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Towards Sustainable and Energy-Efficient Construction: Thermal Assessment Using Experimental and Numerical Methods

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Abstract. The construction industry increasingly seeks sustainable insulation solutions. This study evaluates the thermal performance of a novel bio-based material made from recycled cardboard and esparto fibers, compared to conventional hollow concrete blocks. The approach combines experimental characterization of material properties with dynamic thermal simulations of a residential building using DesignBuilder, under two contrasting Moroccan climates: hot (Marrakech) and cold (Ifrane). Results reveal a strong climate influence: cooling demand dominates in Marrakech (5,163.75 kWh annually), whereas heating demand is higher in Ifrane (6,772.45 kWh annually). These findings emphasize the importance of tailoring insulation strategies to local climatic conditions to improve energy efficiency.
Keywords: Bio-based insulation; Thermal performance; Hollow concrete blocks; Thermal simulation; Sustainable building materials

1 Introduction

The construction industry consumes approximately a quarter of the total energy consumed in the world, and it is also a top producer of the greenhouse gases. This has seen it become a major research topic in a bid to develop strategies that can ensure there is an acoustic and thermal comfort without a significant environmental impact. Conventionally, insulation has been based on petrochemical substances such as polystyrene or natural resources whose processing needs energy intensive processing such as glass wool and rock wool [1]. End-of-life disposal particularly of plastics is one of the greatest environmental issues. In reaction, sustainability ideas have become common in building, and more and more people are interested in insulation materials of natural or recycled materials. Natural fibers and waste-based products are renewable and biodegradable and usually have lesser environmental impact than synthetic products.

Venkatarajan et al. [2] have indicated that synthetic fibers can be substituted by plant-fiber-based composites using polymer matrices, and they could be used in sustainable construction. Some of the studies show that natural and recycled fibers are effective in acoustic insulation. Gle et al. [3] discovered hemp particles that were smaller in size exhibited better sound absorption especially at low frequencies. In a study conducted by Cherradi et al. [4], composites composed of polyvinyl acetate, esparto fibers, and wood fibers were compared and it was established that such natural composites can compete with synthetic acoustic insulators. On the same note, Delhomme et al. [5] examined the

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Australian hemp where thermal conductivity was found to be 0.064-0.097 $W.m^{-1}.K^{-1}$ and sound absorption coefficient was found to be 0.88-0.99 meaning that hemp would perform well both thermally and acoustically. A study by Ricciardi et al. [6] on a panel using polyurethane adhesive using rice husks, cork and spent coffee as the building materials revealed that a mixture of 20% rice husks, 60% cork, and 20% coffee flakes were the ones that have the best thermal performance and low environmental impact. According to these ideas, the current paper will create and describe new insulation panels based on cardboard waste materials and natural fibers available locally. The scanning electron microscopy (SEM) was made to analyze microstructural data and the basic performance indicators such as sound absorption, transmission loss, airflow resistivity, thermal conductivity, thermal diffusivity, heat capacity, and bulk density were measured systematically. Also, the effect of sample thickness and air-back cavity on acoustic performance was considered, and a thorough analysis of these sustainable materials was made. International Energy Environment and the Moroccan Construction industry.

The global energy demand has been on an upward trend in recent years and this has captured economic, social and industrial transformations in the world. The global energy consumption is anticipated to grow by an average of almost 50 percent between 2020-2050 primarily as a result of population growth and the growing industrial operations [7]. In this respect, the building industry is at the centre stage, as it constitutes a large portion of the ultimate energy demand of the globe [8]. However, this significance is associated with a price: it is also in buildings that they emit a significant percentage of the total CO_2 generated in the world, mostly because of the energy needed to heat, cool, light, and fulfill other crucial purposes [9] . This further makes it more urgent to find out effective methods of decreasing consumption and still ensure that the occupants remain comfortable. To deal with this issue both a technical and an architectural solution is needed. The modern technologies like the heat pumps, solar thermal and photovoltaic (PV) power generation systems can be introduced to the building to ensure energy performance is considerably increased by well-designed envelopes [10]. These measures have the potential not only to yield less energy use but also to have a smaller impact on the environment of buildings when they are applied appropriately. Such technologies have become very common in some countries, especially in Europe and North America because of stringent regulation and monetary stimuli in support of the high-performance building industry. In this aspect, Morocco has been doing well too. The country has over the years enacted bold policies in order to enhance energy efficiency [11, 12].

The national objective is evident: the energy use will be lowered by 20 percent by 2030, and the building industry will occupy a significant portion of the energy use. The residential sector which comprises houses and apartments consumes about 27 percent of the total energy of the country, second only to the transport sector [11, 12]. These values demonstrate the strategic significance of implementing the solutions specific to the situation in Morocco to minimize the consumption of energy and the emissions of CO2. In order to steer these, Morocco came up with a Thermal Building Regulations (RTCM) that incorporates a system of climate zoning to deal with the environmental conditions of the area. There are six homogeneous climate zones in the country: Zone 1 - Atlantic, mild (Agadir), Zone 2 - Mediterranean (Tangier), Zone 3 - Continental, temperate (Fes), Zone 4 - Cold, continental (Ifrane), Zone 5 - Hot semi-arid (Marrakech) and Zone 6 - Hot desert (Errachidia). With this zoning, it is possible to develop climate-specific construction practices, maximizing the performance on building energy and providing thermal comfort to the occupants. Nonetheless, the issue extends past rules. Building performance in Morocco is largely affected by the diversity of local materials and building construction methods [13]. In most of the urban and rural regions, the residential structures have diverse shapes and designs that are usually passed on through the historical practices or limited by economic provisions. It is essential to know how these materials and techniques will affect the result and how to find out the most effective ways to decrease the energy consumption without compromising the comfort of the occupants. A part of the current buildings has already an adequate performance, and other buildings need specific improvements. That is why it is important to take into account regional peculiarities: a universal solution does not always fit all the places. Having examined the diversity of building envelopes, construction methods, and climate areas, one can create useful context-dependent strategies that would use the most energy and save money without losing the comfort. Based on this, the current research is expected to investigate the energy performance and thermal comfort of the current residential buildings in Morocco. The research will aim to offer viable remedies to enhance the energy efficiency by coming up with the most effective configurations of the building to be constructed in every type of climate and material. The final aim is to ensure a good base that will in the future steer the building perspective to a much more sustainable, intelligent and environmentally friendly model.

2 Materials and Methods

2.1 Study Objective

The main objective of this study is to assess the impact of building envelope materials on the thermal performance of a residential building under two contrasting climatic conditions in Morocco: Marrakech (hot, semi-arid climate) and Ifrane (cold, mountainous climate).

The adopted methodology is structured in several complementary steps:

1) Material characterization: Experimental determination of the thermophysical properties of conventional materials, as well as alternative and bio-based materials, particularly those made from doum fibers and recycled cardboard waste.
2) Numerical modeling: Integration of the measured thermal properties into a digital model representing the studied building.
3) Energy simulation: Estimation of heating and cooling demands for different scenarios, taking into account the specific climatic conditions of Marrakech and Ifrane.
4) Comparative analysis: Evaluation of the energy performance of bio-based materials compared to conventional materials to determine their suitability for improving energy efficiency and thermal comfort in the Moroccan context.

This approach not only identifies the most effective materials but also supports sustainable solutions that respect both the local climate and architectural heritage.

2.2 Construction Materials

Several materials from different origins have been collected and received in our laboratory for thermal characterization to build up a database of thermophysical properties of local materials. Once the materials have been received, they are stored in ventilated, moisture-isolated areas, bearing a reference code.

Some materials (cement, gypsum, sand) are prepared in the laboratory according to standardized procedures, such as sieving, mixing, blending, homogenizing and vibrating. The paste is poured into square molds (150x150mm^2) or circular molds with a diameter of 100mm. While the base material, either hollow concrete blocks or wood, requires cutting and sanding to the above-mentioned dimensions, using appropriate tools.

In this study, we focused on a range of construction materials to better understand their thermal and mechanical behavior. These included hollow concrete blocks and bricks, commonly used in lightweight construction for their strength, affordability, and aesthetic flexibility, with compositions that vary regionally (the samples we studied came from the SADEC plant in Salé, Morocco). We also examined cement mortar, made from CPJ35 cement and local sand, mixed with water, and cast into 150×150×30 mm^3 molds. Gypsum plaster was prepared from LAFARGE gypsum powder with a water-to-gypsum ratio of 0.6, while traditional Zellij—handcrafted, sun-dried, and kiln-fired clay tiles—was studied through samples from a local workshop in Salé. Wood samples were cut along the grain into cylindrical pieces 100 mm in diameter and 20 mm thick, with carefully sanded and balanced surfaces for accurate measurements. Finally, glass was included as a common building material to evaluate its thermal and optical performance alongside the other elements (Fig. 1).

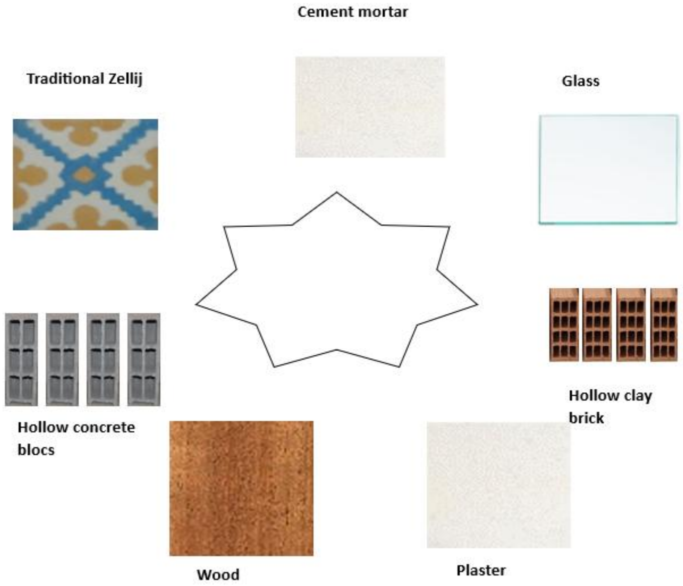

Fig. 1. The materials considered in this study.

2.3 Sustainable Insulation Material

In addition to traditional concrete, we developed an eco-friendly insulation material combining cardboard waste with esparto fibers (Stipa tenacissima), a plant native to Morocco. The goal was to create insulation panels that are not only environmentally sustainable but also perform comparably to conventional materials.

Esparto fibers were collected from the Errachidia region and thoroughly washed under high-pressure water to remove dust and impurities. They were then air-dried for 24 hours and oven-dried at 40 °C to minimize residual moisture. The fibers were pre-cut, crushed, and sieved to obtain uniform filaments approximately 5 mm long and less than 2 mm in diameter.

Cardboard waste was cut into small pieces and soaked in water for 30 minutes to form a viscous paste that would act as a binder. A 40% mass fraction of esparto fibers was mixed into this paste, and the mixture was thoroughly blended in a mixer for 5 minutes to ensure uniform dispersion. The resulting composite paste was poured into parallelepiped molds measuring 150 × 150 × 20 mm³. Samples were first air-dried for 48 hours and then oven-dried at 50 °C until the mass stabilized within ±0.02 g. Each sample was wrapped in plastic to preserve its dry state (Fig. 2). This approach allowed us to produce consistent and reproducible samples for thermal testing.

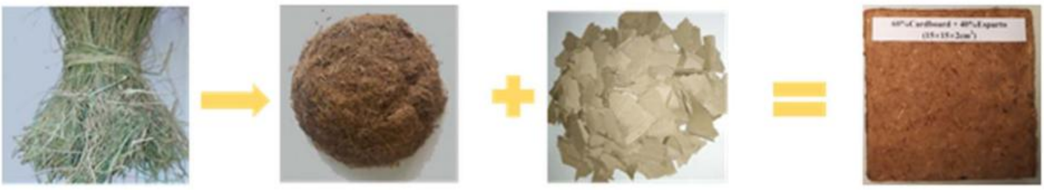

Fig. 2. Composite preparation using cardboard and esparto fiber.

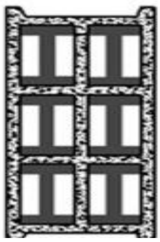

Fig. 3. Optimized hollow concrete bloc.

We aimed to optimize the thermal performance of hollow concrete blocks commonly used in construction in Morocco by inserting a thermal insulation material into their cavities (Fig. 3). According to Ouakarroch et al. [14], partially or fully filling these cavities with an insulating material can significantly reduce heat losses through the building envelope. The insulation acts as a barrier to heat transfer, improving the overall thermal resistance of the block and contributing to better regulation of indoor temperatures. This approach preserves the lightweight and modular characteristics of hollow concrete blocks, as the insulation is integrated within the existing cavities without modifying the block geometry or increasing its structural mass, while simultaneously reducing heating and cooling energy demand by limiting heat transfer through the building envelope. It highlights the importance of combining structural design with energy performance to achieve more sustainable constructions adapted to the Moroccan climate.

2.4 Experimental Methods

2.4.1 Specific Heat Capacity

We measured the specific heat capacity (c) of the materials using a Differential Scanning Calorimeter (DSC), following ISO 11357-4. This method allows precise determination of the heat required to raise the temperature of a sample. All measurements were conducted in an inert nitrogen atmosphere, and the system includes a cryostat to stabilize temperature fluctuations during testing (Fig. 4a). This setup ensures accurate and reliable evaluation of the thermal properties of both concrete and composite samples.

2.4.2 Thermal Conductivity

Thermal conductivity (λ_s) was determined using the guarded hot plate method (λ-Meter EP500e), in accordance with ISO 8302. Samples (150 × 150 mm²) were positioned between a hot plate and a cold plate, and the heat flux through the material was measured (Fig. 4b). Multiple measurements were taken at different temperatures ranging from 10 to 40 °C, with temperature differences of 5 K and 15 K on the sensor plate, to ensure reliable and repeatable results.

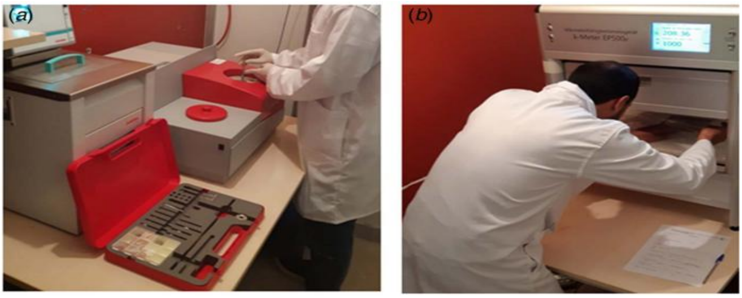

Fig. 4. Experimental setup: (a) calorimetry, (b) guarded hot plate.

2.4.3 Bulk Density

The bulk density (ρ_{app}) of the samples was calculated following NM ISO 17892-2, using the dry mass and precise dimensions of each specimen. Masses were recorded using an electronic balance accurate to 0.01 g (capacity 2000 g), while dimensions were measured using a high-precision vernier caliper accurate to 0.1 mm (Figs. 5a and 5b). Each sample was measured three times to obtain an average value, and density was calculated using the standard mass-to-volume relationship.

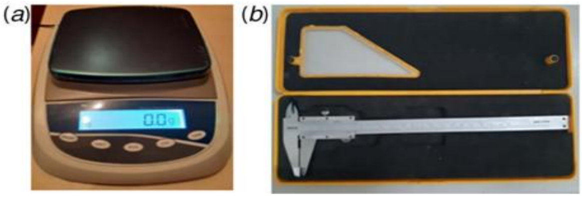

Fig. 5. Experimental tools: (a) electronic balance, (b) caliper.

2.5. Thermal Properties of the Studied Materials

The construction materials considered in this work are presented in Table 1, including their composition and main thermal properties such as apparent density (ρapp), thermal conductivity (λ), and specific heat capacity (c). Cement mortar and traditional Zellij exhibit intermediate thermal conductivities, generally between 0.48 and 1.05 W.m^{-1}.K^{-1}, and relatively high specific heat capacities, allowing them to store moderate amounts of heat and contribute to the thermal inertia of walls. Wood, including cedar, mahogany, and beech, has low densities (400–700 kg.m^{-3}) and moderate thermal conductivity (0.13–0.20 W.m^{-1}.K^{-1}), combined with high specific heat capacity (up to 2382 J.kg^{-1}.K^{-1}), which enhances its ability to moderate indoor temperature fluctuations while providing insulation. Hollow concrete blocks and bricks, with internal air cavities, present intermediate thermal conductivities (0.59–0.85 W.m^{-1}.K^{-1} for concrete blocks and 0.35–0.46 W.m^{-1}.K^{-1} for clay bricks), reducing heat transfer compared to solid materials and combining structural strength with improved thermal resistance. Glass, as a transparent envelope material, contributes to solar heat gains and daylighting, while its moderate conductivity and low heat capacity influence the overall energy performance, especially when integrated with other building elements. The data summarized in the tables demonstrate how the combination of density, conductivity, and specific heat capacity of these materials impacts thermal behavior, indoor comfort, and building energy efficiency.

The last two materials presented in Table 1 highlight the performance of insulation-focused solutions. Sustainable insulation materials exhibit very low density (276.5 kg.m^{-3}) and extremely low thermal conductivity (0.072 W.m^{-1}.K^{-1}), combined with a high specific heat capacity of 1254.6 J.kg^{-1}.K^{-1}. These properties make them highly effective for reducing heat transfer while providing moderate thermal storage, demonstrating their suitability for energy-efficient building envelopes. Optimized hollow concrete blocks, with a density of 932 kg.m^{-3}, thermal conductivity of 0.316 W.m^{-1}.K^{-1}, and specific heat capacity of 810 J.kg^{-1}.K^{-1}, show improved thermal performance compared to standard concrete blocks. The reduced conductivity allows for better insulation without compromising structural integrity, making them a practical solution for walls that need both mechanical strength and enhanced energy efficiency.

Table 1. Thermal Properties of the Studied Materials.

Materials	**ρ_{app} (Kg.m^{-3})**	**λ (W.m^{-1}.K^{-1})**	**c (J.kg^{-1}.K^{-1})**
Hollow clay brick	$585 \le \rho \le 937$	$0.35 \le \lambda \le 0.46$	750
Hollow concrete blocs	$923 \le \rho \le 1369$	$0.59 \le \lambda \le 0.85$	810
Sustainable insulation materials	276.5	0.072	1254.6
Optimized hollow concrete bloc	932	0.316	810

3 Dynamic simulation of a building

In this section, we describe the dynamic thermal simulation process carried out with DesignBuilder to assess how a residential building performs energetically in two very different Moroccan climates: the hot and dry conditions of Marrakech and the cold, mountainous environment of Ifrane. The main goal of this simulation is to understand how the building's heating and cooling needs change when using two types of wall assemblies: one reflecting the materials typically used in local construction (reference scenario), and another using improved materials with higher thermal resistance (optimized scenario).

Through this approach, we explore how key parameters, such as the thermal conductivity of walls, material thicknesses, glazing properties, and the overall behavior of the building envelope, respond to climatic variations. By comparing the outcomes between the two cities and across both scenarios, we aim to clearly quantify how much these envelope improvements can reduce the building's thermal loads. Ultimately, this work supports a broader effort to enhance energy efficiency by identifying construction strategies suited to each climatic zone, while still ensuring comfortable indoor conditions for occupants.

3.1 Activity Data

Activity data form a key element in setting up the thermal zones in DesignBuilder, as they describe how the different spaces in the residential building are actually used. They include information such as occupancy density, usage schedules, and the type of activities taking place in each space. These inputs are essential for estimating internal heat gains generated by occupants, which directly influence heating and cooling requirements.

For the residential building studied, thermal zones were organized according to the main domestic spaces—bedrooms, living room, kitchen, bathrooms, and circulation areas. The distribution of these thermal zones within the building is illustrated in Figure 6, which shows how each zone corresponds to a specific function and occupancy pattern. DesignBuilder provides predefined residential activity categories, making it possible to assign realistic occupancy profiles to each space.

The occupancy density of each room is determined based on its size and function. Bedrooms generally experience prolonged nighttime occupancy, while the living room and kitchen are more intensively used during daytime hours, following typical household routines. These zoning and activity definitions are integrated into the three-dimensional simulation model presented in Figure 7, allowing the model to accurately reproduce internal heat gains and reflect the thermal and energy behavior of the building under the contrasting climatic conditions of Marrakech and Ifrane.

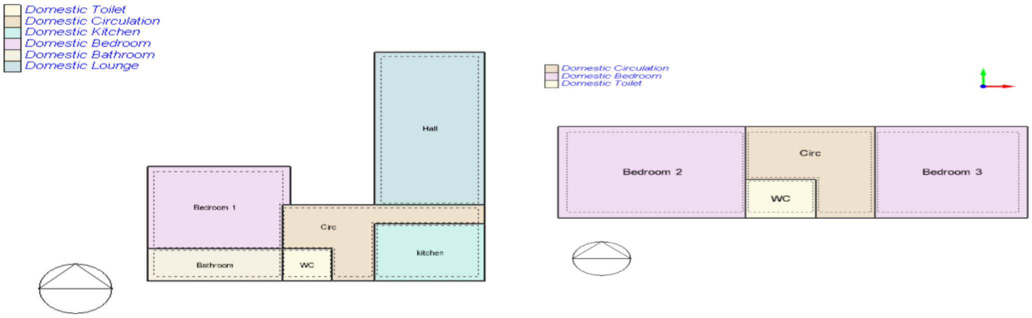

Fig. 6. Different thermal zones of the studied building.

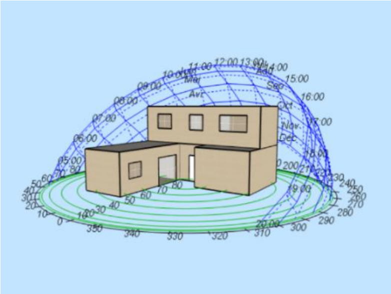

Fig. 7. Simulated building model.

3.2 Reference case

In the reference scenario, we rely on the types of construction materials typically used in standard building projects. While these materials are adequate for conventional structures, they offer only moderate thermal performance, which can significantly affect the building's overall energy use. The table 2 summarizes the key characteristics of the materials chosen for this scenario.

Table 2. Construction materials (baseline scenario).

	Layers	**Thickness (cm)**	**Thermal conductivity ($W.m^{-1}·K^{-1}$)**	**Density ($kg.m^{-3}$)**	**Specific heat ($J.kg^{-1}·K^{-1}$)**
External wall	Mortar	0,02	0,88	2800	896
	Concrete bloks /tiles	0,2	0,62	1040	840
	Mortar	0,02	0,88	2800	896
Floor on ground	Ceramic/porcelain	0,13	1,3	2300	840
	Floor/Roof Screed	0,07	0,41	1200	840
	Concrete, cast - heavyweight Dry	0,2	1,3	2000	840
	Gravel	0,3	0,36	1840	840
Roof	Ceramic/porcelain	0,015	1,3	2300	840
	Floor/Roof Screed	0,07	0,41	1200	840
	Concrete Roofing Slab, Aerated	0,2	0,16	500	840
	Plasterboard	0,03	0,25	2800	896

3.3 Heating and Cooling Loads of the Building

The simulation results clearly show differences in energy needs between the two climatic zones (Fig. 8). In Marrakech, cooling represents the main energy demand, with an annual consumption of 7,016.38 kWh, while heating requirements remain relatively limited at 3,019.51 kWh. This reflects the hot climate of the region, where high outdoor temperatures lead to increased use of air-conditioning systems.

In contrast, the situation in Ifrane is quite different. Heating demand is dominant, reaching 7,700.62 kWh per year, whereas cooling needs are lower, at 3,828.90 kWh. This behavior is directly linked to the colder climatic conditions of Ifrane, which require significant heating to maintain indoor comfort.

Overall, these results underline the strong impact of climate on building energy consumption and confirm the importance of adapting design strategies and energy solutions to local climatic conditions in order to improve energy efficiency.

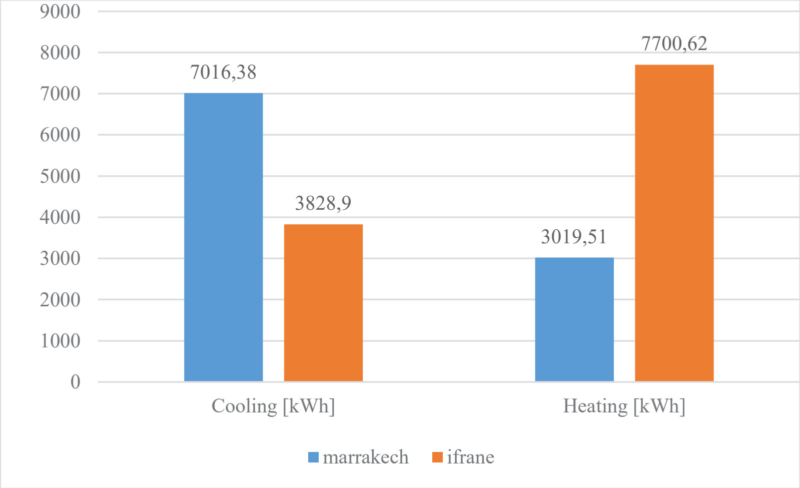

Fig. 8. Energy Loads for Heating and Cooling – Reference Case.

3.4 Development of the Second Simulation Scenario

In order to enhance the thermal performance of the building and its energy consumption, the second simulation scenario was created, where the exterior wall material was changed. In particular, the traditional brick walls were substituted by the optimized hollow concrete blocks of better thermophysical characteristics. The material chosen is with a density of 932 $kg.m^{-3}$ with thermal conductivity of 0.316 $W.m^{-1}.K^{-1}$ and a specific heat capacity of 810 $J.kg^{-1}.K^{-1}$.

These properties provide thermal insulation as well as thermal inertia to the building envelope and restrict heat exchanges through the walls. Consequently, this low-energy wall design minimizes both heat gain with the summer and heat loss with the winter and leads to better thermal comfort indoors and reduces cooling and heating energy costs. The second simulation scenario is based on this optimized material, and it is possible to directly compare the energy performance of the reference scenario with the optimized simulation scenario.

The second scenario was conducted after the analysis of the first simulation, which is the standard building layout and evaluated the effect of the optimized brick material. These findings indicate that there is a great decrease in the demand of energy in both climatic zones. Cooling demand in Marrakech dropped to 4827.91 kWh per year, heating demand dropped to 2104.57 kWh, and this represents improved thermal insulation and lower heat gain through the envelope. In Ifrane, heating and cooling load were 5,356.63 kWh and 2,692.39 kWh, respectively. These findings support the fact that optimized bricks are utilized significantly to enhance thermal efficiency of the building that leads to lower energy usage and a higher adjustment of the building to the specifics of the local climate (Fig. 9).

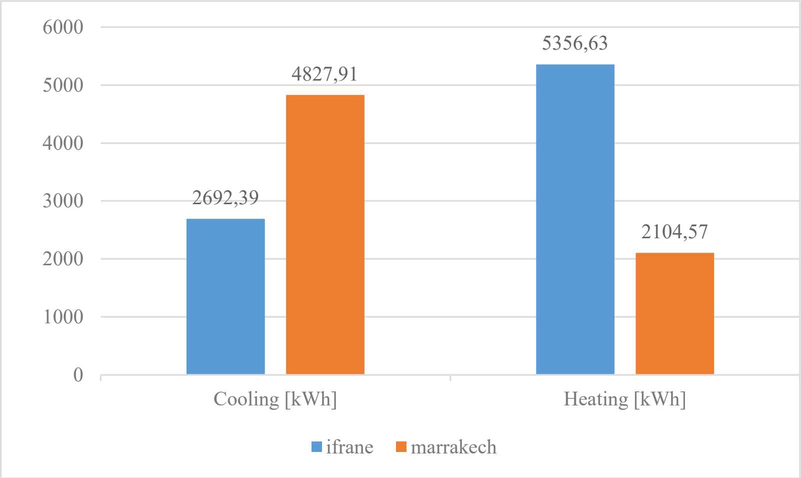

Fig. 9. Energy Loads for Heating and Cooling – Optimized Case.

4 Comparative analysis of scenarios

The comparison of the results of the simulation in the base scenario and the improvement scenario has shown that there is a significant decrease in power consumption throughout the two climatic zones, Marrakech and Ifrane. Such outcomes indicate the success of the energy efficiency practices followed in the better case (Figs. 10 and 11). In the cooling scenario, Marrakech shows a decrease between 7016.38 kWh of the basic case and 4827.91 kWh of the better case that is 31.2%. The cooling demand also drops down in Ifrane by 3828.9 kWh to 2692.39 kWh, an overall reduction of 29.7%. The fact that absolute savings are higher in Marrakech, can be discussed by the fact that climate is hotter and cooling requirements are more important, and such improvements as better wall and roof insulation, high-tech glazing, and optimal shading play an important role in decreasing cooling loads. In terms of heating, in Marrakech the energy demand reduces to 2104.57 kWh (3019.51kWh -30.3), and in Ifrane the energy demand reduces to 5356.63kWh (7700.62kWh -30.4). The greater absolute decrease of Ifrane is associated with its colder climate which needs more heating energy in the base scenario. This shows that the implemented strategies are quite efficient to minimize the losses of heat in the building envelope, maximize the performance of heating systems, and enhance thermal comfort inside the building in colder seasons. In general, the improvement scenario will result in a steady energy savings of approximately 30 percent of heating and cooling needs in various climates. The resulting decrease in this case is the direct translation into lower costs of operation, decreased greenhouse emissions, and improved building energy performance. Furthermore, the findings emphasize the role of design solutions (which are climate sensitive) with the implications that customized enhancements are effective in meeting both heating and cooling requirements based on the weather conditions in that area. Conclusively, the enhanced scenario allows to save energy use, as well as offer a solid solution to sustainable building design, which is not only energy-efficient and comfortable all year round but also with the least harm to the environment.

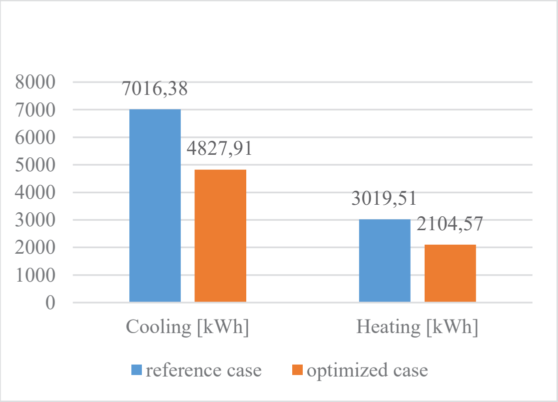

Fig. 11. Scenarios Comparison – Marrakech.

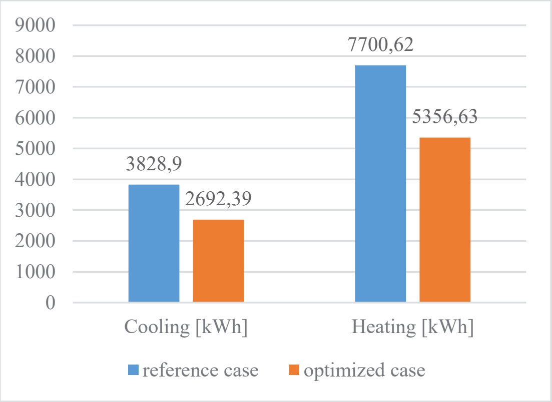

Fig. 10. Scenarios Comparison – Ifrane.

5 Conclusion

The paper has looked at how building envelope materials can influence the thermal performance of a residential building in Morocco and compared traditional solutions to the biosourced and optimized materials. The comparative analyses were made between the two opposite climates: Marrakech (hot, semi-arid) and Ifrane (cold and mountainous), and the following points were revealed: Climate effect: The cooling is the major energy demand in Marrakech (7,016.38 kWh in the case scenario), and the heating is the major energy demand in Ifrane (7,700.62 kWh). Sustainable materials performance: The bio-composite produced by using cardboard waste and alfa fibers has good insulating properties and the thermal conductivity is very low. Optimization outcomes: Substitution of the conventional walls with optimized hollow concrete blocks resulted in a considerable decrease in the energy usage, with about 31.2 percent energy saved in cooling of the buildings in Marrakech and 30.4 percent in heating in Ifrane. Total savings: In general, the better scenario will result in a steady 30 percent energy savings on heating and cooling. To sum up, these findings show that environmental footprint of the building industry may be diminished by employing locally sourced substances and maximizing building envelopes, at the same time preserving energy consumption and comfort of occupants. They also emphasize the need to embrace design strategies that are specific to the conditions of the regional climatic conditions in order to realize national energy efficiency goals by 2030.

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