Building thermal comfort improving by using PCM and super insulators: Thermal and economic studies

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Abstract. The climate of the northern region of Morocco is Mediterranean, while the southern one is arid-type. They are both characterized by significant solar radiation during nearly eight months of the year, and as a result, direct and indirect solar energy contribute mainly to human discomfort in residential buildings. In this study, passive techniques such Phase Change Material (PCM) and super insulators (Aerogel and Vacuum Insulated Panels (VIP)) are used and analyzed to improve thermal comfort in the building. The resulting thermal behavior was studied using dynamic simulations and an experimental investigation of two test cavities located in the city of Casablanca. The potential energy savings to reach human comfort conditions were evaluated for a real scale cubicle. The comparison is performed with the active solution (air conditioning with classical local building wall composition), and the economic performances of these materials are evaluated by the Net Present Value (NPV) and Internal Rate Return (IRR). Special emphasis is given to the bulling roof. The optimum insulation thicknesses and payback periods were determined in the present study over 20 years. The results showed that PCM, VIP, and Aerogel could provide respectively as much as 94 %, 76.51%, and 73.61% economic benefit during the cooling period and 59.3 %, 46.56%, and 44 % during the heating period than the case of the roof without insulation.

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1 Introduction

With the increase in energy needs and the amplification of greenhouse gas emissions [1], the building sector has received wide attention as one of the largest energy consumers in the world. Indeed, it alone represents 40% of total energy consumption [2].

However, it is a target sector for energy savings and carbon emission reduction, which can reach six gigatons [3]. In Morocco, this amount is about 33% of the total energy consumption, and the trend is going ahead owing to the relative improvement of living standards [4]. In this framework, the authority has recently established the first thermal building regulations in the country [5], which aim to reduce global energy consumption in buildings. The built environment is one of the largest energy consumers worldwide.

Indeed, modern construction uses lightweight materials to control the weight and thickness of building envelopes, which has reduced thermal inertia and increased heating and cooling requirements. Therefore, 60% of building energy losses is through envelopes. Indeed, the dilemma in the building is to respect the thermal requirements while using light materials. The use of PCM and innovative insulators such as vacuum panels and aerogel seems like a better option for reducing annual energy needs while keeping a light envelope [6] [7] and [8].

Many studies deal with improving the energy efficiency of buildings in similar Moroccan climates [9] [10] and [11]. The optimum insulation thickness was determined primarily based on air conditioning needs and life cycle cost analysis, which includes the costs of insulation materials (purchase, installation, and transport), the cost of energy, and current discount rates. Several approaches have been used to quantify economic studies, such as net present value (NPV), payback analysis, and internal rate of return (IRR). It's considered an accurate and reliable investment method [12].

Among these works, Dlimi [13] conducted a study on the thermal performance of a building under dynamic temperature conditions in Meknes (Morocco). Numerical investigations were carried out to determine the optimum thickness of thermal insulation for the building envelope. The simulation reported that the optimum thickness of the insulation is 5 cm for the west and east, followed by the south and north (respectively 4 and 3 cm). Braulio-Gonzalez and Bovea [14] focused their study on identifying optimal thermal and energy insulation solutions for building envelopes. The approach adopted was based on thermal demand, life cycle, and cost analysis. The findings indicate that the highest eco-efficient performance corresponds to sheep's wool and recycled cotton, with a 40% reduction in energy demand compared to the regulatory standards traditionally used. Bojic et al. [15] carried out a study to optimize thermal insulation in a residential house in Kragujevac, Serbia. Their findings show that for thermal insulation, the energy payback period for mineral wool varies from 0.84 to 2.7 years and for polystyrene from 3.18 to 5.21 years. An experimental study conducted by Cabeza et al. [16] has evaluated the effect of insulation in buildings.

Four cabins (size 2.4×2.4×2.4 m^3) were built in Lleida (Spain). One of the cells serves as a reference cell (without insulation), while the others. The experimental study showed that energy savings can reach 64% and 37% in the summer and winter, respectively. The polyurethane cell had the lowest energy consumption. However, the differences between the insulation materials were relatively small. The authors also compared the transmission coefficient (U value) experimentally and theoretically in the two periods studied and reported a difference of 12 and 14%, respectively. In buildings, the concept of performance must combine energy efficiency and cost, as well as the minimum insulation thickness, to reduce the volume of the building envelope. To achieve better thermal insulation resistance and a lightweight envelope, new thin materials that have low thermal conductivity are needed.

Traditional insulation materials require significant thickness in building envelopes. However, the architecture of modern houses requires lightweight envelopes for several reasons. Starting with the issue of space regarding economy, architectural restrictions, and other limitations [17]. In this regard, several studies have appeared. Shoa et al. [18] conducted an economic study on the performance of vacuum insulation panels (VIPs) using the LCCA method. The results showed that over a lifetime of 40 years, up to 136.92% and 88.28% savings could be achieved for VIP 30T® and VIP 20T®, respectively, compared to traditional insulation panels.

Alam et al. [19] assessed the thermal and economic performance of three non-domestic UK buildings. The study focuses on the integration of fiberglass (GF) and fumed silica (FS) VIPs. Results showed that VIP insulation over a 60-year life span resulted in space heating energy savings of 1395.3 MWh, 1661.2 MWh, and 3391.6 MWh. Schuss et al. [20] studied the performance of aerogel-based insulating plasters in several configurations. A significant improvement in the U value (reduction from 1.25 to 0.46 $W.m^{-2}. K^{-1}$) was observed when applying 4 cm of aerogel to a 42 cm brick wall.

Mourid and El Alami [21] [22] evaluated the effect of integrating phase change materials (PCMs) on improving summer thermal comfort in lightweight buildings with different configurations (thicknesses, positions). The results indicated that a thickness of 10.52 mm on the exterior face of the roof reduced daily temperature fluctuations and transmitted heat flux by 88%.

The purpose of the present study is to compare the thermal performance of selected materials (PCM, Aerogel, and PIV) under optimal conditions. The study focused on the thermal insulation of the roof, and its thermal performance was evaluated by comparison with a reference case (conventional construction materials without insulation). Two test cavities were installed in Casablanca; Morocco is used for the experiments. TRNSYS® software is used to calculate the corresponding cooling and heating loads and to determine the optimal insulation thickness of the test cavity roof. For the economic analysis, we applied the Net Present Value (NPV), payback analysis, and internal rate of return (IRR).

2 Test cavities description

The test cavities are real scale, located at the Faculty of Sciences Ain Chock (Casablanca). They are built as typical conventional Moroccan construction that stands without any thermal insulation, the northern wall (Figure 1) is equipped with a simple glazed window and a wooden door.

Fig. 1. View of the cubicle

3 Weather conditions

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Casablanca is located on the coast of the Atlantic whose coordinates are: Latitude 33°35'N, Longitude 7°36'O, and Altitude 27m. Its climate is warm and mild. It is classified as Cwb by the Köpper-Geiger system [23]. The meteorological data for a typical year in Casablanca are summarized in figure 2 and show the monthly minimal, maximal, and average temperature and also the monthly global solar radiation. Notice that the monthly average temperature is simply computed using the daily average temperature which is, again, the average between the daily minimal and maximal temperature.

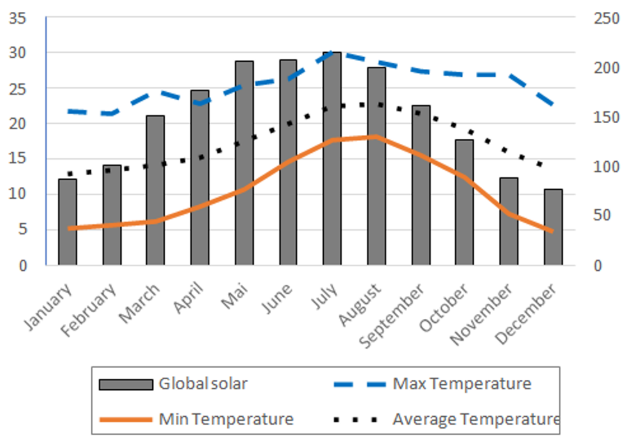

Fig. 2. Meteorological data of a typical year in Casablanca [24]

4 Numerical simulation

The thermal behavior of the cavities was simulated through TRNSYS software [25] [26], with a time step of 1 hour. To simulate a wall with PCM, the type 399 was used.

4.1 Bondary conditions

The annual variations of the outdoor temperature and the global radiation values are obtained by using Meteonorm software for Casablanca city [24], with one-hour time step.
The simulation calculates the hourly temperature of the cells. The cooling/ heating loadsin each cell are calculated by setting points of 20 ◦C for heating and 26 ◦C for cooling [27].
The following assumptions are considered:
-The thermal zones are described by an air node describing the uniform temperature of the cell volume.
- The door and the windows are closed.
-No interior gain.
-The initial air temperature and humidity in all areas were taken at 20 ◦C and 50%.
-A constant infiltration rate of 0.5 ACH was retained.
-The convection coefficient for the outer walls is calculated according to the following relation:

$$h_{cv,ext} = 4.955 + 1.44\times V \quad [28] \tag{1}$$

-The coupling of the PCM to the building is carried out using Type 399 from TRNSYS [29].

4. 2. Simulation validation

The validation of the TRNSYS simulation model is based on the harvested experimental data from the test-cavities during two summer months. The actual meteorological data measured on the site are used for validation purposes.

For the internal air temperatures of the cavities, the measured and the simulation values are depicted in Tables 1 and 2.

These Tables show a good agreement between the experimentally monitored data and simulation results, taking into account the thermocouple accuracies and uncertainties related to the thermo-physical properties. The deviations are less than 0.84 °C in the reference cavity (Table 1) and 0.8 °C in the PCM-cavity (Table 2).

Table 1. Temperature variation inside the cavity with PCM

Table 2. Temperature variation inside the reference cavity

Time (Hours)	Simulation(°C)	Experimental(°C)	Variance (°C)	Tim (Hours)	Simulation(°C)	Experimental(°C)	Variance (°C)
0	28.05	27.93	0.13	0	27.68	27.99	0.30
2	27.47	27.35	0.12	2	26.96	27.42	0.46
4	26.95	26.78	0.16	4	26.39	26.90	0.50
6	26.41	26.21	0.20	6	25.87	26.35	0.48
8	26.12	26.15	0.03	8	25.85	26.08	0.23
10	26.82	26.98	0.16	10	26.82	26.87	0.04
12	28.38	28.19	0.19	12	27.98	28.31	0.32
14	29.80	29.29	0.51	14	29.09	29.58	0.49
16	30.36	30.11	0.26	16	29.78	30.14	0.35
18	29.89	30.39	0.49	18	29.76	29.57	0.20
20	29.30	29.72	0.42	20	29.30	29.08	0.23
22	28.75	29.10	0.35	22	28.64	28.56	0.08

5 Cost analysis and optimization of insulation thickness

We performed an economic analysis to estimate the insulation thickness that minimizesthe total cost. The dilemma is to achieve a high level of energy economy with a minimum insulation thickness. When designing a building envelope. Indeed, one had to find a compromise between the total costs of the annual energy consumptions (the Operational Expenditure (OPEX)) and the total capital investment (the CAPEX Capital expenditure) to set up the insulating materials. Neither excessive nor impairment isolation is desirable for economic reasons. Excessive insulation results in a decrease in the annual total cost of energy consumption but requires a high initial investment cost. Controversially, low insulation induces low initial investment costs but leads to an increase in the total energy cost. In this respect, one of the most important considerations that we have to consider in building design is the insulation thickness.

Traditionally investigations consider only the annual cooling and heating requirements as well as the interest rate.

This study introduces a new definition that considers also the influence of the evolution of the electricity price on profitability. In Casablanca, the electricity price evolves each year by 3.46% [30]. For that, we will consider the discounting of the electricity price.

The total annual cost of energy C_{En} (MAD.m^{-2}. year^{-1}) is calculated from the total annual heat loads. In this study heating and cooling loads are calculated and processed separately. The annual cost depends on the method and efficiency of the equipment heating and cooling. The total heating and cooling loads of the cavity are designated by Q_l and Q_g respectively. C_{En} is given by the equation below:

$$C_{En} = \left(\frac{Q_l C_E}{COP} + \frac{Q_g C_E}{COP}\right) \quad (2)$$

C_{EN} is the cost of electricity (MAD/kWh) and the COP is the average coefficient of performance of the heating/ cooling system. The COP values of the heating and cooling systems considered are 2.5 and 3 respectively.

The actual value of energy cost during a building life cycle is obtained by multiplying the annual cost of energy by PWF. The PWF is the present worth factor and depends on the interest rate i and the life cycle. In this case PWF is defined as below:

$$\sum_{K=1}^{k=n} (1+\mathrm{i})^{-K} = \sum_1^n \mathrm{PWF}_{k.i} = \frac{[1-(1+\mathrm{i})^{-n}]}{\mathrm{i}} \quad (3)$$

To calculate the profitability of each studied variant, the Net Present Value (NPV) was calculated. This factor is considered to be the most reliable tool for the evaluation of a project in terms of economic efficiency [31]. The NPV is the present value of a long-term project, discounting all future costs. Coupled with Internal Return Rate (IRR), the NPV is the second necessary measure of profitability. It reflects the balance of the cash inflows (incomes) and expenses (outflow) at the end of the lifecycle of investment n (Eq.4). Normally, those annual quantities refer to the year of the investment. In this work, we applied a nominal discount rate of 5.16 %, according to Bank Al Maghrib report [27]. Moreover, we used a real cost approach, thus not accounting for the inflation rate, as suggested by Islam et al. [32]. We considered a time horizon of 20 years.

$$NPV = \left[(R-D)\sum_1^n PWF_{k.i} = \frac{[1-(1+i)^{-n}]}{i}\right] - I \quad (4)$$

Where i is the investment capital and R-D is the operation profit

On the other hand, the IRR of the investment is defined as the value of the discount rate (i) that leads to NPV = 0. If the IRR is above the nominal discount rate, which refers to the cost of financing the project, the investment is feasible from an economic standpoint.

Table 3. Parameters used in calculations

Parameter	Value
Initial electricity cost. C_E	1.51 MAD/kWh
Coefficient of performance. COP heating and cooling. respectively	2.5 – 3
Interest rate. i	5.16 %
Lifetime n	20 years

6 Result and discussion

In this work, the optimum insulation thickness of a roof with three different materials is sought under the actual climate conditions of Casablanca (Morocco). Four configurations were simulated; the first one doesn't contain any insulation material and is made of heavy concrete (reference cavity). The second one is equipped with Vacuum Insulation Panel (VIP) , the third one is with Aerogel, and the fourth one is with phase change material (PCM)[10]. Table 4 summarizes the used materials and their thermal conductivity.

The internal temperature variations and energy consumption are evaluated over the year and the comparison between the four studied configurations is performed for January and July.

Table 4. Thermal conductivity of the used materials [10] [33]

Material	PCM	Aerogel	VIP
Thermal conductivity	0.18 - 0.22 W/ (m.K)	13.1 mW/(m.K)	4mW/(m.K)

6.1 Thermal behaviors analysis

Before discussing the impact of passive techniques on reducing the energy demand for cooling and heating. The thermal performance of materials is analyzed by comparing it with that of the reference case.

6.1.1 Thermal behavior during the hot season

July is selected to analyze the thermal behavior of the cells during summer. This month is the sunniest of the year, in Morocco, with high levels of solar radiation (about 214.12 kWh/m², Fig.2). The outside air temperature reaches a maximum of 30.05 °C with an average of 24.08 °C and daily amplitude (peak-to-peak difference) up to 10.4 °C.

Fig.3 shows the evolution of the internal temperatures of the cavities during the 20-22 July periods. The indoor air temperature in the reference cavity has a 5 °C difference between the day and the night (ranging from 28.84 to 33.87 °C), leading to a real thermal discomfort.The indoor temperature in the insulated cavity is lower than the reference one. It varies between 27.74 and 32.23 °C and between 27.85 and 32.33 °C for the VIP and Aerogel cases, respectively.

The ambient temperature of the case of PCM is much reduced compared to other insulators.It does not exceed 30.33 °C. The temperature oscillations have a 3.87 °C difference between the day and the night pics.

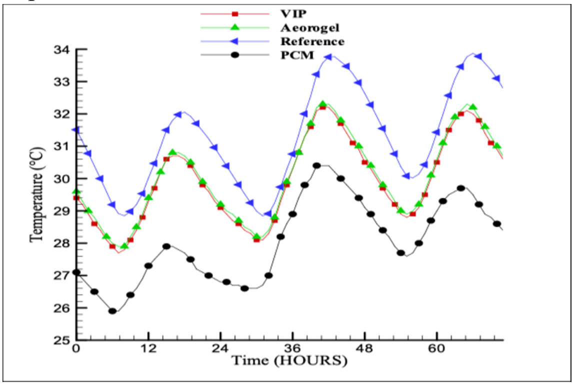

Fig. 3. Evolution of the internal temperature of the cavities during summer

6.1. 2 Thermal behaviors during the cold season

To analyze the thermal behavior of the cavities during the cold season, January is selected as the period of study since it's the coldest month (Fig.2). The outdoor temperature reached a minimum of 5.15 °C and did not exceed 16.95 °C, and solar radiation was around 3.31 kWh.m^{-2} / day. Fig. 4 illustrates the variations in the internal temperature of the cavities during the winter period (11-13 January). The indoor temperature of the insulated cavity is higher compared to the reference cavity, which is explained by the enhanced insulation effect and the thermal inertia walls. Moreover, the indoor air temperature in the reference cavity falls at night below 12.5 °C, which causes thermal discomfort. The indoor temperature obtained when using PCM as an insulator is the most efficient compared to the other insulation materials. It is ranging from 14.00 °C to 17.20 °C. It should be emphasized here that the PCM is not only an insulator, but it also stores the energy to be lost to restore it to the interior of the room, once the indoor temperature begins to drop.

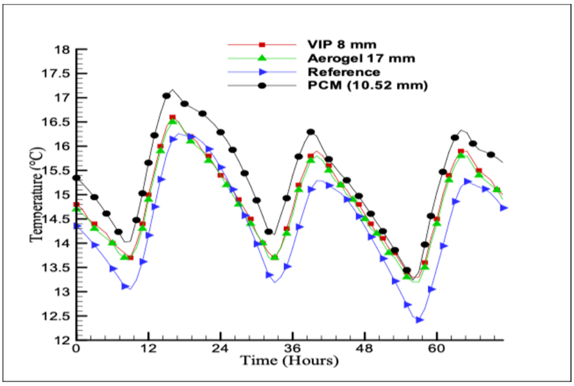

Fig. 4. Evolution of the internal temperature of the cavities during winter

6.2 Energy performance

In this section, simulations are performed using data from the Typical Meteorological Year (TMY) for Casablanca [24]. To calculate the annual cooling and heating thermal loads for the four configurations of cavities. the heating and cooling instructions are respectively set at 20-26 °C according to the international standard NM ISO 7730 [10].
Figs. 5 and 6 show the monthly consumptions for heating and cooling of the cavity with the four tested insulation materials and those of the reference cavity. The comparison of the consumption of heating and cooling shows that the insulated cell consumes less energy than the non-insulated one. The distribution of energy load requirements in heating and cooling shows that the predominant period of the year is that of cooling and that the maximum power in this period corresponds to the July. This is because the outside temperature is at itsmaximum during this month.

During the winter period, the month of January has the highest energy consumption of the heating season. The test cavity with a conventional roof building uses 10.01 kWh/m² of heating in December, when the insulated cavities consume less than 3.24 kWh/m² depending on the used insulator. In the summer period, the month of July has the highest consumption of the cooling season. Air conditioning energy consumption in August was 21.04 kWh/m² for the reference cavity and 14.68 kWh/m² for the other cavity.
For the case of PCM, the monthly cooling requirements range from 0.13 kWh/m² in Aprilto 9.60 kWh/m² in July. For heating, they vary between 0.91 kWh/m² in November and 6.16kWh/m² in January. A reduction of 59.3% and 94% is obtained for the heating and cooling requirements, respectively.
For the Aerogel, cooling loads were 0.29 kWh/m² in April (as a minimum) and reached a maximum consumption of 14.67 kWh/m² in July. On the other hand, for heating requirements, the minimum energy consumed is 1.25 kWh/m² in November and the maximum energy is 7.41 kWh/m² in January.
For the Vacuum insulated Panels (PIV), cooling requirements range from 1.50 kWh (0.25 kWh/m²) in April to 81.73 kWh (14.02 kWh/m²) in July. While heating requirements fluctuate between 6.99 kWh (1.20 kWh/m²) in November and 41.30 kWh (7.08 kWh/m²) in January.
According to these results, one concludes that the PCM remains the best insulator among the tested ones since it allows a better economy in cooling and heating needs.

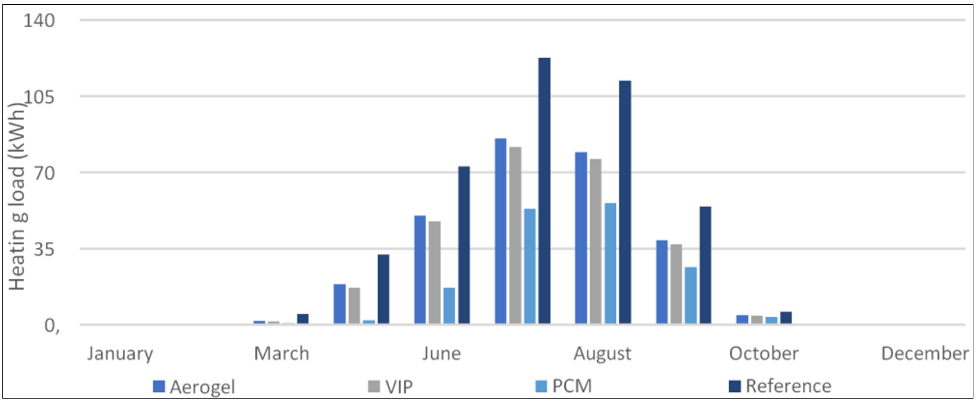

Fig.5. Annual heating load requirements for the optimum insulation thickness

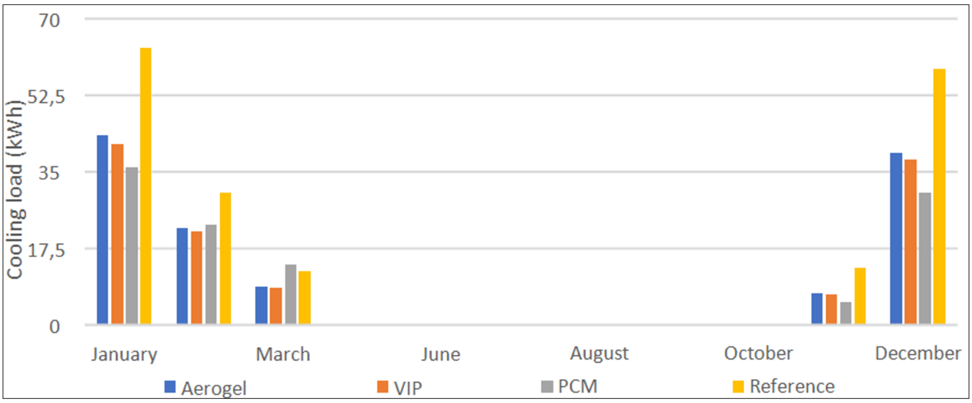

Fig. 6. Annual cooling load requirements for the optimum insulation thickness

The energy savings per square meter of the cell were defined as the difference between the energy requirements of the cavity without and with thermal insulation of the roof, which are given in Tables 5 and 6 for the optimum thickness of each type of insulation. These savings vary between minimum and maximum values (27.12 and 94.01%) depending on the considered month. They range for PCM from 24.5 to 59.3% in heating load and 40.7 to 94.01% in cooling f load, followed by VIP, which has a saving of 29.14 to 46.4% and 31.15 to 70.49% of heating and cooling loads, respectively. While, the Aerogel saves 27.12 to 43.99% of the heating loads and 27.98 to 66.34% of the cooling loads, according to its optimum thickness. However, savings in heating needs are negative for the PCM during March. This means that the PCM panels placed on the outer face of the roof prevent the cell from being warmed by possible solar gains, which generates a surplus of heating needs. Consequently, we deduce that the incorporation of the PCM in the building during March is unfavorable to its energy efficiency.

Table. 5. Savings (energy basis) in cooling requirements for the optimum insulation thickness (%)

Months	Savings in cooling requirements (%)		
	PCM	Aerogel	VIP
January	0	0	0
February	0	0	0
March	100	73.61	76.51
April	85.2	66.34	70.49
May	94.0	42.77	47.11
July	56.5	30.24	33.37
August	50.1	29.16	32.21
September	51.2	28.79	32.15
October	40.7	27.28	31.52
November	0	0	0
December	0	0	0

Table.6. *Savings* (energy basis) in heating requirements for each optimum insulation thickness (%)

Months	Savings in heating requirements (%)		
	PCM	Aerogel	VIP
January	43.3	31.78	34.85
February	24.5	27.67	29.79
March	-22.1	24.26	25.62
April	0	0	0
May	0	0	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	0
October	0	0	0
November	59.3	43.99	46.56
December	48.2	32.69	35.33

6. 3 Optimization of Insulation Thickness

As mentioned, the constraint put on the optimization procedure was the fact that the indoor temperature in summer had to be kept at 26 °C and 20 °C during winter. For each studied insulation material, the most economical insulation thickness is that corresponding to the minimum of the total cost over the considered life duration. The energy cost decreases when increasing the thickness of the insulator. The cost of the insulation increases linearly with the thickness of the insulator. The total cost is the sum of insulation and energy cost.

The optimum insulation thickness, energy savings, net present value, internal return rate, and payback period according to insulation material are given in Table 7. Results show that the optimum insulation thicknesses vary between 8 and 17 mm, the energy savings vary between 31.47 and 54.06 kWh/m^2, and the payback periods vary between 4.32 and 37.67 years

Regarding the economic parameters, we conclude that the highest NPV is reached for the PCM (10950.66 MAD), followed by the VIP (1150.45 MAD). Aerogel is deficient with a NPV of -8203.86 MAD. The internal Rate Return values are higher than the interest rate (i) and in the 6.04–28.18% range for the PIV and PCM, respectively.

Table. 7. Optimum insulation thickness, energy savings and payback period for VIP, Aerogel and PCM

Materials	Optimum insulation (mm)	Energy savings (kWh/m^2)	NPV (MAD)	IRR %	Payback period (years)
Aerogel	8	31.47	-8203.86	0.92%	37.67
VIP	17	34.62	1150.45	6.04%	18.99

PCM	10. 52	54.06	10950.66	28.18%	4.32

7 Conclusion

This paper deals with the effect of the integration of innovative insulation materials with very high thermal resistance on the dynamic thermal behavior of buildings. It consists of test cells situated in the Mediterranean climate of Casablanca (Morocco).
The impact of these materials on heat load and comfort is analyzed through experimental and dynamic simulations.
The study focuses on the thickness optimization of three selected materials: Aerogel, VIP, and PCM. The thermal performance is evaluated by comparison with the reference cavity (built with conventional building materials without any insulation). Dynamic simulations were performed using TRNSYS'17®. The simulations have been validated, and the deviation between measured and calculated temperatures does not exceed 0.88 °C.
The determination of the optimal insulation thickness of a roof was carried out over a lifetime of 20 years for the three considered insulation materials. The results show that the integration of these materials has a remarkable effect on indoor air temperature, thermal comfort, and heating and cooling loads compared to the reference case. Without heating or cooling in winter, the indoor air temperature has increased by 1.44 °C, 1.33 °C and 1.43 °C for the VIP, Aerogel and PCM, respectively. In summer, the indoor air temperature has beenreduced by 2.99 °C, 1.92 °C and 3.48 °C for the VIP, Aerogel, and PCM, respectively, compared to the reference cavity. It should be specified here that these reductions can be much higher than these values for the arid zones of Morocco, where the temperatures of thehot and cold seasons are very different from those of comfort. Furthermore, the use of thesematerials reduces the annual thermal load. Indeed, the energy savings range from 24.5% to 94.00%.

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