Comparative experimental and numerical studies of usual insulation materials and PCMs in buildings at Casablanca

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Abstract. In this paper, we present a comparative thermal study of the usual insulation materials used in the building as well as the innovate one like phase change materials (PCMs). Both experimental study and numerical approach were applied in this work for summer season. In the experimental study the PCM was installed on the outer surface on the ceiling of one of two full-scale rooms located at FSAC, Casablanca. A simulation model was performed with TRNSYS’17 software. We have established as a criterion of comparison the internal temperatures. An economic study also has been carried out. Based on this latter, that the PCM is most efficient.

Keywords: Insulation materials, Energy efficiency, full-scale room, experimental study, PCMs, TRNSYS’17

1. Introduction
According to the international energy agency, the global energy consumption related to the residential sector in Morocco has almost doubled (47%) between 2004 and 2011[1]. During the summer season, a large part of this energy consumption is related to space cooling [2]. Generally, in residential buildings, the surface that has the largest exposure to the outdoor environment (solar radiation) and, consequently, most subjected to the climate change is represented by the roof [3]. In fact, lightweight, cannot provide the necessary mass to buffer thermal gain. So far, the addition of new insulation layers appears a promising solution to improve the thermal behavior of roof components [4].

Over the last few decades, several studies and models are interested in developing new technologies to improve the thermal behavior of roofs taking into account the limitation of thickness and weight of insulation materials and the height reduction of the internal space. New technology has been developed like the supper insulating [5,6], radiant barriers [7,8], ventilated air cavity [9, 10], green roof [11] and the cool materials [12,13]. Another approach based on the dynamic thermal properties has developed by the implantation of phase change materials [14, 15, 16].

Guechchati et al. [17] conducted a dynamic simulation study using TRNSYS’16 to evaluate the effect of insulation materials on energy consumption of a building located in Oujda (Morocco). Various solutions have been proposed, the authors have concluded that the insulation of the roof coupled with the external wall insulation both with 6 cm of polystyrene reduce the heating load by 16.4% and 19.8% respectively without and with double glazing. Yrney et al. [18] investigated the in situ thermal behaviour of a case study building located in Ireland. Both The ceiling and the external wall has been thermally insulated. The authors have compared data before and after the fixing of insulation. The authors concluded that predicted values of heat losses using standard material properties did not reflect the actual values achieved in situ. Indeed, the predicted thermal resistances based on standard materials properties, overestimated the reduction in heat losses through the ceiling by nearly 50% and through the wall by nearly 20%. Furthermore, a thickness of 10 cm of polystyrene led to heat losses reduction of 56% and
35% through the walls and the roof respectively.

Ibrahim et al. [5] examined the effectiveness wall structure and insulation layer positions for different construction materials for French Mediterranean climate. Both experiment and numerical model was carried out, the best performance is achieved when placing the insulation at the interior wall surface. In general, the aerogel-based insulating coating is most performed compared to the other insulating materials. Elarga et al. [19] investigated the thermal performances of PCM integrated in a residential attic in Torino (Italy). The PCM was applied to a roof a with three different solutions during summer season. The authors conducted that PCM-enhanced components are a promising solution to improve the thermal performance of the roof. The experimental results showed a reduction of the ongoing heat peak load between 13% and 59% depending on the PCM thermal characteristics. Mourid et al. [16] studied the effectiveness of PCM to improve the thermal comfort during summer period, the PCM was installed on the roof, to parameters has been investigate (thickness and the emplacement of PCM). The results indicate that the integration of the PCM on the roof, led a reduction of daily temperature swings (up to 2°C) and heat flux (more than 88%). The most benefits configuration was the emplacement of the PCM on the outer face of the roof with the thickness of 10.52 cm.

This paper reports the development of a lightweight with an integrated of different types of insulation layer aimed at buffering external gains during summer. Both experimental and numerical study are detailed and the assessment of thermal performance and financial study are discussed.

2. Experiment

2.1. Description of the cells

Building rooms were constructed at Faculty of sciences Ain chock Casablanca as detailed earlier in [16]. The cells have an internal dimension of 2.8 m x 2.8m x 2.8 m. The northern wall is equipped with a door of dimension of 1 m×2 m and window 1 m× 1 m. The ratio of the window to wall area in the northern sides is 17%. The thickness of the window glass is 5 mm while the details of building envelopes along with the thermos-physical properties of the building materials are given in Tables 1 respectively.

Table 1. Detail construction of the building and the thermal properties of Building materials

| Building elements | Construction (outside-inside) | U-Heat transfert coefficient (W/m².K) |
|-------------------|-------------------------------|----------------------------------------|
| Roof              | Cement mortar                 | 2.722                                  |
|                   | Bitumen                       |                                        |
|                   | Cement mortar                 |                                        |
|                   | Heavy concrete                |                                        |
|                   | Cement mortar                 |                                        |
| Vertical Wall     | Cement mortar                 | 0.531                                  |
|                   | Yellow brick                  |                                        |
|                   | Air layer                     |                                        |
|                   | Yellow brick                  |                                        |
|                   | Cement mortar                 |                                        |
| Floor             | Cement mortar                 | 0.694                                  |
|                   | Clay                          |                                        |
|                   | Polystyrene                   |                                        |
|                   | Heavy concrete                |                                        |
|                   | Limestone                     |                                        |
2.2. Climate in Casablanca city
Casablanca is located in the central-western part of Morocco at latitude 33°35’N and longitude 7°36’O. It has a warm and temperate climate (Mediterranean). It’s classified as Cwb by the Köppen-Geiger system. July and August are the most warmer months of the year with temperature ranging from 24.23°C to 32.44°C.

2.3 Instrumentation
Thermocouples, K-type (2/10mm) were used, they have been verified and calibrated. The accuracy from the thermocouples is about ±0.20 °C.

The meteorological data was measured using vantage Pro 2 weather station. It’s installed on the roof of one of the cells. This station allows us to measure the outside temperature (±0.50°C), the humidity, the speed and wind direction (±1.00 m/s) and using pyranometer, we measured the global solar radiation (±5%). All the instruments are connected to a data logger, which is in turn connected to a computer.

2.4 Measured weather data
The experimental results were used to study the thermal performance of the roof and to validate the numerical model. Two days of experimental results (from 28th to 29th June 2015) representative of the summer conditions are reported in Figures 1 and 2.

In the monitored period, the outdoor temperature was between ~26.24°C (minimum night temperature) and ~31.15°C (maximum daily temperature). During the studied days, the incident global solar radiation reached a peak of 871 W.m⁻² at 1:00 pm with average value of 466 W.m⁻².

The wind speed is characterized by wind velocity varying within 1.3 m/s <v <11.6 m/s, Figure 2. The minimum value was recorded during the night.

![Figure 1. Outdoor temperature and global solar radiation](image1)

![Figure 2. Wind speed variation](image2)

2.5 Studied Configuration
In this study different type of thermal insulation were studied. Six different configurations are investigated: The first and the second cases are realized experimentally using the reference cavity with standard walls (Case 1) and the other cavity with PCM on the external face of roof (Case 2). The other
configurations are performed numerically for different kinds of insulation, using TRNSYS’17. These investigations are summarized as follow:

Case 1: reference cavity
Case 2: PCM panels
Case 3: Rockwall
Case 4: Cork
Case 5: Extruded polystyrene (XPS)
Case 6: Aerogel
Case 7: Vacuum insulation panels

The extruded polystyrene foam, cork, rock with thermal conductivity of 39 mW/(m.K), 40 mW/(m.K) and 41 mW/(m.K) was used as thermal insulation material. The aerogel used in this study, is called Spaceloft® and developed by Aspen Aerogels [20]. Spaceloft® is a flexible aerogel blanket has a thermal conductivity of 13.1 mW/(m.K) at 273 K, 2–2.5 times lower than traditional thermal insulation materials. The Vacuum insulated panels (VIPs) used is fumed silica, it has thermal conductivities of 4mW/(mK) it’s called Vacupor® NT-B2 [21].

The phase change material (PCM) used is a mixture of ethylene based polymer (40%) and paraffin wax PCM (60%). The melting temperature of PCM is in the range of 20 °C ≤ T_{melt} ≤ 35 °C and a heat latent enthalpy $h_{PCM}$ of 72.4 kJ/kg [22]. Its thermal conductivity is 0.18 W.m$^{-1}$.K$^{-1}$ in solid phase and 0.22 W.m$^{-1}$.K$^{-1}$ in liquid phase.

3. Simulation details

In order to study the effect of PCM and the insulations Materials on thermal performance and energy consumption for a room building located in Casablanca, the TRNSYS’17 software through transient multi-zone modeling was employed with a step of one hour. The validation of the simulation model is based on the experimental data of two months of measures during summer season. In order to validate this model, meteorological data measured on the site were used. The air temperatures of the cavity obtained from the simulations are compared with those measured. Generally, the comparison of the calculated and the measured temperatures show a good agreement, taking into account the thermocouple accuracy and approximate computational errors. The deviations do not exceed 0.84 °C in cell without PCM (figure 3) and 0.8°C in the cell with PCM (figure 4).
Figures 5 and 6 present the assembly panel windows of our TRNSYS project for both cells reference and PCM cavity, including all the involved modules (Types) and links. The cooling loads in the cells are calculated on the basis of the set air temperatures of 21 °C, and the humidity comfort at 60% in summer.

Figure 5. Assembly panel windows of our TRNSYS project for the reference cavity

Figure 6. Assembly panel windows of our TRNSYS project for the cell with PCM
Simulations were performed using the following assumptions:
- Initial air temperature and humidity are taken equal to 20 °C and 50% respectively in studied zone.
- Internal heat generation (Lighting (5W/m²)).
- The doors and windows are closed all the time (no free cooling).
- Constant infiltration rate of 1 ACH.
- The absorption coefficients of the exterior face of the roof of the reference cavity and the PCM cavity are set to 0.7 and 0.245 [16].
- The wall external emissivity is taken equal to 0.9.
- Convection heat transfer coefficient at the outside surfaces $h_{out}$ is calculated using (Eq 1) which takes into account the wind velocity $V$ [23]:

$$h_{out}=1.44*V + 4.955$$ (1)

- TYPE 77 was used to calculate the ground temperature
- Type 399 models phase change materials (PCM) in wall constructions.

The comparison criteria are the internal temperature and the thickness of the PCM. Indeed, the experimental results are obtained for a PCM thickness of 5.26 mm. The obtained results will be compared with those obtained numerically.

4. Results and discussion

4.1 Experimental results

In this section, the thermal performance of an office building (with and without PCM) located in Casablanca, Morocco is evaluated for a typical two days climate of July 2015. It should be noted that in the case 2 (with PCM application), PCM was incorporated on the outer surface of the roof. The interior temperature profiles for the cavities (with and without PCM) are presented for the considered period in Figure 7. It shows that ceiling surface temperature was reduced by an average of 1.15 °C due to the passive application of PCM with a maximum reduction of 1.28 °C. It can be explained by the increase of the thermal inertia of the roof through the storage and release of energy. Thereby, the thermal behavior of PCM allows reducing the amplitude of temperatures. This figure also shows that PCM temperature varied between 26.28 °C to 29.90 °C during the studied period although the outdoor air temperature doesn’t reach below 21.0°C all considered period. This means that a small part of PCM was solidified at night, which does not allow the PCM layer to work at full capacity during the day.
4.2 Numerical results
Since our experimentation does not allow a complete study with different insulating materials, we have therefore proceeded numerically to complete our comparative study. Indeed, for the numerical configurations, we present the temporal evolutions of the temperatures of these different cases compared to that of Case 2. The curve relating to the insulation for each case is obtained for an optimal thickness, which must be established. This thickness is obtained in the following way: we start the calculations with an exhaustive thickness of insulation that we start to reduce with a step of 2 cm. We compare the curve obtained with that of case 2 for each step. Once we find that the curves start to approach, we reduce the pitch to 1 mm and we continue to reduce the thickness until the two curves are almost identical. In addition, we also verify that we have almost the same energy consumption of the cooling system. Once these two criteria are verified, we consider the thickness as optimal.

In Figures 8, 9, 10, 11 and 12, we present a comparison of the internal temperatures of Case 2 and Cases 3, 4, 5, 6 and 7, respectively. These curves are obtained for the following optimal thicknesses, Table 2:

| Insulation material | PCM | Rockwall | Cork | XPS | Aerogel | VIP |
|---------------------|-----|----------|------|-----|---------|-----|
| Thicknesses (mm)    | 5.26| 15       | 15   | 12.5| 8       | 6   |

Table 2. Optimal thicknesses of considered insulating materials

It should be remembered that the trend for recent constructions is in the direction of light materials as well as thin but heavy envelopes (in terms of thermal mass). For all these reasons, we find that cases 3, 4 and 5 have relatively large optimal thicknesses and should be considered out of competition.

The Other materials of cases 6 and 7 (Aerogel and VIP) have low optimal thicknesses. They can be considered for new buildings. However, the thickness of case 2 (case with PCM) remains the lowest and therefore, we conclude that our phase change material remains the best current insulator by its thermal inertia and its ability to store heat in latent form.
Figure 8. Rockwall (Case 3)

Figure 9. Cork (Case 4)

Figure 10. Polystyrene (Case 5)

Figure 11. Aerogel (Case 6)
5. The financial study

The energy requirements for cooling of the cavities is calculated by TRNSYS’17 software, with a set point of 21°C, as reported above. Simulations are conducted using measured meteorological data of Casablanca. Conventional energy demand for the cavities with or without insulation is about 40878.709 kJ and 48109.78 kJ respectively.

Since we set the internal temperature and energy consumption right from the start, so the investment cost will be the decisive factor in this study.

The investment cost of the studied configuration is about 2,000 MAD (around 175 EURO), 4,420 MAD (around 400 EURO), 9,090 MAD (around 822 EURO) for the Case 2 (PCM), Case 6 (Aerogel) and Case 7 (VIP), respectively as shown in table 3.

| Insulation types | Insulation material cost (MAD) (m²) | Cost of making (MAD) | Total cost (MAD) |
|------------------|-------------------------------------|----------------------|------------------|
| PCM              | 331.66                              | 30                   | 2000             |
| Aerogel          | 763.7                               | 30                   | 4420             |
| VIP              | 1207.33                             | 30                   | 9090             |

6. Conclusion

The aim of this paper is to provide experimental and numerical data in order to evaluate a thermal behavior and financial benefit of PCM and insulation materials in the building. Two test cells were used to measure the indoor temperatures of the cells subject to the real conditions of Casablanca. A numerical study was involved using Trnsys’17. In order to validate the numerical model, two steps of validation were presented. The first step consists in comparing with experimental data related to the reference cavity and the second one was with the cavity with PCM.

The results show that the PCM application is the most efficient compared to the supper insulation as Aerogel and VIP. Indeed, it represents the thinnest thickness (5.56 mm) and so the cheapest investment (175 EURO).
7. References

[1] International Energy Agency (AIE) 2014, OECD/IEA, MAROC 2014

[2] Agence de Développement des Energies Renouvelables et de l’Éfficacité Energétique ADEREE, (2012), Règlement Thermique de Construction au Maroc.

[3] U.S. Department of Energy, 2011 Buildings Energy Data Book, 2012, p. 286.

[4] Ballarini I, Corrado V, 2012n Analysis of the building energy balance to investigate the effect of thermal insulation in summer conditions, Energy and Buildings 52 p168–180.

[5] Ibrahim M, Biwole P H, Wurtz E, Achard P, 2014 A study on the thermal performance of exterior walls covered with a recently patented silica-aerogel-based insulating coating, Building and Environment 81 p 112-122.

[6] Voellinger T, Bassi A, Heitel M, 2014 Facilitating the incorporation of VIP into precast concrete sandwich panels, Energy and Buildings, 85 p 666-671.

[7] Fontaninia AD, Pr’Outa K M, Kosnyb J, Ganapathy subramaniana B, 2016, Exploring future climate trends on the thermal performance of attics: Part 1 – Standard roofs, Energy and Buildings 129 p 32–45.

[8] Escudero C, Martin K, Erkoreka A, Flores L, Sala J M, 2013 Reflective thermal insulation systems in building: A review on radiant barrier and reflective insulation, Energy and Buildings 59 p 62-72.

[9] Sunwoo L, Park S H, Myong S Y, Kwang W K, 2009, An experimental study on airflow in the cavity of a ventilated roof, Building and Environment, 44, Pages 1431-1439.

[10] Fantucci S, Marinosci C, Serra V, Carbonaro C, 2017, Thermal Performance Assessment of an Opaque Ventilated Façade in the Summer Period: Calibration of a Simulation Model through in-field Measurements, Energy Procedia, 111, p 619-628, https://doi.org/10.1016/j.egypro.2017.03.224.

[11] Alvizuri J, Cataldo J, Small-Mantey L A, Montalto F A, 2017, Green roof thermal buffering: Insights derived from fixed and portable monitoring equipment, Energy and Buildings 151, p 455-468.

[12] Xiang B, Xiuping Y, Zhang J, 2017, A novel cool material: ASA (acrylonitrile-styrene-acrylate) matrix composites with solar reflective inorganic particles, Composites Science and Technology, 145, p 149-156.

[13] Ong KS, 2011, Temperature reduction in attic and ceiling via insulation of several passive roof designs, Energy Conversion and Management 52, p 2405-2411. http://dx.doi.org/10.1016/j.enconman.2010.12.044.

[14] Min Hee, C. Jin Chul, P.2016, Development of PCM cool roof system to control urban heat island considering temperate climatic conditions, Energy and Buildings,116, p 341-348.
[15] Mourid, A, El Alami, M, 2016, Passive Study of Energy Efficiency of a Building with PCM on the Roof during Summer in Casablanca, Journal of Power and Energy Engineering, 4, p 26-37.

[16] Mourid A, Alami M, 2017, Thermal Behavior of a Building Provided with Phase Change Materials on the Roof and Exposed to Solar Radiation, Journal of Solar Energy Engineering 139(6).

[17] Guechchati R, Moussaoui M A, Mezrhab Ahm, Mezrhab Abd, 2010, Simulation de l’effet de l’isolation thermique des bâtiments : Cas du centre psychopédagogique SAFAA à Oujda. Revue des Energies Renouvelables,13, p 223-232.

[18] Byrne A, Byrne G, Davies A, Robinson A J, 2013, Transient and quasi-steady thermal behavior of a building envelope due to retrofitted cavity wall and ceiling insulation, Energy and Buildings 61 p 356-365.

[19] Elarga H, Fantucci S, Serra V, Zecchin R, Benini E, 2017, Experimental and numerical analyses on thermal performance of different typologies of PCMs integrated in the roof space, Energy and Buildings 150, p 546-557

[20] Spaceloft® Safety Data Sheet, Retrieved November 19, 2009, from http://www.aerogel.com/products/pdf/Spaceloft MSDS.pdf.

[21] Vhttp://www.porextherm.com/en/products/vacupor.html

[22] Kuznik, F, Virgone, J, Johannes, K, 2010, Development and validation of a new TRNSYS type for the simulation of external building walls containing PCM. Energy and Buildings, 42, p 1004–1009

[23] Mourid, A, El Alami, M, 2017, Experimental analysis of the thermal behavior of two cavities kind of living space with and without PCM on envelopes, International Journal of Modern Embedded System, 5, p 7-12 ISSN: 2320-9005.