Thermal and Energetic Contributions of PCM Plaster According to Its Location and Type of Masonry—Experimental and Numerical Studies in a City With a Temperate Mediterranean Climate

ABDELAZIZ MECHOUET, TAOUFIQ MOUHIB, ADIL BALHAMRI, FARIDA BENDRIAA, TARIK RAFFAK, AND EL MOSTAFA OUALIM
Hassan First University of Settat, École Nationale des Sciences Appliquées, LISA Laboratory, Berrechid 26100, Morocco
Corresponding author: Abdelaziz Mechouet (a.mechouet@uhp.ac.ma)

ABSTRACT
The integration of phase change materials (PCMs) in the construction sector is very promising for the improvement of the thermal and energy performance of buildings. This multi-variable study aims to reveal the contribution of PCM plaster according to the type of masonry (single cement bricks or double clay bricks), the type of plaster (PCM or cement plaster) and its location (interior or exterior) to reduce indoor temperature fluctuations and energy consumption levels. Small-scale experimentation and dwelling dynamic modelling of several types of rooms have revealed that compared to cement plaster, PCM plaster on the interior surface of exposed walls reduces the indoor temperature fluctuation range by up to 2.5°C on winter days and by up to 2.6°C on summer days if it is applied on the exterior surface of the single-partition walls. In the case of double-partition walls, the reduction in the indoor temperature fluctuation range reaches 1°C on winter days and 1.3°C on summer days. Interior PCM plaster reduces the heating energy demand in winter by up to 25% for single partitions and 21% for double partitions. In summer, the reduction in cooling energy demand with exterior PCM plaster is up to 36% for single walls and 44% for double walls. Compared to cement plaster, although the thermal and energy reduction percentages of PCM plaster are greater for single-partition walls, the temperature fluctuations and energy consumption are lower for double-partition walls. Determination of the optimum melting temperature and thickness of PCM plaster would improve the performance obtained.

INDEX TERMS
Building, materials, phase change materials, cement plaster, modelling, thermal comfort, cooling, heating, energy.

NOMENCLATURE
COP Coefficient of performance.
Cp Specific heat capacity of the material (kJ/kg K).
i Node being modelled.
i+1 Adjacent node towards the inner side.
i-1 Adjacent node towards the outer side.
j Previous time step.
j+1 Simulation time step.
kE Thermal conductivity between nodes i and i-1 (W/m.K).
kW Thermal conductivity between nodes i and i+1 (W/m.K).
PCM Phase change material.
T Node temperature (°C).
TA Average daily indoor temperature (°C).
Tk Thermal conductivity (W/m.K).
TM Melting temperature (°C).
Tmax Maximal daily indoor temperature (°C).
Tmin Minimal daily indoor temperature (°C).
Tout Outdoor temperature (°C).
The resistance of the walls [16].

It also depends on the external temperature and the thermal properties of the matrix, considering the climatic conditions and thermal loads to avoid a poor winter result.

Childs and Stovall [18] studied a building with cellulose walls incorporating PCM by treating the impact of different elements of interest such as the PCM dosage, PCM location in walls, outside temperature and wall orientation and showed that the installation of PCM at the inner face of the walls allowed to obtain a major energy gain.

An experimental study was conducted by Yang et al. [19] on walls impregnated with rectangular encapsulated hydrated salt under a temperature mode corresponding to transition seasons characterized by unstable temperatures.

The experiment showed that the amplitude of the indoor air temperature was reduced by more than 32% when PCM was placed near the inner face of the wall over the temperature amplitude of the indoor air temperature when PCM was placed on the outer face.

Scalat et al. [20] concluded, in a large-scale experimental study, that wall panels impregnated with PCM could attain charging and discharging times of approximately 7 hours, which enables energy storage in the heating mode but also in the cooling mode, and they pointed out that the rate of heat loss varied according to the temperature difference, construction method, room size, occupancy characteristics, and heat losses and gains.

Olivier [21] studied gypsum board with 45% PCM and concluded that under the same test conditions, it stored 5 times more energy per unit mass than a thermal brick wall, 9.5 times more energy than a brick wall, and almost 3 times more energy per unit mass than a common gypsum board.

Athienitis et al. [22] investigated the thermal performance of PCM gypsum panels used in a passive solar building. They found that the room temperature could be reduced by approximately 4°C during the day, and the heating load could be reduced by 15%. Other experimental studies revealed that the integration of PCM in gypsum panels could reduce indoor air temperature fluctuations by 4°C, especially in summer [23], [24].

Kuznik and Virgone [26] applied two identical test cells to investigate the effects of PCM wallboards; a heating/cooling step with a sinusoidal evolution was tested. The PCM wallboards caused a time lag between the indoor and outdoor temperature evolutions and reduced the external temperature amplitude.

The same conclusion was drawn by Shilei et al. [27] when combining gypsum panels with PCMs in winter in the northeast of China.
In a study on concrete walls containing PCMs in San Francisco and Los Angeles, Thiele et al. [28] found that the cooling load that could be reduced in summer was greater than the heating load in winter.

Kuznik et al. [29] installed plasterboard containing PCM on the sidewalls and ceiling of an office in a building under renovation, and compared to another office not containing PCM, they found a reduction in the operating temperature of up to 3°C.

Considering the advantages offered by PCMs cited in the scientific literature, through this study, we wanted to provide a clear answer on the impact of PCM plaster on the thermal comfort and energy consumption necessary for cooling and heating if used as interior and/or exterior wall cladding instead of the cement plaster widely used in the Mediterranean countries.

The major contributions of this study are:

- To address the point not sufficiently covered by the literature, namely, the thermal and energy contributions of PCM plaster through a multi-variable study considering the type of masonry (single cement brick partition or double clay brick partition), the type of rendering (PCM rendering or cement plaster) and its location (interior and/or exterior).
- To verify and quantify the thermal and energy contributions of PCM plaster and compare them to those of cement plaster.

The subject is addressed in the context of a temperate Mediterranean climate where the outside temperatures are neither very high in summer nor very low in winter.

II. METHODOLOGY

The study consisted of:

- A small-scale experiment aimed at observing the thermal performance of eight cells of identical dimensions whose sidewalls exhibit several configurations, namely, the walls are either single-partition cement bricks or double-partition clay bricks, and on the internal and external faces of these sidewalls, either a cement plaster widely used in construction in Morocco is applied as external or internal plaster or a plaster containing micro-encapsulated PCM.
- A dynamic modelling experiment of a dwelling with rooms of different sizes and exposures with the same walls and plaster configurations as the small-scale experiment. The indoor temperatures in winter and summer as well as the energy required for cooling and heating of the different rooms were observed and compared.

The cooling and heating energy demands are then evaluated considering an on/off wall-mounted split heating and cooling system with a coefficient of performance of 2.5.

For heating, the required set point of the indoor temperature is 22°C and the minimum starting threshold is 18°C. For cooling, the set point is 24°C and the maximum starting threshold is 28°C. The reduction in heating and cooling energy provided by PCM plaster as the interior and/or exterior plaster was evaluated via comparison to the result obtained with cement plaster with the following equation:

\[
\text{Energy Reduction by PCM} = \frac{\text{Energy with PCM} - \text{Energy Without PCM}}{\text{Energy without PCM}}
\]

III. SMALL-SCALE EXPERIMENTATION

A. EXPERIMENTATION SET UP

Eight cells of identical internal dimensions (50 cm × 50 cm × 60 cm) are made. Figure 1 shows a photo of the used experimental cells.

The walls of the cells are either single or double partitioned:

- The single-partition walls are made of cement bricks, which offer a high wall strength, easy installation and suitable price, but their thermal insulation is poor (\(T_k = 0.84\) W/m.K).
- The double-partition walls are made of clay bricks, which are lighter and more fragile, but they are more expensive, and their installation is more complicated than the cement bricks since the exterior walls contain a cavity allowing for the possible insertion of thermal insulation. However, this allows for a greater thermal insulation than cement bricks (\(T_k = 0.35\) W/m.K).

The interior and exterior faces of these walls are then lined with either PCM or cement plaster.

Table 1 summarizes the different configurations of the walls and plaster materials of the cells studied.

Figure 2 shows the walls composition of cells S1, S2, S3 and S4 made from cement bricks. These cells have a single 15-cm thick cement brick partition wall. On the inner surface of these sidewalls, either plaster containing micro-encapsulated PCM (INERTEK 23; latent heat: 180 J/g;
melting temperature = 23°C) with a thickness of 15 mm is applied or cement plaster with the same thickness. On the outside of these walls, either 12 mm of the same PCM plaster is applied or cement plaster, followed by a 3-mm layer of exterior paint plaster. The floor and slab are made of 70-mm thick concrete.

Calibrated thermocouples are installed at the cell centres to simultaneously measure the internal temperatures. They are connected to a data acquisition device that measures and records the temperature every 15 minutes. The outdoor temperature is monitored and recorded by a small weather station. Figure 4 gives a scheme of the experimental set up.

### TABLE 1. Wall and plaster configurations of the cells.

| Configuration       | S1     | S2     | S3     | S4     |
|---------------------|--------|--------|--------|--------|
| **Single-partition**| Plaster | PCM plaster | PCM plaster | Cement plaster | Cement plaster |
| Internal plaster    | PCM plaster | PCM plaster | Cement plaster | Cement plaster |
| External plaster    | PCM plaster | Cement plaster | PCM plaster | Cement plaster |
| **Double-partition**| Plaster | D1     | D2     | D3     | D4     |
| Internal plaster    | PCM plaster | PCM plaster | Cement plaster | PCM plaster | Cement plaster |
| External plaster    | PCM plaster | Cement plaster | PCM plaster | Cement plaster |

Figure 3 shows the wall composition of cells D1, D2, D3 and D4: these cells are double-sided walls made of 70-mm thick clay bricks separated 100 mm with the same plaster configurations on the inner and outer surfaces as the S1, S2, S3 and S4 cells (PCM plaster or cement plaster). The floor and slab are also made of concrete and are 70 mm thick.

Table 2 lists the material characteristics of the different layers of the cell walls.

### TABLE 2. Characteristics of the cell wall components (bricks and plaster).

| Brick and plaster types | Melting temperature (°C) | Latent heat (J/g) | Thermal conductivity (W/m.K) | Specific heat (3/kg.K) | Thickness (mm) |
|-------------------------|--------------------------|-------------------|-------------------------------|------------------------|----------------|
| PCM plaster             | 23                       | 180               | 0.148                         | 2500                   | 15             |
| Cement plaster          | -                        | -                 | 1.4                           | 650                    | 15             |
| Clay brick              | -                        | -                 | 0.35                          | 840                    | 70             |
| Cement brick            | -                        | -                 | 0.84                          | 1050                   | 150            |

**B. RESULTS**

Figure 5 shows the results of the outdoor and indoor temperatures measured for single-partition cells S1 to S4 over 2 days with the outdoor temperatures ranging from 3°C to 15°C. For cell S4 with cement plaster on the interior and exterior faces, the indoor temperature ranges from 8.6°C to 23.7°C within a fluctuation range $\Delta T = T_{\text{max}} - T_{\text{min}}$ of 15.1°C. For cell S1, with its interior and exterior faces covered with PCM plaster, the indoor temperature ranges from 6.6°C to 16.2°C within a fluctuation range of 9.6°C. Cell S2 with interior PCM plaster and exterior cement plaster has an indoor temperature ranging from 7.5°C to 16.6°C with a fluctuation range of 9.1°C. Cell S3 with interior cement plaster and exterior PCM plaster exhibits a fluctuation range of 12.9°C since the indoor temperature ranges from 6.8°C to 19.7°C.
Figure 6 shows the measured outside and inside temperatures for double-walled cells D1 to D4 over 2 days under the same conditions as those of cells S1 to S4. For cell D4 with both interior and exterior cement plaster, the indoor temperature ranges from 7°C to 15.1°C within a range of 8.1°C. Cell D1 with interior and exterior PCM plaster, the indoor temperature ranges from 7.6°C to 16.2°C within a fluctuation range of 8.6°C.

On winter days, as the S1, S2, D1 and D2 cells have internal surfaces covered in PCM plaster, this enables them to attain a small temperature fluctuation and low sensitivity to outdoor temperature variation. Simulation of the thermal behaviour in winter and summer seasons will allow the determination of the behaviour under other conditions of outside temperatures and the corresponding energy based on the different wall configurations and the use of either PCM or cement plaster.

IV. MODELLING
A. CASES STUDIED
To investigate the impact of the degree of exposure to outdoor weather on the effect of PCM utilization on the indoor temperature, a residential dwelling with exterior walls exhibiting different surfaces and orientations was modelled (Figure 7). Different configurations of the external walls were simulated in the small-scale experiment. Thus, these external walls were either single- or double-partitioned walls with their internal and external faces coated with either PCM or cement plaster. Exterior paint plaster was applied on top of the exterior PCM plaster layer to avoid its deterioration due to the outdoor weather conditions (rain, UV rays, etc.).

As shown in Figure 8, room 2 has a south orientation and receives solar radiation on two of its walls throughout the day. Room 1 also faces south. Rooms 3 and 4 are oriented north and east, respectively, which allows them to receive solar radiation only in the morning, while room 5 has little exposure. Table 3 summarizes the areas and orientations of the walls and windows of the different rooms.

The simulations were performed in DesignBuilder software, which uses the EnergyPlus calculation engine and allows the modelling of multi-layer walls and thermal properties of PCMs using the finite difference method for the spatio-temporal discretization of the thermal equation and boundary conditions.

The heat transfer equation is written as [30]:

$$ c_p \rho \Delta x \frac{T_{i+1}^{j+1} - T_i^{j}}{\Delta t} = k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} $$

(1)

The thermal conductivities ($k_W$ and $k_E$) are written as:

$$ k_W = \frac{k_{i+1}^{j+1} + k_i^{j+1}}{2} $$

(2)

$$ k_E = \frac{k_{i+1}^{j+1} + k_i^{j+1}}{2} $$

(3)

The heat capacity of the PCM also varies with each time step and its value is expressed as a function of the specific
TABLE 3. Areas and orientations of the walls and windows of the rooms.

| Room | Area   | External Walls: Area/Orientation | Internal Wall Area | Windows Area/Orientation |
|------|--------|---------------------------------|--------------------|--------------------------|
| Room 1 | 37.3 m² | 27.6 m²/S                       | 52.2 m²            | 4.8 m²/S                 |
| Room 2 | 23.5 m² | 17 m²/S                         | 31.25 m²           | 3.0 m²/S                 |
| Room 3 | 22 m²   | 20.1 m²/E                       | 34.5 m²            | 2.16 m²/N               |
| Room 4 | 21.5 m² | 11.8 m²/E                       | 29.4 m²            | 2.16 m²/E               |
| Room 5 | 23.5 m² | 19 m²/N                         | 41.2 m²            | 3 m²/N                  |

B. RESULTS AND DISCUSSION

1) DAILY INDOOR TEMPERATURE

Figures 9 and 10 show the evolution of the indoor temperature for well-exposed room 2 on typical winter and summer days when the walls are under the single partition.

On a typical winter day, compared to cement plaster (S4), the PCM plaster on the interior surfaces (S1 and S2) reduces the fluctuation range of the indoor temperature. The fluctuation range is only 3.4°C if PCM is applied on the interior surface and is 5.4°C if it is applied on the exterior surface, and if both the interior and exterior surfaces are coated in cement plaster, the range is 6.2°C. This reduction in the indoor temperature fluctuation with interior PCM plaster occurs because the low indoor temperature is nearer the melting temperature of the PCM ($T_M = 23°C$) on a winter day, in the proximity of which phase change occurs, thus allowing heat storage and transfer. When PCM is applied to the exterior surfaces of the walls (S3), the contribution of PCM plaster is reduced because the outdoor temperatures to which it is subjected are low and far from its melting temperature.

On a summer day, the amplitude of the indoor temperature is 2°C if PCM plaster is applied to the exterior surfaces (S1 and S3) and is 4.1°C if it is applied to the interior surfaces, while the amplitude of the indoor temperature is 4.7°C if both the interior and exterior surfaces are coated in cement plaster. This reduction in the indoor temperature fluctuation with exterior PCM plaster occurs because on a summer day, the PCM placed on the exterior surfaces (S1 and S3) is...
close to the heat source (solar radiation), thus subjecting it to outdoor temperatures ranging from 21°C to 30.5°C near its melting temperature ($T_M = 23°C$), which allows the PCM to melt and solidify and thus store and transfer heat, respectively. When PCM plaster is applied only on the interior surface ($S2$) where the indoor temperature is above the melting temperature, the PCM effect is reduced. In this case, the contribution to the indoor temperature is not much different from that obtained with cement plaster ($S4$).

On a typical winter day, compared to cement plaster ($D4$), the PCM plaster on the interior surface of the walls ($D1$ and $D2$) reduces the indoor temperature fluctuation. The fluctuation range is 3.1°C if PCM is applied to the interior surface and is 3.9°C if it is applied on the exterior surface. It is 4°C in the case of cement plaster on both the interior and exterior surfaces.

Similar to the single-partition case, PCM plaster on the interior surface results in a small indoor temperature fluctuation because on a winter day, the indoor temperature is closer to the PCM melting temperature where phase change occurs. Whereas if PCM is applied to the exterior surface of the walls ($D3$), the contribution of PCM plaster is reduced because the outdoor temperature is farther removed from its melting temperature.

On a typical summer day, the indoor temperature fluctuation range is 2.6°C with interior PCM plaster and is 2.9°C with cement plaster whereas for exterior PCM plaster, the fluctuation range is reduced to 1.6°C. This reduction occurs because the PCM placed on the exterior surfaces ($D1$ and $D3$) receives solar radiation, which subjects it to a temperature near its melting point, thus allowing heat storage and transfer. When PCM plaster is applied only on the interior surface ($D2$), the indoor temperature is higher than the PCM melting temperature, which reduces its contribution. The observed indoor temperature is therefore not very different from that obtained with cement plaster ($D4$).

**TABLE 4. Room 2 indoor temperature fluctuations with PCM plaster.**

| Location       | $T_{min}$ | $T_{max}$ | $T_{A}$ | $\Delta T^\circ$ reduction (compared to cement plaster) |
|----------------|-----------|-----------|---------|---------------------------------------------------|
| Winter day     |           |           |         |                                                   |
| Single partition | Inside    | 12.4      | 15.8    | 14       | 3.4       | 2.8       |
| Double partition | Inside    | 13.9      | 17      | 15.3    | 3.1       | 0.9       |
| Summer day     |           |           |         |                                                   |
| Single partition | Outside  | 27.2      | 29.2    | 28.2    | 2         | 2.7       |
| Double partition | Outside  | 28.4      | 30.1    | 29.3    | 1.6       | 1.2       |

Table 4 summarizes the results of the PCM plaster contributions obtained for room 2: in the case of single-partition walls, on a typical winter day and with interior PCM plaster, the indoor temperature varies between 12.4°C and 15.8°C, i.e., a fluctuation range of 2.8°C, which is smaller than that obtained with cement plaster. In the case of double-partition walls, the indoor temperature varies between 13.9°C and 17°C, i.e., a range of 0.9°C, which is smaller than that obtained with cement plaster. Although the gain in fluctuation reduction due to the double partition is less notable than that due to the single partition (0.9°C instead of 2.8°C), the fluctuation range is less important (3.1°C instead of 3.4°C) and the temperatures are slightly higher and therefore closer to the thermal comfort level.

On a typical summer day, with exterior PCM plaster, the indoor temperature varies between 27.2°C and 29.2°C, i.e., a fluctuation range that is 2.7°C smaller than that
obtained with cement plaster. In the case of double-partition walls, the indoor temperature varies between 28.4°C and 31°C, i.e., a range that is 1.2°C smaller than that obtained with cement plaster. The gain in fluctuation range reduction due to the double partition is less notable than that due to the single partition (1.2°C instead of 2.7°C), but the fluctuation is less important (1.6°C instead of 2°C).

### TABLE 5. Indoor temperature range - single partition - winter day.

| Room   | $\Delta T_{S1}^o$ | $\Delta T_{S2}^o$ | $\Delta T_{S1}$ | $\Delta T_{S4}$ | $\Delta T_{S4} - \Delta T_{S1}$ | $\Delta T_{S4} - \Delta T_{S2}$ |
|--------|-------------------|-------------------|-----------------|-----------------|-------------------------------|-------------------------------|
| Room 1 | 8.2               | 8.5               | 9.5             | 10.1            | 1.9                           | 1.6                           |
| Room 2 | 3.4               | 3.7               | 5.3             | 6.2             | 2.8                           | 2.5                           |
| Room 3 | 4.8               | 5.0               | 6.1             | 6.3             | 1.5                           | 1.3                           |
| Room 4 | 1.8               | 1.8               | 2.3             | 2.5             | 0.7                           | 0.7                           |
| Room 5 | 5.7               | 5.9               | 6.6             | 6.8             | 1.1                           | 0.9                           |

2) INDOOR TEMPERATURE FLUCTUATION RANGE
   a: SINGLE-PARTITION WALLS

Table 5 lists the daily fluctuation ranges of the indoor temperature for the five rooms with single-partition walls on a winter day:

As previously observed for room 2, compared to cement plaster, interior PCM plaster reduces the indoor temperature fluctuation for the other rooms: the values of $\Delta T_{S1}^o$ and $\Delta T_{S2}^o$ are lower than the values of $\Delta T_{S3}^o$ and $\Delta T_{S4}^o$, respectively. The room indoor temperature fluctuation ranges are the largest in the case of interior and exterior cement plaster: $\Delta T_{S4}^o$ ranges from 2.5°C for room 4 to 10.1°C for room 1. Exterior PCM plaster does not drastically improve the fluctuation range of $\Delta T_{S4}^o$: it ranges from 2.3°C for room 4 up to 9.5°C for room 1. PCM plaster is rather interesting as interior plaster because the indoor temperature is closer to its melting temperature, thus allowing the exploitation of its heat storage and transfer capacities. Thus, the temperature fluctuation interval $\Delta T_{S2}^o$ ranges from 1.8°C for room 4 to 8.5°C for room 1 in the case of PCM plaster only on the interior surface. As in the case of room 2, applying PCM plaster to the outside of a wall with interior PCM plaster will only slightly improve the fluctuation ($\Delta T_{S1}^o$, from 1.8°C for room 4 to 8.2°C for room 2). The indoor temperature fluctuation range obtained with PCM plaster is compared to that obtained with cement plaster: it is observed that the reduction in indoor temperature fluctuation range $\Delta T_{S4}^o - \Delta T_{S1}^o$ varies between 0.7°C and 2.8°C with both interior and exterior PCM plaster. With interior PCM plaster, the reduction, i.e., $\Delta T_{S4}^o - \Delta T_{S2}^o$, ranges from 0.7°C to 2.5°C. Moreover, the contribution to $\Delta T_{S4}^o - \Delta T_{S2}^o$ is smaller in the case of exterior PCM plaster: it ranges from 0.2°C to 0.9°C.

### TABLE 6. Indoor temperature range - single partition - summer day.

| Room | $\Delta T_{S1}^o$ | $\Delta T_{S2}^o$ | $\Delta T_{S1}$ | $\Delta T_{S4}$ | $\Delta T_{S4} - \Delta T_{S1}$ | $\Delta T_{S4} - \Delta T_{S2}$ |
|------|-------------------|-------------------|-----------------|-----------------|-------------------------------|-------------------------------|
| Room 1 | 6.5               | 7.5               | 6.7             | 7.7             | 1.2                           | 0.2                           |
| Room 2 | 4.3               | 6.1               | 4.4             | 6.5             | 2.2                           | 0.4                           |
| Room 3 | 1.9               | 2.5               | 1.8             | 2.7             | 0.8                           | 0.2                           |
| Room 4 | 5.2               | 6.2               | 5.3             | 6.5             | 1.3                           | 0.3                           |
| Room 5 | 2.0               | 4.0               | 2.0             | 4.6             | 2.6                           | 0.6                           |

As indicated in table 6, on a summer day, compared to cement plaster, PCM plaster on the exterior surface reduces the room indoor temperature fluctuation ranges of rooms 1 to 5: the values of $\Delta T_{S1}^o$ and $\Delta T_{S2}^o$ are lower than the values of $\Delta T_{S3}^o$ and $\Delta T_{S4}^o$, respectively. The fluctuation is the largest in the case of both interior and exterior cement plaster: $\Delta T_{S4}^o$ ranges from 2.7°C for room 3 to 7.7°C for room 1. Interior PCM plaster does not reduce the fluctuation interval of $\Delta T_{S4}^o$: it ranges from 2.5°C for room 3 up to 7.5°C for room 1. For room 2, exterior PCM plaster allows for a greater reduction in the indoor temperature fluctuation because under the effect of solar radiation, and the temperature oscillates around the melting point: The temperature fluctuation of $\Delta T_{S4}^o$ ranges from 1.8°C for room 3 to 6.7°C for room 1 in the case of PCM plaster only on the outside. As in the case of room 2, applying PCM plaster to the interior surfaces has no major impact on the indoor temperature fluctuation interval of $\Delta T_{S1}^o$: it ranges from 1.9°C for room 3 to 6.5°C for room 1.

The reduction in the indoor temperature fluctuation range obtained with exterior plaster is more notable than that obtained with cement plaster: $\Delta T_{S4}^o - \Delta T_{S1}^o$ ranges from 0.8°C to 2.6°C, and $\Delta T_{S4}^o - \Delta T_{S3}^o$ ranges from 0.9°C to 2.6°C. In contrast, the contribution to $\Delta T_{S4}^o - \Delta T_{S2}^o$ is reduced in the case of interior PCM plaster: it ranges from 0.2°C to 0.6°C.

b: DOUBLE-PARTITION WALLS

In the case of double-partition walls and as previously observed for room 2, on a winter day and compared to cement plaster, indoor PCM plaster reduces the indoor temperature fluctuation in the other rooms: the values of $\Delta T_{D1}^o$ and $\Delta T_{D2}^o$ are lower than the values of $\Delta T_{D3}^o$ and $\Delta T_{D4}^o$, respectively (Table 7). The fluctuation is more notable in the case of both interior and exterior cement plaster: $\Delta T_{D4}^o$ ranges from 1.9°C for room 4 to 8.3°C for room 1. Exterior PCM plaster did not improve the fluctuation: the $\Delta T_{D3}^o$ values are almost the same as those of $\Delta T_{D4}^o$. For room 2, PCM plaster is rather interesting as interior plaster because the indoor temperature is closer to the PCM melting temperature, which allows the exploitation of its heat storage and transfer capacities. The temperature fluctuation range $\Delta T_{D4}^o$ ranges from 1.7°C for
room 4 to 7.9°C for room 1 in the case of PCM plaster applied only to the interior. Applying exterior PCM plaster in combination with interior PCM plaster will only slightly improve the fluctuation of the indoor temperature $\Delta T_D^{0}$: it ranges from 1.7°C for room 4 to 7.5°C for room 1.

As for the single partition, the reduction in fluctuation in the case of interior PCM plaster is more notable than that in the case of cement plaster ($\Delta T_D^{0} - \Delta T_D^{c}$ ranges from 0.2°C to 1.4°C, and $\Delta T_D^{0} - \Delta T_D^{i}$ ranges from 0.2°C to 1°C) and is smaller than that in the case of exterior PCM plaster ($\Delta T_D^{0} - \Delta T_D^{d}$ ranges from −0.1°C to 0.4°C).

As indicated in table 8, on a summer day and compared to cement plaster, exterior PCM plaster reduces the indoor temperature fluctuation in rooms 1 to 5: $\Delta T_D^{0}$ in the case of cement plaster is lower than $\Delta T_D^{0}$ in the case of exterior PCM plaster. Compared to the thermal resistance of exterior cement plaster, the fluctuation reduction is more notable in the case of both interior and exterior cement plaster.

As shown in Figure 13, on a typical winter day and compared to cement plaster, the use of PCM plaster as interior plaster reduces the heating energy demand. This reduction ranges from 17% for room 4 to 27% for room 2 and is comparable to the contribution of interior PCM plaster to the reduction in indoor temperature fluctuations previously observed. The use of exterior PCM plaster does not reduce the heating energy demand.

Over a whole winter season, the use of PCM plaster only on the external surfaces of exposed walls (before the coating of exterior paint plaster) imposes a negative effect on the heating energy required, since it is 4 to 36% higher than that required when using cement plaster (Figure 14). This can be explained

### Table 7. Indoor temperature range - double partition - winter day.

| Room | $\Delta T_D^{0}$ | $\Delta T_D^{c}$ | $\Delta T_D^{i}$ | $\Delta T_D^{0} - \Delta T_D^{c}$ | $\Delta T_D^{0} - \Delta T_D^{i}$ | $\Delta T_D^{0} - \Delta T_D^{a}$ | $\Delta T_D^{0} - \Delta T_D^{b}$ |
|------|-----------------|-----------------|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Room 1 | 7.5             | 7.9             | 8.2             | 0.8                          | 0.4                          | 0.1                          |
| Room 2 | 2.9             | 3.3             | 3.9             | 1.4                          | 1                             | 0.4                          |
| Room 3 | 4.7             | 4.9             | 5.4             | 0.6                          | 0.4                          | 0.1                          |
| Room 4 | 1.7             | 1.7             | 1.9             | 0.2                          | 0.2                          | 0                            |
| Room 5 | 5.6             | 5.9             | 6.1             | 0.5                          | 0.2                          | 0                            |

### Table 8. Indoor temperature range - double partition - summer day.

| Room | $\Delta T_D^{0}$ | $\Delta T_D^{c}$ | $\Delta T_D^{i}$ | $\Delta T_D^{0} - \Delta T_D^{c}$ | $\Delta T_D^{0} - \Delta T_D^{i}$ | $\Delta T_D^{0} - \Delta T_D^{a}$ | $\Delta T_D^{0} - \Delta T_D^{b}$ |
|------|-----------------|-----------------|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Room 1 | 6               | 6.4             | 6.2             | 0.5                          | 0.4                          | 0.1                          |
| Room 2 | 4               | 4.2             | 4.2             | 5.2                          | 1.2                          | 0.2                          |
| Room 3 | 1.8             | 2.1             | 2.2             | 0.4                          | 0.2                          | 1                            |
| Room 4 | 5               | 5.5             | 5.2             | 0.6                          | 0.1                          | 0.4                          |
| Room 5 | 1.6             | 2.7             | 1.7             | 3                            | 1.4                          | 0.3                          |

### Table 9. Indoor temperature fluctuation ranges with PCM plaster.

| Winter day | Single partition | Double partition |
|------------|------------------|------------------|
| Location   | $\Delta T_D^{0}$ | $\Delta T_D^{0}$ reduction (compared to cement plaster) |
| Inside     | 1.8 to 8.5       | 0.7 to 2.5       |
| Inside     | 1.7 to 7.9       | 0.2 to 1         |

| Summer day | Single partition | Double partition |
|------------|------------------|------------------|
| Location   | $\Delta T_D^{0}$ | $\Delta T_D^{0}$ reduction (compared to cement plaster) |
| Outside    | 1.8 to 6.7       | 0.9 to 2.6       |
| Outside    | 1.7 to 6.2       | 0.3 to 1.3       |

3) HEATING AND COOLING ENERGY

a: SINGLE-PARTITION WALLS

As shown in Figure 13, on a typical winter day and compared to cement plaster, the use of PCM plaster as interior plaster reduces the heating energy demand. This reduction ranges from 17% for room 4 to 27% for room 2 and is comparable to the contribution of interior PCM plaster to the reduction in indoor temperature fluctuations previously observed. The use of exterior PCM plaster does not reduce the heating energy demand.
by the fact that, in contrast to PCM plaster, cement plaster allows a higher heat flux due to solar radiation in winter and thus affords a slight increase in the interior temperature. Conversely, compared to cement plaster, interior PCM plaster reduces the heating energy demand for all of the modelled rooms. This reduction ranges from 17% for room 1 to 25% for room 2 (the heating energy with an interior PCM plaster ranges from 519 kWh for room 5 to 1230 kWh for room 1).

On a typical summer day, compared to cement plaster, the use of interior PCM plaster does not reduce the cooling energy demand for rooms 1 and 5 (Figure 15). This is in line with what has been observed on its impact on temperature fluctuations, namely, the use of exterior PCM plaster imposes a major impact. It allows reducing the cooling energy demand for all rooms from 13% for room 5 to 29% for room 3.

During the summer season, compared to cement plaster, interior PCM plaster does not reduce the cooling energy demand for rooms 1, 3, 4 and 5 (Figure 16). The reduction is 22% for room 2. Compared to cement plaster, the contribution of exterior PCM plaster applied to the exposed external surfaces of the rooms is more notable since it allows a reduction in the cooling energy demand for all the rooms. This reduction ranges from 12% for room 5 to 36% for room 1 (the cooling energy with an exterior PCM plaster ranges from 11 kWh for room 2 to 941 kWh for room 5).

b: DOUBLE-PARTITION WALLS
As for single-partition walls, on a typical winter day and compared to cement plaster, the use of PCM plaster as interior plaster on double-partition walls reduces the heating energy demand (Figure 17). This reduction ranges from 14% for rooms 1 and 4 to 24% for rooms 2 and 3. The heating energy demand for the rooms with PCM on the external surfaces is higher than that for rooms 1, 2 and 3 in the case of cement plaster.
In the winter season, the use of PCM plaster only on the external surfaces of the exposed double-partition walls imposes a negative effect on the heating energy required, and it is 7 to 51% higher than that required when cement plaster is used for the same reason cited in the case of the single-partition wall (Figure 18). The use of interior PCM plaster reduces the heating energy demand for all the rooms from 4% for room 1 to 21% for room 3 (the heating energy with an interior PCM plaster ranges from 385 kWh for room 2 to 1104 kWh for room 1).

As in the case of the single-partition walls, on a typical summer day and compared to cement plaster, interior PCM plaster on the double-partition walls does not reduce the cooling energy demand for rooms 1, 4 and 5, which is in line with what has been observed on its impact on temperature fluctuations, namely, the contribution of PCM plaster applied to the exposed external surfaces of the rooms is beneficial as it allows a reduction in the cooling energy demand for all the rooms. This reduction ranges from 19% for room 5 to 44% for room 1 (the cooling energy with an exterior PCM plaster ranges from 13 kWh for room 2 to 820 kWh for room 5).

The results obtained during the summer season are shown in the Figure 20. Compared to cement plaster, interior PCM does not reduce the heating energy demand for rooms 1, 4 and 5, which is in line with what has been observed on its impact on temperature fluctuations, namely, the contribution of PCM plaster applied to the exposed external surfaces of the rooms is beneficial as it allows a reduction in the cooling energy demand for all the rooms. This reduction ranges from 19% for room 5 to 44% for room 1 (the cooling energy with an exterior PCM plaster ranges from 13 kWh for room 2 to 820 kWh for room 5).

Comparing the heating energy demands of the rooms with single- and double-partition walls, it can be observed that compared to cement plaster, the contribution of the application of PCM plaster to the interior surfaces is slightly more notable for the single-partition walls than for the double-partition walls in terms of the percentage reduction of the heating energy demand (from 17 to 25% for the single partition and from 4 to 21% for the double partition). However, the energy required for heating is lower for
Regarding the energy level:

- Interior PCM plaster reduces the heating energy demand by up to 25% with the single partition and by 21% with the double partition.
- Exterior PCM plaster reduces the cooling energy demand by up to 36% with the single partition and by 44% with the double partition.
- The heating and cooling energy required to maintain the thermal comfort of the double partition is reduced compared to the single partition (since it allows for less indoor temperatures fluctuations values).

The results reveal a major contribution of the PCM plaster, but the performance should be optimized by considering other variables in future works such as the thickness of the PCM coating and PCM melting temperature in addition to the type of climate.

V. CONCLUSION

Through this multi-variable study, we verified and quantified the contribution of plaster containing micro-encapsulated PCM used as wall-covering material.

Different configurations of the use of PCM plaster were therefore examined, namely, the types of walls and bricks and PCM location on either the inside or outside surfaces of walls, and the performance obtained with PCM plaster was compared to that obtained with cement plaster.

The results of the dynamic modelling of a dwelling with several types of rooms showed the following in terms of the thermal performance:

- In winter, the PCM coating is more beneficial on the interior surface of the single- and double-partition walls: it reduces the indoor temperature fluctuation range from 0.7°C to 2.5°C for the single partition and from 0.2°C to 1°C for the double partition.
- In summer, the PCM coating is more beneficial on the exterior wall surface: it reduces the indoor temperature fluctuation range from 0.9°C to 2.6°C for the single partition and from 0.3°C to 1.3°C for the double partition.
- The contribution of PCM is less notable in terms of the percentage reduction of the indoor temperature fluctuation range for the double-partition walls, but the temperature fluctuations with this type of wall are smaller, and the temperatures are closer to the thermal comfort level even with cement plaster (double-partition walls made of clay bricks attain a suitable thermal insulation) compared to the case of single-partition walls.

Regarding the energy level:

- Interior PCM plaster reduces the heating energy demand by up to 25% with the single partition and by 21% with the double partition.
- Exterior PCM plaster reduces the cooling energy demand by up to 36% with the single partition and by 44% with the double partition.

REFERENCES

[1] (May 2016). International Energy Outlook. U.S. Energy Information Administration. vol. 484. [Online]. Available: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf
[2] T. Kousskou, P. Bruel, A. Jamil, T. El Rafahi, and Y. Zeraouli, “Energy storage: Applications and challenges,” Solar Energy Mater. Solar Cells. vol. 120, pp. 59–80. Jan. 2014.
[3] I. Sarbu and C. Sebarciucici, “A comprehensive review of thermal energy storage,” Sustainability, vol. 191, pp. 1–4. Jan. 2018.
[4] 2019 Global Status Report for Buildings and Constructi on. (2019). Towards a Zero-Emissions. Efficient and Resilient Buildings and Construc- tion on Sector. International Energy Agency. [Online]. Available: http://wedocs.unep.org/bitstream/handle/20.500.11822/30950/2019GSR.pdf?sequence=1&isAllowed=y
[5] F. Jin-Mei, Z. Xiang-Ping, W. Peng, and L. Jian-Ping, “Study on PCM application in old building energy efficiency.” in Proc. 5th Int. Conf. Measuring Technol. Mechatronics Autom., Jan. 2013, pp. 1080–1083.
[6] A. V. Sá, M. Azzena, H. de Sousa, and A. Samagao, “Thermal enhance- ment of plastering mortars with phase change materials: Experimental and numerical approach,” Energy Buildings, vol. 49, pp. 16–27. Jun. 2012.
[7] M. A. Izquierdo-Barrientos, J. F. Belmonte, D. Rodríguez-Sánchez, A. E. Molina, and J. A. Almendros-Bláñez, “A numerical study of external building walls containing phase change materials (PCM),” Appl. Therm. Eng., vol. 47, pp. 73–85. Dec. 2012.
[8] E. M. Alawadhi, “Thermal analysis of a building brick containing phase change material,” Energy Buildings, vol. 40, no. 3, pp. 351–357. Jan. 2008.
[9] F. Wei, Y. Li, Q. Sui, X. Lin, L. Chen, Z. Chen, and Z. Li, “A novel thermal energy storage system in smart building based on phase change material,” IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 2846–2857. May 2019.
[10] M. Rastogi, A. Chauhan, R. Vaish, and A. Kishan, “Selection and performance assessment of phase change materials for heating, ventilation and air-conditioning applications,” Energy Convers. Manage., vol. 89, pp. 260–269. Jan. 2015.
[11] M. Thambidurai, K. Panchabikesan, K. M. N., and V. Ramalingam, “Review on phase change material based free cooling of buildings— The way toward sustainability.” J. Energy Storage, vol. 4, pp. 74–88. Dec. 2015.
[12] K. Cellat, B. Beyhan, B. Kazanci, Y. Konuklu, and H. Paksoy, “Direct incorporation of butyl stearate as phase change material into concrete for energy saving in buildings,” J. Clean Energy Technol., vol. 5, no 1, pp. 64–68. Jan. 2017.
[13] A. Madad, T. Mouhib, and A. Mouhshen, “Phase change materials for build- ing applications: A thorough review and new perspectives,” Buildings, vol. 8, no. 5, p. 63, Apr. 2018.
[14] F. Kuznik, D. David, K. Johannes, and J.-J. Roux, “A review on phase change materials 964 integrated in building walls,” Renew. Sustain. Energy Rev., vol. 15, pp. 379–391. Jan. 2011.
[15] H. Zhang, Q. Xu, Z. Zhao, J. Zhang, Y. Sun, Z. Sun, F. Xu, and Y. Sowada, “Preparation and thermal performance of gypsum boards incorporated with microencapsulated phase change materials for thermal regulation,” Sol. Energy Mater. Sol. Cells, vol. 102, pp. 93–102. Jul. 2012.
[16] D. A. Neeper, “Thermal dynamics of wallboard with latent heat storage,” Sol. Energy, vol. 68, no. 5, pp. 393–403. 2000.
[17] K. El Omari, Y. Le Guer, and P. Bruel, “Analysis of micro-dispersed PCM-composite boards behavior in a building’s wall for different seasons,” J. Building Eng., vol. 7, pp. 361–371, Sep. 2016.
[18] K. W. Childs and T. K. Stovall, “Use of phase change material in a building wall assembly: A case study of technical potential in two climates,” in Proc. Int. High Perform. Buildings Conf., Jul. 2012, pp. 1–11. [Online]. Available: https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1057&context=ihpbc

[19] L. Yang, Y. Qiao, Y. Liu, X. Zhang, C. Zhang, and J. Liu, “A kind of PCMs-based lightweight wallboards: Artificial controlled condition experiments and thermal design method investigation,” Building Environ., vol. 144, pp. 194–207, Oct. 2018.

[20] S. Scalat, D. Banu, D. Hawes, J. Parish, F. Haghigdeta, and D. Feldman, “Full scale thermal testing of latent heat storage in wallboard,” Sol. Energy Mater. Sol. Cells, vol. 44, no. 1, pp. 49–61, Oct. 1996.

[21] A. Oliver, “Thermal characterization of gypsum boards with PCM included: Thermal energy storage in buildings through latent heat,” Energy Buildings, vol. 48, pp. 1–7, May 2012.

[22] A. K. Athienitis, C. Liu, D. Hawes, D. Banu, and D. Feldman, “Investigation of the thermal performance of a passive solar test-room with wall latent heat storage,” Building Environ., vol. 32, no. 5, pp. 405–410, Sep. 1997.

[23] S. Behzadi and M. M. Farid, “Experimental and numerical investigations on the effect of using phase change materials for energy conservation in residential buildings,” HVAC&R Res., vol. 17, pp. 366–376, Jun. 2011.

[24] P. Schossig, H.-M. Henning, S. Gschwander, and T. Haussmann, “Micro-encapsulated phase change materials integrated into construction materials,” Sol. Energy Mater. Sol. Cells, vol. 89, pp. 297–306, Nov. 2005.

[25] F. Kuznik, J. Virgone, and J.-J. Roux, “Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation,” Energy Buildings, vol. 40, no. 2, pp. 148–156, Jan. 2008.

[26] F. Kuznik and J. Virgone, “Experimental investigation of wallboard containing phase change material: Data for validation of numerical modeling,” Energy Buildings, vol. 41, no. 5, pp. 561–570, May 2009.

[27] L. Shilei, Z. Neng, and F. Guohui, “Impact of phase change wall room on indoor thermal environment in winter,” Energy Buildings, vol. 38, no. 1, pp. 18–24, Jan. 2006.

[28] A. M. Thiele, A. Jamet, G. Sant, and L. Pilon, “Annual energy analysis of concrete containing phase change materials for building envelopes,” Energy Convers. Manage., vol. 103, pp. 374–386, Oct. 2015.

[29] F. Kuznik, J. Virgone, and K. Johannes, “In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard,” Renew. Energy, vol. 36, no. 5, pp. 1458–1462, May 2011.

[30] S. Kenzhekhanov, S. A. Memon, and I. Adilkhanova, “Quantitative evaluation of thermal performance and energy saving potential of the building integrated with PCM in subarctic climate,” Energy, vol. 192, pp. 7–8, Nov. 2019.

ABDELAZIZ MECHOUIE received the B.E. degree in production means design from the University of Technology of Belfort-Montbéliard, France, in 2005. He is currently pursuing the Ph.D. degree in energy engineering with the Interdisciplinary Applied Sciences Laboratory, University of Hassan I, Settat, Morocco. He has worked on both large- and small-scale experiments and dynamic modelling of buildings. Since 2006, he has been working on the study and implementation of HVAC projects in the residential and tertiary sectors.

TAOUFIQ MOUHIB received the M.Sc. degree in condensed matter and materials physics from Hassan II Mohammedia University, Casablanca, Morocco, in 2003, and the Ph.D. degree in applied physics, in 2008. In 2004, he joined the Catholic University of Louvain, Louvain-la-Neuve, Belgium, for a joint doctoral thesis with Hassan First University of Settat, Morocco. From 2008 to 2011, he was a Postdoctoral Researcher with the Institute of Condensed Matter and Nanosciences, Catholic University of Louvain. In 2011, he moved to the Hassan First University of Settat, where he is currently a Professor in applied physics with the National School of Applied Sciences. His research interests include the thermal comfort in buildings with passive acclimatization, energy efficiency, sustainable energy, and 3-D chemical analysis at the sub-nanometre scale.

ADIL BALHAMRI received the Ph.D. degree in materials science from Hassan I University, Settat, Morocco, in 2012. He is currently a Professor with the National School of Applied Science. His research interests include new materials, renewable energy, and energy efficiency.

EL MOSTAFA OUALIM received the Ph.D. degree in atomic physics and optics from the Catholic University of Louvain, Belgium, in 1995. In 1995, he joined Hassan I University, Settat, Morocco, where he is currently a Full Professor in physics. He has directed several Ph.D. theses and has managed several research projects at the local, national, and European levels. His research interests include energy efficiency and heat transfer.

VOLUME 8, 2020

117451