 1999 – 2021).

In this study, all the simulations were carried out using TRNSYS software. All the meteorological data used were taken from the Meteonorm database.

2.2. Description of the studied building

Our work concerns the first floor of a residential building in the city of Al-Hoceima with a surface area of 92 m^2, facing due south. Figure 3 shows the distribution of space inside our building. The composition and construction materials of the building walls are shown in Table 1.

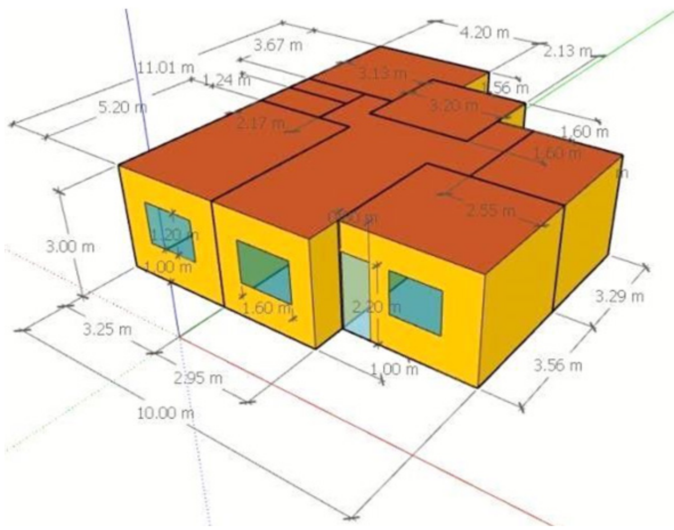

Figure 3. Plan of the building.

Table 1. Thermophysical characteristics of the basic building components.

Envelope components	Materials	Thickness (cm)	Thermal conductivity $(W/m.K)$	Density (kg/m^3)	Thermal capacity $(kJ/(kg.K))$
Floors	Tiles	2	1,30	2300	1,30
	Concrete	7	2,00	2450	2,00
	Hollow slab	16	1,04	1513	1,04
	Plaster	1	0,56	1350	0,56
Interior Wall	Mortar	2	1,30	1900	1,00
	Hollow brick	7	0,19	918	0,74
	Mortar	2	1,30	1900	1,00
Exterior Wall	Mortar	2	1,30	1900	1,00
	Brick	20	0,22	664	0,74
	Mortar	2	1,30	1900	1,00

- Glazing: Single glazing:(Transmission coefficient : $U = 5,66W/m^2.K$, Solar factor : $g = 0.77$)
- The window/wall ratio (WWR) : 8,9%.

3. Building energy simulation

3.1. Physical and mathematical modelling

Our simulation was carried out in the TRNSYS software studio version 18. This software allows dynamic thermal simulations of buildings and contains several simulation tools as well as graphical connection programs to various spreadsheets and plotting tools that can be used throughout the simulation. The dynamic behavior of the building is simulated with a time step of one hour, using TRNSYS multizone transient modelling. Our building is divided into 8 thermal zones. The energy balance in each zone is expressed as :

$$\dot{\phi}_{Total} = \dot{\phi}_{inf,air} + \dot{\phi i}_{vent,air} + \dot{\phi}_{cplg} + \dot{\phi}_{surf} + \dot{\phi}_{int,gain} + \dot{\phi}_{solar} + \dot{\phi}_{Solar,int,sha} \tag{1}$$

Where :

- $\dot{\phi}_{inf,air}$: The flow caused by infiltration of air from outside to the thermal zone.

$$\dot{\phi}_{inf,air} = \dot{\forall}_{inf,air}\rho C_p(T_{outside} - T_{air}) \tag{2}$$

$\dot{\forall}_{inf,air}$ is the air infiltration rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in $(KJ/kg.K)$, and $T_{outside}$ is the outside temperature of the thermal zone in (K).

- $\dot{\phi}_{vent,air}$: The flow caused by ventilation of the thermal zone.

$$\dot{\phi}_{vent,air} = \dot{\forall}_{vent}\rho C_p(T_{vent} - T_{air}) \tag{3}$$

$\dot{\forall}_{vent}$ is the air ventilation rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in $(KJ/kg.K)$, and T_{vent} is the temperature of the ventilated air entering the thermal zone in (K)

- $\dot{\phi}_{cplg}$: The flow caused by air convection between neighboring thermal zones.

$$\dot{\phi}_{cplg} = \dot{\forall}\rho C_p(T_{zone} - T_{air}) \tag{4}$$

$\dot{\mathrm{V}}$ is the air coupling flow rate in (m^3/h), ρ and C_p represent respectively the air density in (kg/m^3) and its heat capacity in $(KJ/kg.K)$, T_{zone} and T_{air} are respectively the temperature of the thermal zone air and the temperature of the air coming from an adjacent zone in (K).

- $\dot{\phi}_{surf}$: The flow caused by convection near opaque surfaces in the thermal zone.
- $\dot{\phi}_{int,gaint}$: The flow caused by internal gains in the thermal zone.
- $\dot{\phi}_{solar}$: The flow caused by solar radiation passing through the glazing towards the thermal zone.
- $\dot{\phi}_{solar,int,sha}$: The flow caused by solar radiation absorbed by internal shading devices in the thermal zone.

The three modes of heat transfer are described by the mathematical equations below:

→ Heat flow due to convection near external surfaces:

$$\dot{\phi}_{convection} = h(T_{air} - T_{surf,out}) \tag{5}$$

→ Heat flux due to radiation on external surfaces:

$$\dot{\phi}_{radiation} = \epsilon\sigma(T^4_{surf,out} - T^4_{sky}) \tag{6}$$

→ Heat flow due to conduction through walls:

$$\dot{\phi}_{conduction} = UA(T_{surf,in} - T_{surf,out}) \tag{7}$$

h is the external convective exchange coefficient $(W/m^2.K)$ T_{air} , $T_{(surf,in)}$, $T_{(surf,out)}$ and T_{sky} are respectively the temperature of the ambient air near the wall surface, the temperature of the inside and outside surfaces of the walls and the temperature of the sky (K).
ε and σ are respectively the emissivity of the external wall surface and the Stephan-Boltzmann constant.
U and A are respectively the thermal transmittance $(W/m^2.K)$ and the exchange surface (m^2).
The convective exchange coefficients are calculated using the following correlation:

$$h = K_1(T_{surf} - T_{air})^{K_2} \tag{8}$$

The values for K_1 and K_2 are taken from the TRNSYS 18 manual [19]. Table 2 shows their values for different surface types.

Table 2. K_1 and K_2 values.

Type of surface	Condition	K_1 $(W.m^{-2}.K^{-n-1})$	K_2
Vertical wall	*******	1,60	0,30
Horizontal ground	T_{surf} - $T_{air} > 0$	2	0,31
	T_{surf} - $T_{air} < 0$	1,07	
Horizontal roof	T_{surf} - $T_{air} > 0$	1,07	0,31
	T_{surf} - $T_{air} < 0$	2	

3.2. Simulation assumptions

To bring our simulation study closer to reality, certain assumptions have been reformulated, as shown in Table 3. In addition, an occupancy schedule has been taken into account, as shown in Table 4.

Table 3. Simulation assumptions.

Simulation assumptions	Value
Solar absorption coefficient of walls	0,5
Infiltration rate	0,6ACH
Heating temperature	20°C
Cooling temperature	26°C

Table 4. Occupancy scenarios.

Element	Type of gain	Daily schedule of use	Internal gains (W)
Lounge	Lighting	7h – 8h et 19h – 21h (5 days a week)	36W
	TV	12h – 13h et 18h – 21h (5 days a week)	100W
	2 persons	7h – 8h et 12h – 13h et 18h – 21h (5 days a week)	166W
Living room	Lighting	7h – 8h et 19h – 21h (2 days a week)	36W
	TV	12h – 13h et 18h – 21h (2 days a week)	100W
	2 persons	7h – 8h et 12h – 13h et 18h – 21h (2 days a week)	166W
Kitchen	Lighting	7h – 8h et 19h – 21h (all week)	12W
	Refrigerator	24h (all week)	300W
	Washing.M	19h – 21h (1 time per week)	2200W
	1 person	7h – 8h et 12h – 13h et 19h – 21h (all week)	126W
Room 1	Lighting	21h – 23h (all week)	12W
	Laptop	21h – 23h (all week)	40W
	2 persons	in activity: 21h – 23h (all week)	166W
		Sleeping: 23h – 7h (all week)	144W
Room 2	Lighting	21h – 23h (all week)	12W
	Laptop	21h – 23h (all week)	40W
	1 persons	in activity: 21h – 23h (all week)	83W
		Sleeping: 23h – 7h (all week)	72W

4. Results and discussion

4.1. Results: base case

Our building was constructed before the application of the Moroccan thermal building regulations in 2014. To verify the similarity of the energy performance of our apartment with the reference performance of the RTCM, as well as the reliability of our numerical calculation, a comparison of the results was carried out as shown in the Figure 4.

To ensure the reliability of our numerical calculation, we need to prove that our numerical results match the real results. To do this, we compare the energy requirements obtained from the simulation with those required by the RTCM. To do this, the root mean square error (RMSE) is used to measure the accuracy of the simulated model, as formulated in equation (9).

$$RSME = \sqrt{\frac{\sum_{i=1}^{n}(E_{act,i} - E_{sim,i})^2}{n}} \tag{9}$$

WhereE_{act} and E_{sim} are the actual energy consumption and the simulated energy consumption, and n is the number of data points. The actual data is that of the RTCM.

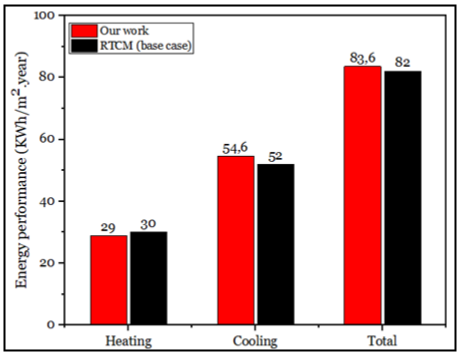

Figure 4. Comparison of the building energy performance with RTCM requirements.

Table 5. Validity of the numerical model.

Energy requirements	Heating	Cooling	Total
Actual data in $(KWh/m^2.year)$	30	52	82
Simulation data in $(KWh/m^2.year)$	29	54,6	83,6
RSME $(KWh/m^2.year)$	1	2,6	1,6

In fact, the results of the simulation of the building's energy requirements are generally in line with the energy needs required by the RTCM. As a result, the simulation model is reliable.

4.2. Energy optimization of the building

- **Effect of integration the hemp concrete in floors and external walls**

In this section, we study the impact of integrating hemp concrete for the thermal insulation of external walls and floors and their impact on the building's heating and cooling requirements.
The external walls are made up of two 7cm hollow bricks separated by a 6cm air gap and a layer of hemp concrete with a 2cm layer of cement mortar on both sides. The floors are built using 2cm of floor tiles, hemp concrete, 7cm of heavy concrete, 12cm of a hollow slab, a 6cm air gap, and 1cm of plaster.

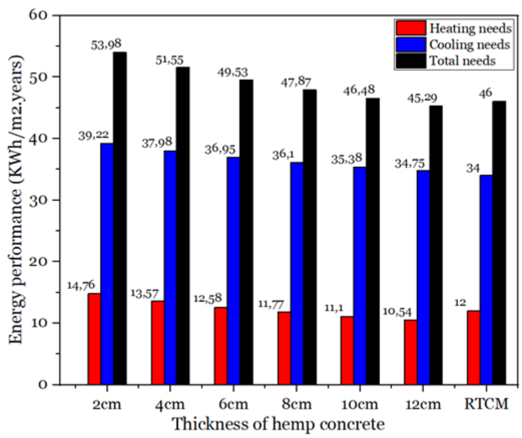

Figure 5. Energy requirements as a function of hemp concrete thickness.

The integration of hemp concrete into the building envelope results in energy savings for heating and cooling compared with the construction scenario without hemp concrete, as shown in Table 6.

Table 6. Heating and cooling energy savings compared with construction without hemp concrete.

Thickness of hemp concrete	Heating energy savings (%)	Cooling energy savings (%)
2cm	49,1%	28,1%
4cm	53,2%	30,4%
6cm	56,6%	32,3%
8cm	59,4%	33,8%
10cm	61,7%	35,2%
12cm	63,6%	36,3%

Table 6 shows that increasing the thickness of the hemp concrete results in a significant reduction in heating requirements while cooling requirements decrease only slightly. This is due to the nature of the Mediterranean climate in the city of Al-Hoceima, with mild winters and hot summers. In other words, the results in Figure 5 show that the optimum thickness of hemp concrete is 10 cm, for which the heating and cooling requirements are almost equal to those recommended by the RTCM. Respectively 12 $KWh/m^2.year$ and 34 $KWh/m^2.year$. This is in line with the results of the work carried out by Dlimi et al [20].

- **Effect of integrating passive strategies**

Effect of glazing type

In this section, single glazing is replaced by double-glazing, the characteristics of which are shown in Table 7.

Table 7. Glazing characteristics.

Type of glazing	U $(W/m.K)$	g (%)
Single	5,66	0,77
Double	1,46	0,52

Figure 6 shows that the use of double glazing reduces the thickness of the hemp concrete by 6cm so that the optimum thickness of this material is reduced from 10cm to just 4cm. In other words, double-glazing combined with 4cm of hemp concrete insulation is enough to ensure that our building meets the RTCM requirements.

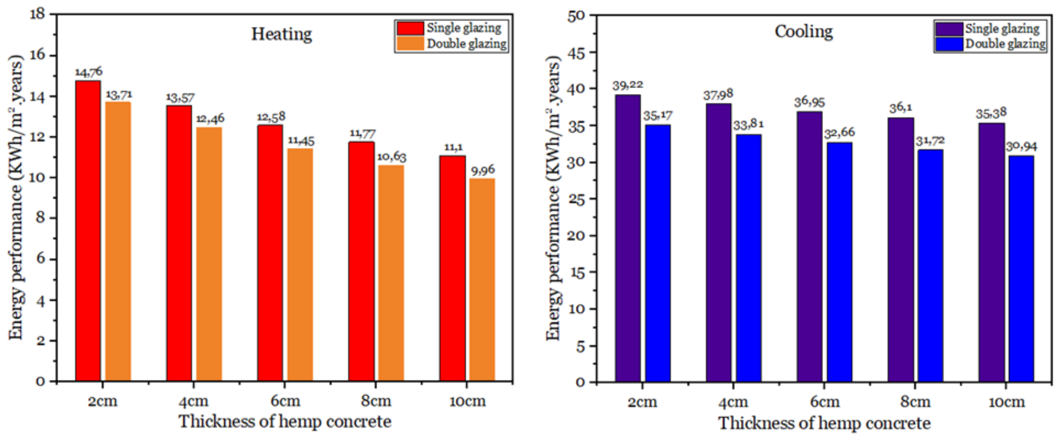

Figure 6. Energy requirements according to type of glazing.

Effect of natural ventilation

Natural ventilation is also an effective passive solution for reducing the building's energy loads. Figure 6 shows the loads of our building for three different natural ventilation scenarios according to the schedule in Table 8 and for a fixed window/wall ratio of 8.9%.

Table 8. Natural ventilation planning.

Scenarios	Winter period	Summer period
1	0,6ACH	0,6ACH
2	0,6ACH	1,5ACH
3	0,6ACH	2,5ACH

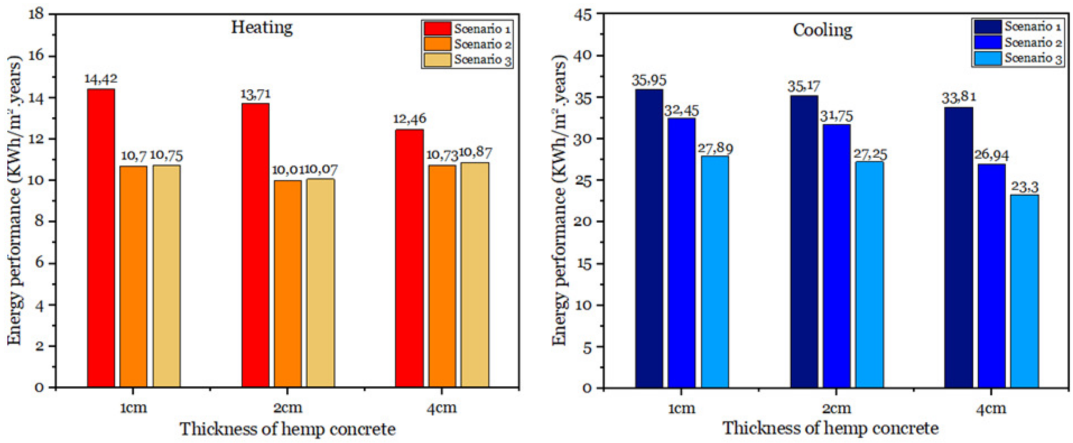

Figure 7. Energy requirements according to three natural ventilation scenarios.

Figure 7 shows that controlled natural ventilation has a positive impact on heating and cooling requirements, so scenario 2 represents the optimum choice, since energy consumption varies slowly above this ventilation rate, especially for heating loads. The use of natural ventilation under scenario 2 can reduce the thickness of the hemp concrete by up to 1 cm and can result in savings of 25.8% and 9.7% for heating and cooling respectively.

5. Conclusion

In this article, we carried out an energy simulation study for a residential building in Al-Hoceima. To meet the technical requirements of the RTCM, we used hemp concrete as a bio-sourced material for the insulation, as well as glazing and natural ventilation as passive strategies.
With regard to the simulation using TRNSYS in this study, the following results were obtained:

- The building can meet the technical requirements of the RTCM if its walls contain 10cm of hemp concrete.
- Using double glazing requires only 4cm of hemp concrete to achieve the first result.
- Controlled natural ventilation has a positive effect on heating and cooling requirements.
- A combination of double glazing and natural ventilation requires only 1cm of hemp concrete.

In conclusion, a combination of green construction (using bio-sourced materials) and passive strategies exponentially increases the energy performance of the building, as opposed to using these techniques separately.

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