Enhancing energy efficiency with poncebloc and hemp wool: a Moroccan case study

Yasser Boukioud, Kaoutar Senhaji Rhazi, Youssef Mejdoub
Laboratory of Networks, Computer Science, Telecommunication, Multimedia (RITM), CED Engineering Sciences ENSEM, Higher School of Technology ESTC, Hassan II University, Casablanca, Morocco

Article Info

Article history:

Received Apr 21, 2024
Revised Jul 17, 2024
Accepted Aug 28, 2024

Keywords:

Building consumption
Energy efficiency
Energy saving
Insulation material
Poncebloc
Transient simulation program

ABSTRACT

In recent years, the building sector's energy consumption in Morocco has been steadily increasing, highlighting the urgent need for sustainable building practices. Optimizing building parameters and the development of new insulation materials have become critical areas of research due to the significant energy losses associated with traditional insulation materials. Insulation materials can be a simple and cost-effective way to improve building energy efficiency and reduce environmental impact. Unfortunately, not all of these materials exhibit favorable thermal characteristics such as conductivity or heat capacity. Some involve complex production processes, while others are prohibitively expensive or toxic. At this juncture, the strategy of integrating ecological materials with insulation materials to enhance thermal performance holds considerable promise. This paper investigates the impact of the integration of poncebloc and hemp wool in inside temperature and annual consumption of a building construction numerically under a transient simulation program (TRNSYS). The results show that by using these two materials along with double-glazed windows, energy savings ranging from 50-55% can be achieved.

Corresponding Author:

Yasser Boukioud
Laboratory of Networks, Computer Science, Telecommunication, Multimedia (RITM)
National Higher School of Electricity and Mechanics, Higher School of Technology ESTC
Hassan II University
Casablanca-20100, Morocco
Email: boukioudyasser@gmail.com

1. INTRODUCTION

The building sector is a significant contributor to energy consumption, accounting for approximately 40% of the global energy demand. In Morocco, the building sector's energy consumption has been increasing steadily in recent years, posing a significant challenge to the country's energy security and sustainability. As a result, there is an urgent need for sustainable building practices that can mitigate the environmental impact and improve energy efficiency. One critical aspect of sustainable building practices is optimizing building parameters and developing new insulation materials. Traditional insulation materials, such as mineral wool, have significant energy losses, making them inefficient and costly in the long term. Therefore, there is a growing interest in developing new insulation materials that can improve building energy efficiency and reduce environmental impact. Building insulation stands as one of the readily accessible and efficient means to conserve energy in our present time. Its versatility extends across various domains, encompassing residential, commercial, and industrial sectors, thereby presenting a myriad of applications [1]. Insulation materials offer a straightforward and cost-effective method to enhance building energy efficiency [2] while concurrently reducing greenhouse gas emissions. A promising solution to achieve these goals involves integrating traditional insulation materials such as rock wool, natural insulations like cork or other natural fibers, or incorporating new materials derived from industrial processes such as expanded or extruded polystyrene and polyurethane.

Numerous studies investigated the thermal effect of these materials [3]–[7] and studied the influence of various building parameters on energy consumption. One noteworthy research conducted by Pescari *et al.* [8] focuses on the significance of enhancing the building envelope as an effective means of reducing energy consumption. Another study by Lafqir *et al.* [9] explores the impact of the building envelope in different climate zones of Morocco. Their findings demonstrate that the utilization of insulation materials can lead to a substantial decrease in the building's thermal load, reaching over 70% in most cases. However, in the cold weather conditions of Ifrane, the reduction never exceeded 57%. In a similar vein, Chegari *et al.* [10] investigated the effects of thermal insulation on a typical R+1 building across the six climate categories in Morocco. They found that thermal insulation had a significant impact on energy self-sufficiency in all zones, with a particular emphasis on Ifrane City and comparable climates. Furthermore, Hamdaoui *et al.* [11] shed light on the influence of insulation materials on the thermal behavior of buildings and their annual load. Through dynamic simulations using a transient simulation program (TRNSYS), they tested three scenarios and discovered that the third scenario, where the external walls, roof, and ground were properly insulated, resulted in the lowest annual load.

In an experimental study, Fang *et al.* [12] conducted a comparison between a non-insulated chamber and a chamber insulated with extruded polystyrene (XPS). The findings revealed that the implementation of XPS insulation resulted in a significant reduction of 23.5% in cooling load during the summer season. Sobhy *et al.* [13] conducted a comprehensive study involving both numerical simulations and experimental analysis on a modern-style house situated in Marrakech. The primary objective of the study was to evaluate the impact of thermal insulation applied to the building's envelope on its thermal load. The findings from the research revealed that the implementation of a 4 cm XPS insulation on the roof resulted in a noteworthy reduction of 10% in heating load and 30% in cooling load when compared to a non-insulated house. Moreover, the presence of 5 cm air gap cavity walls contributed significantly to energy savings. Insulating the cavity walls led to a 13% decrease in heating load and a 5% decrease in cooling load, in comparison to a non-insulated house. Notably, the combined effect of both insulations demonstrated substantial energy savings, with heating and cooling needs being reduced by 26 and 40% respectively. In their investigation, Benhamou and Bennouna [14] delved into the influence of envelope insulation on the external walls and roof, as well as the effects of solar protection on indoor comfort, heating load, and cooling load. The study specifically focused on a villa-type house situated in the city of Marrakech, located in Morocco. Kaynakli [15] showed in their article that the implementation of well-insulated external walls, with optimized thicknesses of insulation, results in substantial reductions in annual energy consumption for heating and cooling systems.

It is unfortunate that not all of these materials provide satisfactory thermal characteristics, such as conductivity or heat capacity. Some require complex manufacturing processes, others are financially costly, and some possess toxic properties. Consequently, the strategy of integrating ecologically-sourced materials with insulation materials to enhance thermal performance could prove highly beneficial. This pioneering approach offers the promise of considerable energy savings and a notable reduction in the environmental impact of buildings.

The proposed configuration for enhancing the thermal behavior of a building involves the use of poncebloc, an ecological material constructed from meticulously purified pumice. This volcanic stone is renowned for its magmatic structure, which effectively enhances heat transfer. The specific composition of the poncebloc block guarantees superior heat insulation properties and remarkable durability, which make it an ideal choice for sustainable construction practices.

A number of studies have highlighted the promising thermal characteristics of new ecological materials in buildings. For instance, Kymäläinen and Sjöberg [16] evaluated the potential of bast fibers derived from flax and hemp for insulation applications, finding these materials to possess favorable properties for insulation purposes. Four years later, Korjenic *et al.* [17] proposed the development of new insulation materials using hemp and flax, demonstrating through various experiments their thermal performance comparable to conventional materials. Subsequently, hemp wool as an insulation material gained significant attention due to these findings [18]. Le *et al.* [19] studied the impact of integrating hemp concrete in the building. They found that this solution could decrease the daily humidity inside, and reach about a 45% reduction in energy consumption.

In addition to poncebloc, hemp wool will also be integrated into the building to enhance its thermal behavior. This insulation material has shown interesting thermal characteristics despite its limited use in building insulation. Several studies have supported this idea, including the work of Dlimi *et al.* [20] which investigated the impact of integrating hemp wool as an insulation material in the wall structure of Moroccan buildings, specifically in the city of Meknes with a Mediterranean climate. The study showed that the integration of hemp wool could result in energy savings and consequently lead to a decrease in overall costs. In another research published in 2020, Dlimi *et al.* [21] compared an insulated building in the same city with a scenario where no insulation was present. They found that insulation with hemp wool yielded significant results, providing a 65% reduction when the external walls and roof were insulated. Other studies have also explored the integration of hemp wool in parallel with other materials. In their work, Charai *et al.* [22] demonstrated that integrating hemp wool with plasterboard significantly improves the thermal efficiency of buildings.

Poncebloc also exhibited interesting thermal behavior and could be used as a construction material for its mechanical properties. One of the studies demonstrating its good thermal characteristics is the research by Babaharra *et al.* [23] which investigated the effect of replacing hollow bricks with Poncebloc in the wall structure in the cities of Casablanca and Khouribga. The results showed a heating load reduction ranging from 26-28% in Casablanca, and a reduction from 26-29% in Khouribga. However, a decrease from 16-18% was observed in cooling load in Casablanca, and from 15-17% in Khouribga, depending on the studied scenarios. In another work, Ouhaibi *et al.* [24] conducted a study on the integration of poncebloc and aerogels in semi-arid and cold climates. The results showed that the proposed configuration simultaneously provided comfort for occupants inside the building and resulted in a decrease of about 44% in annual load in Marrakech and 42% in Ifrane. They concluded that using these two materials could be an ecological solution not only because of their effect on comfort and energy consumption but also due to their reduction in greenhouse gas emissions.

Most research in the literature does not investigate the impact of combining two different types of insulators, especially natural with ecological materials. In this context, this paper investigates the impact of the integration of poncebloc and hemp wool parallel as insulation materials in building construction across different climate types in Morocco. The study is done using TRNSYS simulation software, and the impact factor used for the comparison between climate types will be the inside temperature of the building and its annual load. This work is composed of three sections. The first section includes the studied case parameters, considerations, and the plan of our research. The second part shows the work’s results and then conducts a discussion about these results. The third part contains a conclusion where some future dimensions for research are mentioned. The paper aims to evaluate the energy performance of the proposed insulation materials in building construction and determine their potential for energy savings. Finally, the research results could encourage future studies to explore the combination of existing insulation materials.

2. METHOD

2.1. Building description

Our investigative sample is a cell located inside the Faculty of Sciences of Casablanca (Ain Chock), the structure has a footprint of 9 m^2 and a total volume of approximately 27 m^3. The entrance to the space faces north, while a single-glazed window with an aluminum frame measures 1 m in height and width Figure 1. The walls of the structure are 29 cm thick. The cell is located at an altitude of 57 m and in longitude and latitude respectively of 07°36 W and 33 °36′ N. The building is made up of four exterior walls, a roof, and a floor. Each exterior wall consists of two parts of cement mortar with red bricks separated by an air gap. The floor comprises successive layers of limestone, heavy concrete, polystyrene, and clay, covered with a layer of cement mortar, however, the roof structure is composed of three layers of cement mortar and one layer of heavy concrete, moreover a bitumen layer Table 1. The total resistance of the exterior wall is 1.883 m^2.K/W, for the roof is about 0.367 m^2.K/W, finally, it’s about 0.673 m^2.K/W for the floor Table 2.

Figure 1. Picture of the studied cell (building)

2.2. The climate of Morocco

The climate in Morocco is categorized into six distinct climatic zones as defined by Moroccan thermal regulations [25]. These zones encompass numerous cities across Morocco, as depicted in Figure 2. Each zone reflects varying environmental conditions that influence building design and energy efficiency strategies.

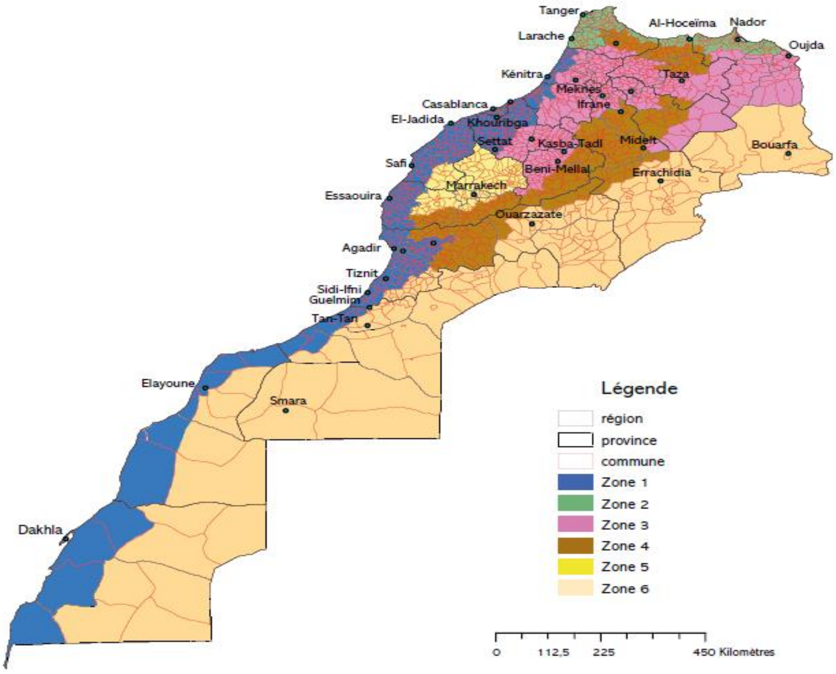


Figure 2. Moroccan climatic zones map [26]

Table 1. Wall characteristics for the reference configuration [25]

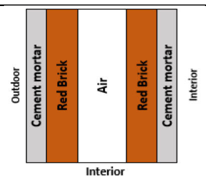
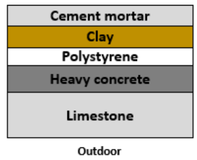
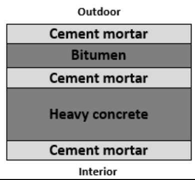
Cell part	Layers	Thickness (cm)	Density (kg/m^3)	Thermal conductivity (W/m.K)	Thermal capacity (kJ/kg.K)	Structure
Exterior wall	Cement mortar	1	1,700	1.15	1	
	Red brick	7.2	1,700	1.15	0.794	
	Air	12.6	1	0.08	1.227	
	Red brick	7.2	1,700	1.15	0.794	
	Cement mortar	1	1,700	1.15	1	
Floor	Cement mortar	5	1,700	1.15	1	
	Clay	3	2,000	0.6	1.5	
	Polystyrene	2	25	0.039	1.38	
	Heavy concrete	4	2,300	1.75	0.92	
	Limestone	10	2,400	2.25	0.8	
Roof	Cement mortar	2	1,700	1.15	1	
	Bitumen	3	1,700	0.5	1	
	Cement mortar	2	1,700	1.15	1	
	Heavy concrete	15	2,300	1.75	0.92	
	Cement mortar	2	1,700	1.15	1	

Table 2. Resistance of each wall in the reference configuration

Cell composition	Resistance (m^2.K.W^{-1})
Exterior wall	1.883
Floor	0.673
Roof	0.367

2.3. Research plane

The building under study is located in Casablanca, and its characteristics are detailed in the methods section. In this paper, we propose a new wall configuration for buildings. This configuration will be tested in various scenarios where the building is located in Agadir, Marrakech, Ifrane, Fes, Errachidia, and Tangier. Climatic data for each zone, provided by the METEONORM software, along with building parameters, will be used as inputs for the dynamic simulation system of TRNSYS. The impact of the proposed configuration will be assessed by examining the indoor temperature of the building and its cooling and heating requirements. These results will then be compared to a reference case (non-insulated building) to identify where maximum energy savings are achieved, thereby determining the most effective application of the proposed configuration. More details about the proposed configuration and simulation parameters will be provided in subsequent sections.

2.4. The simulation and building energy modeling

The studied case was simulated under TRNSYS16, and by using type 56 under the mode TRNBUILD as shown in Figure 3, with a step of 1 hour. The model used for the calculation of the heat balance is described in (1).

$$C_p.\frac{dT_{int}}{dt} = \dot{Q}_n - \dot{Q}_{HVAC} \quad (1)$$

Where Cp is the specific heat, T_{int} is the inside temperature of the cell, $\dot{Q}_{HVAC}$ is the power output for the considered thermal zone. It is determined by assuming a linear relationship between the temperature change in the zone air and the amount of power supplied and $\dot{Q}_n$ is the global energy flow for node n. It is obtained using the (2).

$$\dot{Q}_n = \dot{Q}_{air} + \dot{Q}_{cplg} + \dot{Q}_{Surf} + \dot{Q}_{solar} + \dot{Q}_{env} + \dot{Q}_{int} \quad (2)$$

Where $\dot{Q}_{air}$ is defined as the rate of heat gain resulting from infiltration and ventilation across the building envelope, $\dot{Q}_{cplg}$ is the gain due to airflow from boundary conditions. $\dot{Q}_{Surf}$ is the heat transfer through convection from all interior surfaces, $\dot{Q}_{Solar}$ is the windows absorbed solar gain rate, $\dot{Q}_{env}$ refers to the rate at which heat is transferred across the building envelope, $\dot{Q}_{int}$ refers to the internal gain produced by people, equipment, illumination, and radiators The Expanded clarification could be provided by the TRNSYS user manual [27].

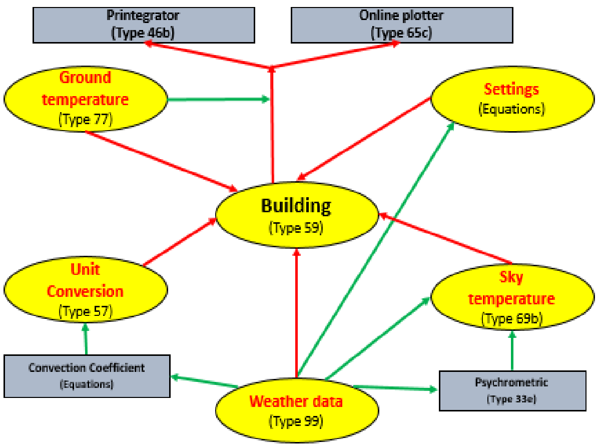


Figure 3. TRNSYS system diagram

2.5. Simulation parameters and considerations

In this instance, the calculations are performed over a one-year period, commencing on January 1st and ending at midnight on December 31st. The simulation was conducted with the following parameters: the temperature inside the cell was set to fluctuate between 20 and 26 °C due to the operation of the cooling and heating equipment, with infiltration fixed at approximately 0.5 l/h. The initial conditions are set to a temperature of 20 °C and a relative humidity of 50%. The contribution of internal gains from the inhabitants is considered to be negligible. The walls and roofs are estimated to have an outer surface absorption coefficient of 0.7 and an emissivity coefficient of 0.9. The cell is equipped with a lamp that generates 5 W/m² of internal heat, and the doors and windows remain closed at all times. TRNSYS 16 will handle these considerations and generate input parameters based on them.

2.6. The investigated configuration

Figure 4 shows the suggested configuration for the roof and external wall, Figure 4(a) proposed configuration involves integrating a layer of 24 cm of poncebloc with two 1.5 cm thick layers of hemp wool in the exterior wall. Additionally, in Figure 4(b) a layer of 3 cm of hemp wool will be integrated into the roof structure between the heavy concrete layer and the cement. This configuration will be tested, taking into consideration the glazing effect on energy consumption. Double glazing was chosen for this configuration due to its low U-value and cost-effectiveness compared to other types of glazing. Table 3 provides more information about the suggested structure, and Table 4 describes the six climate zones.

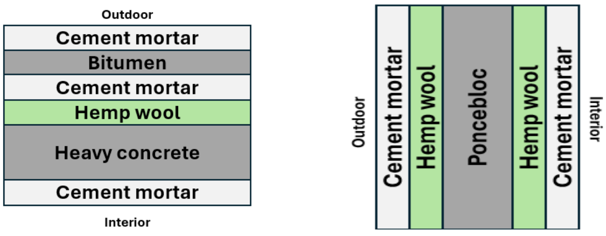


Figure 4. Suggested configuration in roof and external wall (a) roof configuration and (b) external wall configuration

Table 3. Wall characteristics for the suggested configuration

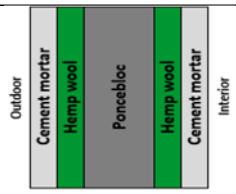
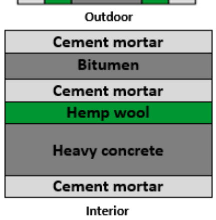
Cell part	Layers	Thickness (cm)	Density (kg/m³)	Thermal conductivity (W/m.K)	Thermal capacity (kJ/kg.K)	Structure
Exterior wall	Cement mortar	1	1,700	1.15	1	
	Hemp wool	1.5	35	0.04	1.2	
	Poncebloc	24	365	0.126	1	
	Hemp wool	1.5	35	0.04	1.2	
	Cement mortar	1	1,700	1.15	1	
Roof	Cement mortar	2	1,700	1.15	1	
	Heavy concrete	12	2,300	1.75	0.92	
	Hemp wool	3	35	0.04	1.2	
	Cement mortar	2	1,700	1.15	1	
	Bitumen	3	1,700	0.5	1	
	Cement mortar	2	1,700	1.15	1	

Table 4. Studied climate description [28]

City	Agadir	Marrakech	Ifrane	Fes	Errachidia	Tangier
Altitude (m)	56	460	1665	415	1084	80
Longitude	-9.59°E	-7.99°E	-5.2°E	-5.00°E	-4.42°E	-5.80°E
Latitude	30.42°N	31.62°N	33.50°N	34.04°N	31.93°N	35.77°N
Climate type	Atlantic	Semi-arid	Cold	Continental	Desert	Mediterranean
T_{max}(°C)	44.06	45.9	40.8	44.62	43	37.26
T_{min}(°C)	3.29	3.7	-5	0.11	0.63	3.07

2.7. Research objectives and scope

The article aims to investigate the effect of the suggested case. In the first section, it will discuss the influence of this suggestion on the temperature inside the cell. The cell temperature for both configurations will be evaluated without using cooling or heating to determine if the proposed configuration provides a comfortable indoor environment. The second part will highlight the potential energy savings that can be achieved by using this configuration in the building. The study will be conducted in the six Moroccan zones to determine where the maximum and minimum savings can be achieved.

2.8. Simulation validation

In order to ensure the accuracy of our simulation program, we conducted a validation simulation based on the study by Mourid *et al.* [29], who performed an experimental study on a building in Casablanca. The validation simulation was carried out over three days, from April 20 to April 23, 2014. Table 5 provides information on the temperature differences between the experimental data reported [29] and the temperatures obtained from our simulation. Table 5 also includes the relative error associated with each time value.

Table 5. Comparison of indoor air temperatures simulated vs measured data

Time (h)	ΔT (°C)	e_r (%)
4	0.4	2.17
8	0.45	2.5
16	-0.5	2.27
24	0.78	3.66
32	0.77	4.05
54	0.15	4.05
64	-0.35	1.77

From Table 5, we can observe that the difference between the experimental and simulation results is not significant, as indicated by the relative error values, which are all less than 5%. This suggests that our simulation model provides accurate results with sufficient precision. Therefore, we can conclude that the results produced by this model align well with the experimental data. Consequently, we can rely on this model for our investigation and to determine the impact of using the proposed configuration in the building.

3. RESULTS AND DISCUSSION

3.1. Temperature inside the cell

Previous studies have explored the impact of different insulation materials on indoor temperature variations and annual building loads. However, most research does not investigate the impact of combining different insulation materials, unlike our study. The indoor temperature was calculated using the simulation program.

It can be observed from Figure 5 which illustrates the temperature variations throughout the year, that the temperature of the proposed configuration (T_sc) is lower than in the reference case (T_ref) during hot seasons, but higher during the cold season. Additionally, the difference between the reference case temperature and the proposed case temperature varies from city to city and from season to season.

For the cold season, the smallest difference between the two scenarios is observed in Agadir (Figure 5(a)). In contrast, for the hot season, the largest difference is noted in Marrakech (Figure 5(b)). In the cold climate, the maximum difference is observed in Ifrane (Figure 5(c)), while Fes (Figure 5(d)) shows the second smallest difference, following Agadir. For the hot climate, Errachidia (Figure 5(e)) presents the second smallest difference, after Marrakech. Therefore, the suggested configuration is a good solution because it provides good comfort, especially in cold and hot climates, where achieving comfort is difficult. Another observation is that in the suggested case, the temperature fluctuation compared to the ambient temperature is less than in the reference case. Specifically, it is around 17.51 °C in Agadir (Figure 5(a)), 23.59 °C in Marrakech (Figure 5(b)), 26.37 °C in Ifrane (Figure 5(c)), 25.01 °C in Fes (Figure 5(d)), 27.59 °C in Errachidia (Figure 5(e)), and 20.29 °C in Tangier (Figure 5(f)). In contrast, in the reference configuration, we observed 21.16 °C in Agadir, 27.15 °C in Marrakech, 30.42 °C in Ifrane, 29.39 °C in Fes, 31.28 °C in Errachidia, and finally 24 °C in Tangier. These results demonstrate that this configuration maintains comfortable indoor conditions. The proposed setup ensures a high level of comfort regarding indoor temperatures, which remains stable and pleasant despite weather fluctuations.

3.2. Heating and cooling needs

One way to evaluate the effectiveness of a wall configuration in the building is to examine its heating and cooling power consumption and determine the potential energy savings. To this end, the heating and cooling requirements of each configuration were investigated, with the target indoor temperature ranging from 20-26 °C. Heating was activated when the temperature fell below 20 °C, while cooling was triggered when the temperature rose above 26 °C. The simulation was conducted over a one-year period, without taking into account the presence of occupants. The results obtained from the suggested configurations will be compared to the reference case where simple glazing is used. Agadir is a city in Morocco with a unique Atlantic climate, characterized by cold temperatures during the winter season and a greater demand for heating than cooling. In this study, we investigate the effectiveness of a suggested configuration for reducing energy consumption in various Moroccan cities.

From the results presented in Figure 6, it is evident that the proposed configuration can significantly reduce energy consumption for both heating and cooling purposes. Specifically, the configuration reduces heating requirements by 54.6% and cooling requirements by 52.6% in Agadir (Figure 6(a)), resulting in a total energy savings of 54.1%. Similarly, in Marrakech (Figure 6(b)), the configuration achieves total savings of 53.3%, with a reduction of 54% in heating and 52.6% in cooling.

For cities with colder climates such as Ifrane (Figure 6(c)), the integration of poncebloc with hemp wool results in a total load savings of 52.5%, with 52.3% savings in heating and 54.3% in cooling. In Fes (Figure 6(d)), a total savings of 53.1% is achieved, with 53% in heating and 53.5% in cooling. In Errachidia (Figure 6(e)), savings of 53.3% and 50.8% are obtained for heating and cooling, respectively, resulting in a total savings of 51.9%. In Tangier (Figure 6(f)), the new configuration achieves a total savings of about 54.4%, with 53.8% in heating and 56.5% in cooling. Overall, the results indicate that the suggested configuration is effective in reducing energy consumption and achieving significant savings in heating and cooling needs in various Moroccan cities. These findings could have significant implications for energy conservation and cost savings in the region.

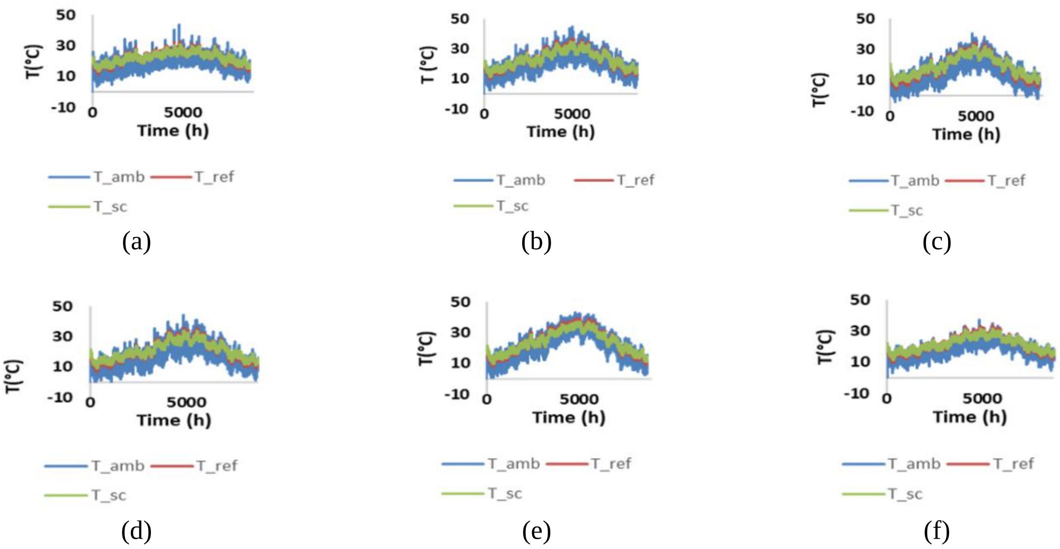


Figure 5. Annual variation of ambient temperature, inside temperature in the reference case, and inside temperature in suggested case of (a) Agadir, (b) Marrakech, (c) Ifrane, (d) Fes, (e) Errachidia, and (f) Tangier

Results analysis indicates that the proposed configuration yields significant energy savings in various climatic regions, albeit with varying efficiency levels. Notably, Agadir displays the highest heating savings, while Ifrane shows the lowest. Conversely, Tangier demonstrates the highest cooling savings, while Errachidia has the lowest. In general, the configuration proves to be more effective in Tangier and less effective in Errachidia. These findings underscore the importance of tailoring energy-efficient solutions to local conditions. Additionally, the implementation of the suggested configuration can lead to substantial cost savings and reduced electricity bills, making it a practical and sustainable solution for addressing heating and cooling requirements in diverse climatic zones.

Despite the natural, user-friendly, and lightweight characteristics of the materials used in the proposed configuration, along with their straightforward production processes and sometimes lower costs compared to alternative materials, the energy savings achieved in this study are observed to be comparatively lower than those reported by Ouhaibi *et al.* [30]. However, exploring alternative applications or modifying the utilization of these materials could potentially unlock significant energy-saving potential for buildings in future endeavors. Additionally, further in-depth research is necessary to validate their economic and environmental impacts, particularly in terms of cost-effectiveness and sustainability. Comparative studies across various climate types are also essential. Future research should consider these aspects to promote the adoption of combined insulation solutions.

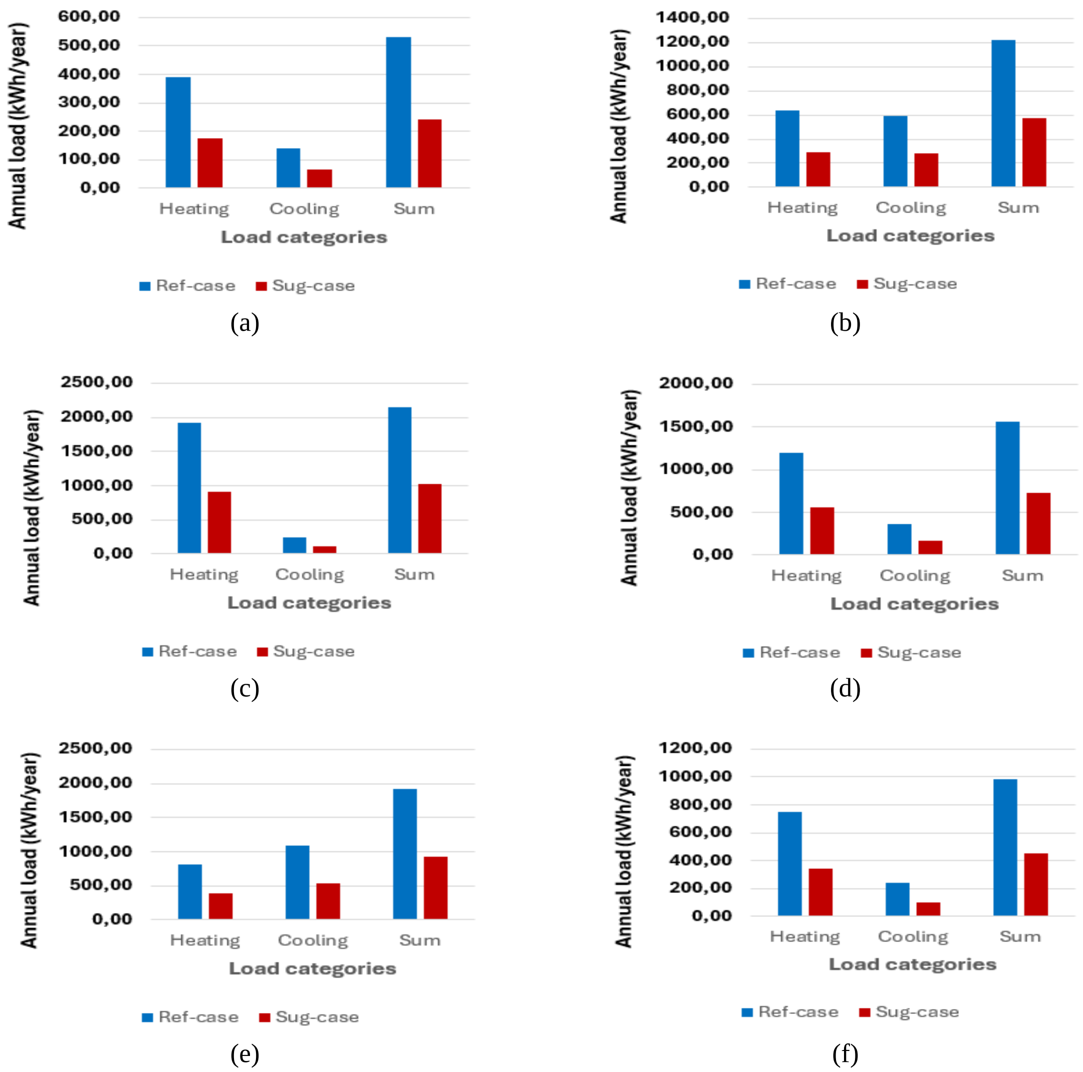


Figure 6. Comparison between the annual consumption for heating and cooling for both reference and suggested configuration for (a) Agadir, (b) Marrakech, (c) Ifrane, (d) Fes (e), Errachidia, and (f) Tangier

4. CONCLUSION

The present study employed a dynamic simulation approach using TRNSYS to investigate the effects of combining different materials in building construction. Specifically, poncebloc was combined with hemp wool, a natural insulation material, in both the building's roof and exterior wall due to their favorable low thermal conductivity properties. The objective of this study was to evaluate the impact of integrating both mineral and natural insulation materials. The analysis commenced with a thermal behavior assessment, with the internal temperature of the building cell being the primary parameter. The findings indicate that the inside temperature was higher in the suggested case compared to the reference during the cold season, while it was lower in the proposed case than the reference during the hot season. Furthermore, the results demonstrate that the proposed case provides less temperature fluctuation throughout the year, thus ensuring greater comfort inside the cell. The study also discovered that the minimum fluctuation value was observed in Agadir, while the maximum was recorded in Errachidia.

In the second section, we evaluated the efficiency of the proposed building configuration and investigated its impact on heating and cooling needs. Our results show a significant decrease in these requirements, resulting in energy savings that vary across different climatic zones. The maximum energy savings in heating were observed in Agadir, with a reduction of about 54.6%, while the lowest energy savings were recorded in Ifrane, with a reduction of about 52.3%. Similarly, the highest value of cooling savings was found in Tangier, with a reduction of 56.5%, while the lowest one was recorded in Errachidia, with a reduction of 50.8%. Based on these findings, we conclude that the proposed building configuration is more effective in Tangier, with a total energy saving of 54.4%, while it is less effective in Errachidia. Despite the variation in efficiency depending on the climate zone, the suggested configuration provides significant energy savings in all climatic zones in Morocco. In conclusion, the proposed configuration is an effective and efficient solution in terms of both indoor comfort and energy savings. This study demonstrates that incorporating multiple types of insulation materials within a building can be advantageous and beneficial for investors. It may encourage researchers to explore and develop further integrations of diverse insulation materials. Future studies could investigate the economic and environmental impacts of such multi-insulation configurations. Additionally, comparative studies could analyze this proposed approach against others utilizing different combinations of insulators.

ACKNOWLEDGEMENTS

The author expresses sincere gratitude to the Superior School of Technology (EST), University of Hassan II of Casablanca, for providing essential resources and support. Special thanks to Professors Youssef Mejdoub and Kaoutar Senhaji Rhazi for their invaluable guidance and mentorship.

REFERENCES

[1] L. Aditya *et al.*, "A review on insulation materials for energy conservation in buildings," *Renew. Sustain. Energy Rev.*, vol. 73, pp. 1352–1365, Jun. 2017, doi: 10.1016/j.rser.2017.02.034.
[2] L. F. Cabeza, A. Castell, M. Medrano, I. Martorell, G. Pérez, and I. Fernández, "Experimental study on the performance of insulation materials in Mediterranean construction," *Energy Build.*, vol. 42, no. 5, pp. 630–636, May 2010, doi: 10.1016/j.enbuild.2009.10.033.
[3] M. Ozel, "Effect of insulation location on dynamic heat-transfer characteristics of building external walls and optimization of insulation thickness," *Energy Build.*, vol. 72, pp. 288–295, Apr. 2014, doi: 10.1016/j.enbuild.2013.11.015.
[4] M. EL Wazna *et al.*, "Experimental and numerical study on the thermal performance of alternative insulation materials based on textile waste: a finite-difference approach," *J. Ind. Text.*, vol. 49, no. 10, pp. 1281–1303, Jun. 2020, doi: 10.1177/1528083718811104.
[5] M. F. Alsayed and R. A. Tayeh, "Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings," *J. Build. Eng.*, vol. 22, pp. 101–112, Mar. 2019, doi: 10.1016/j.jobe.2018.11.018.
[6] B. M. Marino, N. Muñoz, and L. P. Thomas, "Calculation of the external surface temperature of a multi-layer wall considering solar radiation effects," *Energy Build.*, vol. 174, pp. 452–463, Sep. 2018, doi: 10.1016/j.enbuild.2018.07.008.
[7] N. Daouas, "A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads," *Appl. Energy*, vol. 88, no. 1, pp. 156–164, Jan. 2011, doi: 10.1016/j.apenergy.2010.07.030.
[8] S. Pescari, M. Merea, A. Pitroacă, and C.-B. Vilceanu, "A particular case of urban sustainability: comparison study of the efficiency of multiple thermal insulations for buildings," *Sustainability*, vol. 14, no. 23, Dec. 2022, doi: 10.3390/su142316283.
[9] F.-E. Lafqir, I. Sobhy, B. Benhamou, A. Bennouna, and K. Limam, "Thermal performance of passive techniques integrated to a house and the concept of passive house in the six climates of Morocco," *Sci. Technol. Built Environ.*, vol. 26, no. 10, pp. 1490–1508, Nov. 2020, doi: 10.1080/23744731.2020.1805983.
[10] B. Chegari, M. Tabaa, F. Moutaouakkil, E. Simeu, and H. Medromi, "Local energy self-sufficiency for passive buildings: case study of a typical Moroccan building," *J. Build. Eng.*, vol. 29, May 2020, doi: 10.1016/j.jobe.2019.101164.
[11] S. Hamdaoui, M. Mahdaoui, A. Allouhi, R. El Alaiji, T. Kousksou, and A. El Bouardi, "Energy demand and environmental impact of various construction scenarios of an office building in Morocco," *J. Clean. Prod.*, vol. 188, pp. 113–124, Jul. 2018, doi: 10.1016/j.jclepro.2018.03.298.
[12] Z. Fang, N. Li, B. Li, G. Luo, and Y. Huang, "The effect of building envelope insulation on cooling energy consumption in summer," *Energy Build.*, vol. 77, pp. 197–205, Jul. 2014, doi: 10.1016/j.enbuild.2014.03.030.
[13] I. Sobhy, A. Brakez, and B. Benhamou, "Analysis for thermal behavior and energy savings of a semi-detached house with different insulation strategies in a hot semi-arid climate," *J. Green Build.*, vol. 12, no. 1, pp. 78–106, Jan. 2017, doi: 10.3992/1552-6100.12.1.78.
[14] B. Benhamou and A. Bennouna, "Energy performances of a passive building in Marrakech: parametric study," *Energy Procedia*, vol. 42, pp. 624–632, 2013, doi: 10.1016/j.egypro.2013.11.064.
[15] O. Kaynakli, "A review of the economical and optimum thermal insulation thickness for building applications," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 415–425, Jan. 2012, doi: 10.1016/j.rser.2011.08.006.
[16] H.-R. Kymäläinen and A.-M. Sjöberg, "Flax and hemp fibres as raw materials for thermal insulations," *Build. Environ.*, vol. 43, no. 7, pp. 1261–1269, Jul. 2008, doi: 10.1016/j.buildenv.2007.03.006.
[17] A. Korjenic, V. Petránek, J. Zach, and J. Hroudová, "Development and performance evaluation of natural thermal-insulation materials composed of renewable resources," *Energy Build.*, vol. 43, no. 9, pp. 2518–2523, Sep. 2011, doi: 10.1016/j.enbuild.2011.06.012.
[18] L. Liu *et al.*, "The development history and prospects of biomass-based insulation materials for buildings," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 912–932, Mar. 2017, doi: 10.1016/j.rser.2016.11.140.
[19] A. D. Tran Le, C. Maalouf, T. H. Mai, E. Wurtz, and F. Collet, "Transient hygrothermal behaviour of a hemp concrete building envelope," *Energy Build.*, vol. 42, no. 10, pp. 1797–1806, Oct. 2010, doi: 10.1016/j.enbuild.2010.05.016.
[20] M. Dlimi, R. Agounoun, I. Kadiri, K. Sbai, and A. Rahmani, "Effect of the integration of hemp wool as an insulation material for

the construction of the roof and external walls of a typical Moroccan building," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 783, no. 1, Mar. 2020, doi: 10.1088/1757-899X/783/1/012013.

[21] M. Dlimi, O. Iken, R. Agounoun, A. Zoubir, I. Kadiri, and K. Sbai, "Energy performance and thickness optimization of hemp wool insulation and air cavity layers integrated in Moroccan building walls'," *Sustain. Prod. Consum.*, vol. 20, pp. 273–288, Oct. 2019, doi: 10.1016/j.spc.2019.07.008.

[22] M. Charai, H. Sghiouri, A. Mezrhab, and M. Karkri, "Thermal insulation potential of non-industrial hemp (Moroccan cannabis sativa l.) fibers for green plaster-based building materials," *J. Clean. Prod.*, vol. 292, Apr. 2021, doi: 10.1016/j.jclepro.2021.126064.

[23] O. Babaharra, K. Choukairy, K. Khallaki, and S. H. Mounir, "Numerical study of the effect of different construction materials on heating and cooling loads for two climatic zones in Morocco," 2018. doi: 10.1063/1.5084992.

[24] S. Ouhaibi, N. Belouaggadia, R. Lbibb, and M. Ezzine, "Simulation of energy- efficient building prototype using different insulating materials," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 353, no. 1, 2018, doi: 10.1088/1757-899X/353/1/012008.

[25] A. Mourid, M. El Alami, and F. Kuznik, "Experimental investigation on thermal behavior and reduction of energy consumption in a real scale building by using phase change materials on its envelope," *Sustain. Cities Soc.*, vol. 41, pp. 35–43, Aug. 2018, doi: 10.1016/j.scs.2018.04.031.

[26] ADEREE (Agence Nationale pour le Développement des Énergies Renouvelables et de l'E!cacité Énergétique), "Règlement thermique de construction au maroc," AMEE Agence Marocaine pour l'Efficacité Energétique. Accessed: Dec. 30, 2023. [Online]. Available: https://www.amee.ma/sites/default/files/inline-files/Reglement_thermique_de_construction_au_Maroc.pdf

[27] TRNSYS Coordinator, "TRNSYS16-multizone building modeling with type56 and trnbuild," 2007. [Online]. Available: https://web.mit.edu/parmstr/Public/Documentation/06-MultizoneBuilding.pdf

[28] Meteotest, "Meteonorm," Meteotest. Accessed: Sep. 09, 2023. [Online]. Available: https://meteonorm.com

[29] A. Mourid, Y. Bouzlou, M. El Alami, M. Najam, and M. Faraji, "Passive study of thermal inertia and thermal behavior of two locals 'test' with and without PCM located in Casablanca City," in *2014 International Renewable and Sustainable Energy Conference (IRSEC)*, IEEE, Oct. 2014, pp. 851–854. doi: 10.1109/IRSEC.2014.7059753.

[30] S. Ouhaibi, A. Gounni, N. Belouaggadia, M. Ezzine, and R. Lbibb, "Thermal performance of new ecological material integrated into residential building in semi-arid and cold climates," *Appl. Therm. Eng.*, vol. 181, Nov. 2020, doi: 10.1016/j.applthermaleng.2020.115933.

BIOGRAPHIES OF AUTHORS

Yassir Boukioud is a Ph.D. candidate at Hassan II University of Casablanca, Morocco, affiliated with the National Higher School of Electrical and Mechanical Engineering. He completed his Master's degree in Renewable Energies and Energetic Systems at the Faculty of Science in Casablanca. His primary research areas encompass renewable energies, energy efficiency, building energy efficiency, and electrical power. He can be contacted at email: boukioudyasser@gmail.com.

Kaoutar Senhaji Rhazi qualified professor in Electrical Engineering; at the School of Technology in Casablanca, Hassan II University, Morocco. A graduate engineer in electrical engineering from the Mohammadia School of Engineers (EMI) in Rabat. Morocco (in 1991). Had the research preparation certificate (CPR) in telecommunications Ph.D. in July 2006 (in electromagnetic compatibility). Passed academic qualification in the same field in 2014. Became a higher education teacher in 2020. Current research interests are: 'power electronics' and 'electromagnetic compatibility'. She can be contacted at email: senhaji.ksr@gmail.com.

Youssef Mejdoub was born in Morocco, in 1980. He received his Ph.D. Thesis on Modeling of Multiconductor Transmission Lines, in 2014 from Cadi Ayyad University, Marrakech Morocco. Since 2016, he has been a Professor at the Superior School of Technology (EST), Hassan II University, Casablanca, Morocco. He currently works at the Electrical Engineering Department, Superior School of Technology. His current research interests are 'antennas', 'electromagnetic compatibility', and 'MTL lines'. He can be contacted at email: ymejdoub@yahoo.fr or youssef.mejdoub@univh2c.ma.