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Performance of Wood-Based Panels Integrated with a Bio-Based Phase Change Material: A Full-Scale Experiment in a Cold Climate with Timber-Frame Huts

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Abstract: The relatively low thermal mass of timber frame buildings is a limiting factor for their energy efficiency and for the thermal comfort. The aim of this study is to assess the performance of wood-based wallboards integrated with PCM (Phase Change Materials) in a cold climate (Québec, Canada), from the heating season to the summer. Two timber-frame test huts, of 2 × 2.5 × 3 m, were built following the National Building Code of Canada and placed in the LAVAL University Campus. The first hut was equipped with wood-based panels integrated with the commercial bio-based PCM Puretemp®23 with a 23 °C melting point. The second hut was equipped with standard interior wood panels. Large double glaze windows were installed facing south. Dry indoor air temperatures were recorded for both huts and for the heating season, heating consumptions were monitored. The behaviour of the two huts was compared and PCM panels efficiency was evaluated over several seasons. A reduction of heating consumption was observed for cold months. For the heating season, panels were found to be more efficient as the months were getting milder. By gathering solar energy during the day, they allowed to reduce the test-hut heating consumption, by a maximum of 41% in May. In summer, the PCM panels had a positive impact in order to reduce the hut overheating. However their efficiency was found limited by a poor ability of discharge during the night. The solidification of the PCM was often impossible to achieve due to unsuitable night conditions. The results presented in this study will improve the knowledge concerning wood/PCM composites performance and concerning PCMs issues in cold climates. This study exposes the potential of wood-based panels integrated with PCM to achieve winter energy savings and enhance the summer thermal comfort of a timber-frame building, for a cold Canadian climate.

Keywords: phase change materials; PCM; full-scale; huts; thermal energy storage; bio-based

1. Introduction

Phase change materials (PCMs) are recognized as an effective way to improve building's energy management. Such materials are able to store a large amount of energy due to a transition of phase that is most frequently the solid/liquid one. This can enhance the building thermal mass and thus leads to energy efficiency [1]. During the heating season, PCMs can gather solar energy during the day and release it during the night. This can lead to great energy savings [2,3]. In summer, such materials are able to lower overheating by melting as the interior air temperature rises [4]. This requires suitable night conditions that will allow the PCM to discharge its energy in order to operate the next day. This can increase occupant's thermal comfort and reduce or avoid the need of air conditioning. PCMs can be integrated into buildings by different ways and at different places [5]. Various types of materials, either organic, inorganic or mixtures, are classified as PCMs. Historically, organic paraffinic PCMs have been widely used [6,7]. However, their flammability is a weak point for building applications and recent studies are instead focused on salt hydrates and bio-based compounds [8].

Wallboards embodying PCMs can store large amounts of energy and have already demonstrated potential benefits through multiple full-scale experimental studies [9,10]. As the thermal comfort depends on the operative temperature, panels integrated as the innermost layers with the interior air can have an even greater impact [11]. Wallboards can be made of several materials, such as gypsum, aluminium or wood. In 2006, Shilei et al. prepared high thermal mass wallboards by impregnating gypsum with capric and lauric acid, by immersion [12]. They obtained a composite with about 26% PCM in total weight and no leakage occurred after three hundred melting/freezing cycles, which is a good and mandatory result to ensure that the composite has a good durability. In 2018, Damien et al. manufactured and characterized wood-based wallboards integrated with bio-based PCM [13]. The panels were able to store a large amount of latent heat. Still, a full-scale test was needed to assess the performance of such panels. In the literature, a few authors manufactured wood/PCM composites [14–16]. However, not any full-scale test with wood-based PCM composites was reported.

Full-scale tests are a common way to characterize PCMs composites efficiency. In recent decades, multiple studies with wallboards involving test huts were carried out. In 1997, in the province of Quebec, Canada, Athienitis et al. carried out an experimental investigation with PCM gypsum boards impregnated with butyl stearate [17]. An outdoor test hut located in Montreal (45′ N latitude) equipped with a double-glazed window facing 10 degrees south east was used. The results showed a significant reduction of room radiant mean temperature due to absorption of solar gains in the PCM board while the butyl stearate was melting. However, as only one test room was available, both experiments with and without PCM were conducted under different climatic conditions. This lack of reproducibility makes difficult to define precisely the PCM contribution. In 2008, Kuznik et al. 2008b used an internal test hut called MINIBAT to assess PCM panels efficiency [18]. Lighting from projectors were acting as solar radiation. They reported that adding PCM wallboard in the test hut doubled the energy that could be stored within the hut. In 2016, Barreneche et al. assessed the efficiency of shape-stabilized PCM panels in a hot Mediterranean climate. Two test huts made of bricks and without any window were employed [19]. They found that the dry air temperature of the house equipped with PCMs could be lowered up to 3 °C during hot days, from around 35 to 32 °C. Such results are quite promising in order to reduce summer overheating in buildings, even for buildings prepared from a high thermal mass envelope such as bricks.

The energetic performance of a PCM in a building depends on several parameters. The orientation of the building, the architecture and the choice of materials composing the envelope are determinant parameters. The phase change temperature and the thermal conductivity of the composite embodying the PCM are also determinant. In order to advise the optimal PCM characteristics, tools have been developed. In 2011, Jiang et al. have developed a new method to estimate optimal phase change material characteristics in a passive solar room [20]. The simple analytical method they developed is proposed to estimate the optimal phase change temperature and latent heat of interior PCM thermal mass in a passive solar room. This method can be used to guide the design and choice of optimal PCM, according to specific weather data. In 2017, Mazzeo et al. used a numerical simulation method for thermal dimensioning and for energy behaviour evaluation of a building envelope PCM layer [21]. They defined a characteristic day for each month of a study and the numerical simulation was achieved by repeating this characteristic day for the whole month. This method was chosen as it could reduce the burden of the numerical simulation and allow to obtain the most suitable thermophysical PCM properties.

Timber construction is widely used in North America. It is a lightweight type of construction that embody a low environmental impact [22]. The low weight of wood brings an ease for construction but leads to buildings with a low thermal mass, which is a disadvantage for the building energy efficiency [23,24]. Therefore, enhancing thermal mass of timber-frame buildings with PCMs could lead to energy savings and to erect buildings with a lower environmental impact over their lifetime [25].

Quebec City is a city subjected to a cold climate. Average temperatures from December to February are, each year, below 0 °C. Heat requirements in Quebec City were, in 2016 and 2017, of 4827 Heating Degree Days (HDD) and 4968 HDD respectively, according to a base temperature of 18 °C [26]. During the heating season, gathering solar energy with PCMs could help reducing the heating consumption of buildings. In summer, Québec city climate shows large variations between day and night. As an example, the night average temperature in July is 13.7 °C, while the diurnal average is 25.0 °C (Anonym, 2017). This large daily amplitude could help discharging the PCM at night for a cold storage application. This could reduce or avoid the need of air conditioning.

This study aims to improve the knowledge concerning wood/PCM composites in-situ behaviour and concerning PCMs performance in cold climates. In order to reach these objectives, two timber-frame test huts were designed and then implemented in Quebec City (46′ N latitude). One hut was equipped with the wood-based panels containing PCMs while the other hut was equipped with standard wood panels. In the first part of the paper, wood-based wallboards containing PCMs were manufactured according to those previously manufactured and characterized by Mathis et al. in 2018 [13]. Subsequently, the experimental setup, consisting of the two test huts equipped with sensors and instrumentation, is described. Finally, the behaviour of the huts was compared from winter 2017 to summer 2018. According to these results, the thermal performance of the wood-based panels containing PCMs was advised. This study exposes the potential of wood-based panels integrated with a bio-based PCM to achieve winter energy savings and enhance the summer thermal comfort of a timber-frame building, for a cold Canadian climate.

2. Materials and Methods

2.1. Materials

2.1.1. Phase Change Materials

The USDA certified 100% bio-based product PT23 (Puretemp©, Minneapolis, MN, USA) was used for this study. Its exact composition is unknown as this product is under patent protection. However, in 2015 revealed that this product contains ester functional groups [27]. According to Puretemp©, PT23 has a melting temperature of 23.4 ± 0.2 °C, a latent heat of 201 J/g (DSC Q2000, 1°/min) and is stable over 10,000 thermal cycles. PT23 has a thermal conductivity of 0.15 and 0.25 W/m·°C, a specific heat of 1.99 J/g·°C and 1.84 J/g·°C and a density of 0.83 g/mL and 0.91 g/mL for the liquid and solid states respectively. In 2018, Mathis et al. revealed in a little variation for the phase change temperature and enthalpy over 300 cycles of melting/solidification for this product [13]. In 2018, Mazzeo et al. achieved a complete characterization of PT23 in order to achieve the experimental validation of the exact analytical solution to the steady periodic heat transfer problem in a PCM layer [28].

Macroencapsulation was achieved using 0.08 mm thick polyethylene bags, using a vacuum machine set to 70% of vacuum.

2.1.2. Wood-Based Panels Integrated with Puretemp©23

Wood panels were manufactured and integrated with macroencapsulated Puretemp©23. Figure 1 represents the overall structure of the panels. They have an overall thickness of 17 ± 0.5 mm. Such panels were manufactured similar to those prepared by Mathis et al. in 2018 [13].

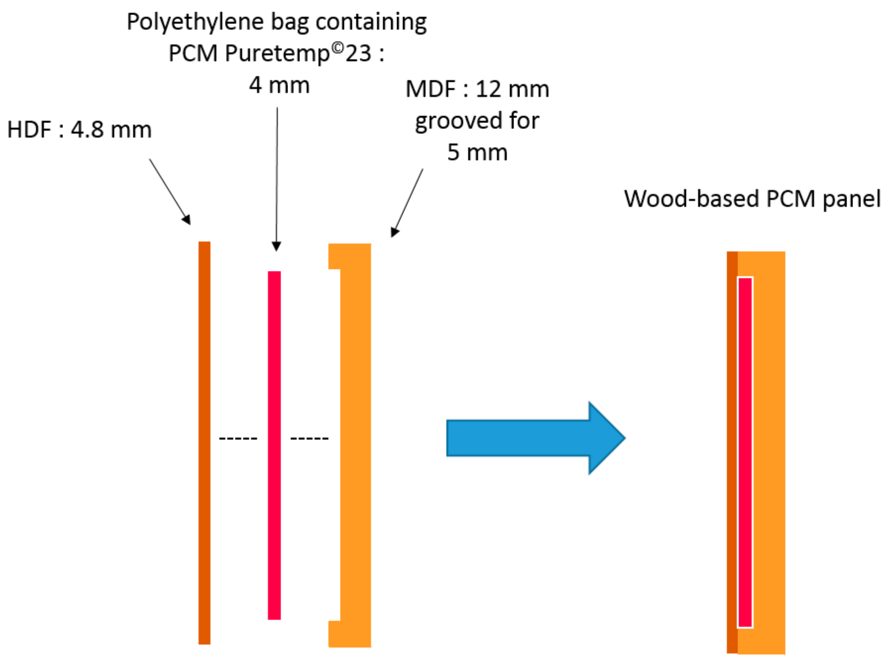


Figure 1. Geometry of the panels.

Medium Density Fibreboard (MDF) was sourced from Uniboard® (Laval, QC, Canada). It was used as the main component of the panels. MDF is a largely used wood product prepared from wood fibres combined and a urea formaldehyde resin by applying high temperature and pressure. The MDF panels were grooved through 5 mm, in order to contain the PT23 pouches. Such an assembly is shown in Figure 2.

Figure 2. Pouch containing PT23 in a grooved MDF panel.

Panels had a length of 70 cm and a width of 46 cm. High density Fibreboard (HDF) Fibrex® 4.8 mm thick, obtained from Goodfellow® (Delson, QC, Canada), was used to close the panels. The HDF was glued to the MDF over its edge with a standard PolyVinyl Acetate (PVA) adhesive. Materials properties are listed in Table 1.

Table 1. Properties of wood panels as provided by the suppliers.

Material	Density (kg/m^3)	Modulus of Rupture (N/mm^2)	Resin	Thickness (mm)	Reference
MDF	525	15	Urea-formaldehyde	13 mm	Uniboard®
HDF	900	42.7	Urea-formaldehyde	4.8 mm	Goodfellow®

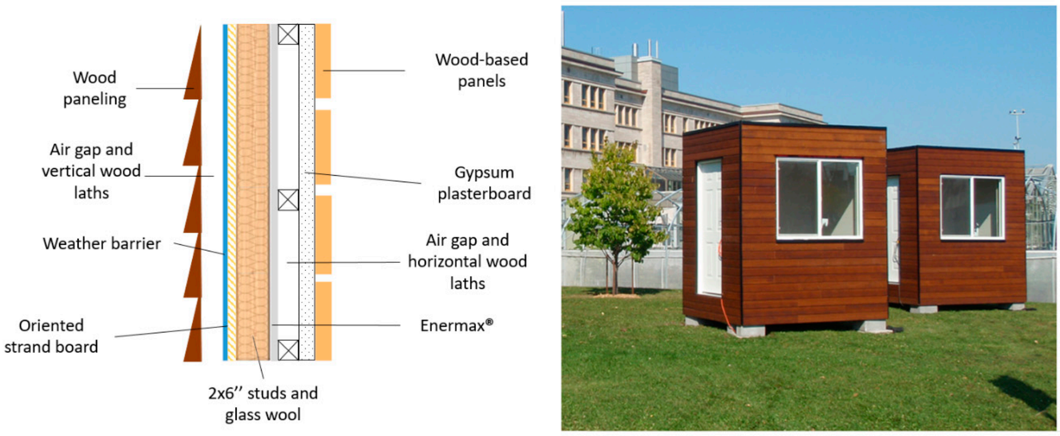
Each panel contained 907 g of Puretemp®23. A previous study by Mathis et al. revealed in 2018 that panels with a similar shape had a latent heat of 57.1 ± 0.5 J/g [13]. Panels dimensions were different but the mass percentage of Puretemp®23 within the panels was similar: 23% for the previous study and 22% for the present study.

Beside, same thickness control panels were manufactured without PCM, simply consisting of MDF glued to HDF. The control panels were not grooved.

2.2. Facilities

2.2.1. Structure of the Huts

Two test huts were built specifically for the present study according to the National Building Code of Canada. Their wall composition is shown in Figure 3a. It is a common composition for a medium/high insulation building in the province of Quebec, Canada. Gypsum was added before the inner wood panels for fire safety considerations. Enermax© is a rigid panel made of wood fibre mixed with a wax emulsion. It is commercialized by the company BP Canada (Pontrouge, QC, Canada). It was added in order to reduce the thermal bridges caused by the wood studs. It also contains an aluminium barrier on its surface that acts as a vapor barrier. Rigid polystyrene insulation was fixed on the inner side of the door in order to avoid losing too much energy from a low cost badly insulated door. In a residential house, front doors are better isolated.



(**a**) Wall composition (**b**) The two huts at Laval UNIVERSITY Campus

Figure 3. Description of the test huts.

One hut was equipped with the wood-based panels containing PT23 presented above, while the other hut was equipped with the control panels. The PCM hut was equipped with about 88.4 kilos of panels, embodying 19.0 kilos of PT23. The two huts were placed on Laval University campus (Quebec City, Canada), such as shown in Figure 3b. Low-E double glass windows size 122 × 152 cm were installed on the wall facing geographic south. Such a design was chosen to induce overheating on purpose. The ratio window/floor was of 55.6%. It was chosen high to maximize solar gains. In an occupied building, a smaller ratio could have been chosen and sunshades could have been implemented. In Canada, for well-insulated houses, such as passive houses, the window/floor ratio can reach 25% [29].

The thermal resistance of the vertical walls is 3.5 RSI (K·m^2/W). The ceiling and the floor are made with I-beams with a height of 25 cm, insulated with fiberglass. The thermal resistance of the floor and the ceiling is 5.6 RSI. Exterior wood panelling thermal resistance was not considered as the air gap is naturally ventilated. Inside dimensions were 2.16 m × 1.55 m. Interior wood-based panels thermal resistance was not considered as it is the component being tested.

2.2.2. Equipment and Instrumentation

Each test hut was equipped with a 500 W, 120 V electrical baseboard heater controlled by a programmable thermostat. In a dwelled building, the interior air is brewed by ventilating and according to people's movements. To simulate this and to avoid air temperature stratification, a small fan (10 cm diameter) was placed in each hut. For the summer period, a standard housing fan with an air flow of 119 m^3/h was added and the heating was turned off.

Dry temperature was measured using a PT100 sensor from the company Kimo (Montpon-Ménestérol, France) and recorded by a data logger Kimo Ami 310. For preliminary experiments, sensors were placed at several heights to assess air stratification, which was revealed important and so the small fans were added. Then, from December, sensors were placed at the same height than the programmable thermostat (160 cm) in order to use the values for numerical simulation. Temperatures were measured every five minutes. Heating consumption was measured using an energy meter TS-836US from the company Floureon (Shenzhen, China). As no data logging was possible with the energy meter, the heating consumptions were manually recovered each week and on some other specific days.

2.3. Methodology

The behaviour of the two huts was compared over different seasons. In winter, the main objective was to assess whether the PCM panels could store solar energy and release it at night and thus reduce the heating consumption. Overall data for each month of the heating season will be presented but also data for specific days. Outside temperature retrieved from Quebec City weather station has been added on graphs.

In summer, the main objective was to assess the thermal comfort improvement. Several daily data are important, such as maximum temperature and average diurnal temperature (from 8 am to 8 pm). As the window selected was oversized, it is not possible to correlate such results with a comfort standard such as ASHRAE55 or to calculate the intensity of discomfort. The interior air temperature would be clearly higher than the comfort standard each day.

For preliminary experiments, different heating setpoints were scheduled to characterize the thermal behaviour of the PCM panels. A low setpoint at night would allow to test whether the PCM panels are able to maintain a high interior air temperature at night during the heating season. From December until the end of May, the setpoints were kept the same: 20 °C during the day (6 am to 8 pm) and 18 °C during the night (8 pm to 6 am). Heating consumption measurements were read at 2 pm. For February, the data presented was gathered only during the first fourteen days of February, as the huts were used to gather other specific data during second half of the month.

Preliminary tests were conducted during 12 days with the two huts before fixing the wood-based interior panels, in order to compare the huts behaviour. Those tests indicated that the two huts had a highly similar thermal behaviour, with a daily maximum temperature difference of 0.3 °C. Heating consumption was also compared and the tests revealed that the hut that would then contain PCMs had a slightly superior heating consumption of 3.3%. This correction factor of 3.3% was applied for the monthly global consumptions that will be presented. This factor was not applied when the consumption of a single day was considered, as this factor was calculated using a two weeks average data.

During winter and spring, no night ventilation was required to solidify the PCMs at night. In summer, a night ventilation (119 m^3/h) was scheduled each night from 8 pm to 6 am. Such a schedule could easily be implemented in an office, so the ventilation could be effective when the office is empty of people.

3. Results and Discussion

3.1. Heating Season

3.1.1. Huts Behaviour for High Solar Gains Days

Temperature of the huts for a sunny fall day (15/11/2017) is shown in Figure 4. For this day, a lower heating setpoint (16 °C) was set for the night, in order to assess whether the panels were able to maintain the hut at a comfortable temperature without any heating.

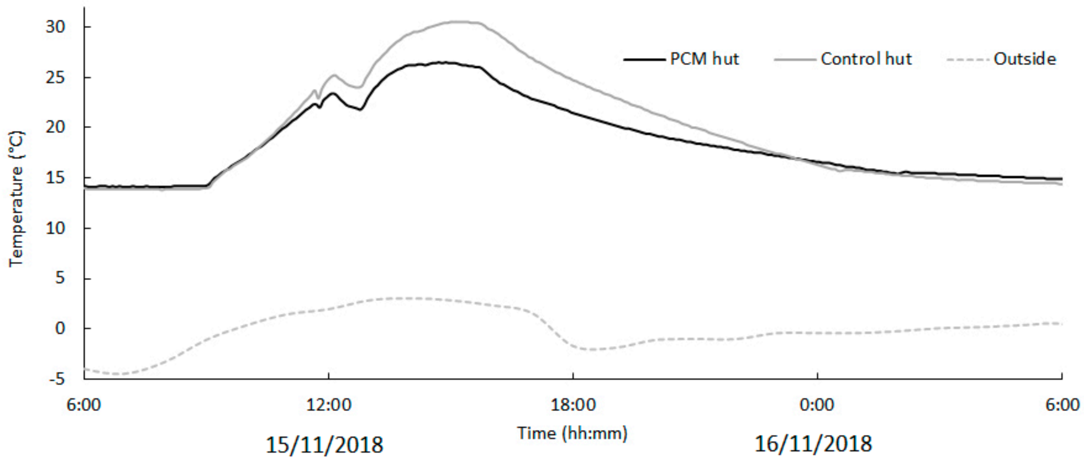


Figure 4. Dry temperature of a sunny winter day, 16 °C setpoint.

This day, the PCM and the control hut respectively reached maximum temperatures of 26.5 °C and 30.5 °C. This indicates that the PCM panels are efficient to reduce daily high temperature peak. During the night, before that the heating starts, the temperature decrease of the PCM hut was slower than for the control hut. Cooling rates between 18 h and 22 h for the PCM and the control hut were respectively 0.9 °C and 1.5 °C per h. This lower cooling rate could be due to the PCM panels releasing heat. However, the control hut reached a higher temperature during the day. Therefore, its temperature differential between the interior and outdoor environment is higher than for the PCM hut. According to the three thermal laws of Fourier, Newton and Stefan-Boltzmann, this higher differential could higher the cooling rate (Bergman et al. 2011). Both huts reached an insufficient night temperature simultaneously (17 °C at 12 pm). For this experiment, the temperature sensor was placed 20 cm above the ground. Thus, as if the setpoint was set at 16 °C, the sensor indicated 14 °C during the night, revealing a high air temperature stratification. As described in the methodology, two small fans were therefore added to stir up the air. From December, temperature sensors were then placed at the same height than the programmable thermostat.

Heating consumptions for the two huts were measured from the 15/11/2017 to the 16/11/2017. The PCM and the control hut respectively consumed 0.949 kWh and 1.255 kWh. Over 24 h, the PCM hut consumed 24.4% less heating energy. This indicates that the PCM panels released some energy during the night. Thus, heating this hut required less electrical energy. However, the PCM do not succeed to keep the interior air temperature above the 16 °C setpoint. The heat is released during the night, while the electrical heater is on. This indicates that the thermal exchange between the panel and the interior air limits the release of the heat.

Then, for the whole study, the setpoints were set at 18 °C at night and 20 °C during the day as described in the methodology section. Figure 5 shows the behaviour of the huts with such setpoints for the 13/02/2018 which was a cold highly sunny day. The maximum temperature reached was 4.7 °C lower for the PCM hut, indicating the panels are able to gather energy during the day. Observations similar to the one shown on Figure 5 were made on other highly sunny days from December to May.

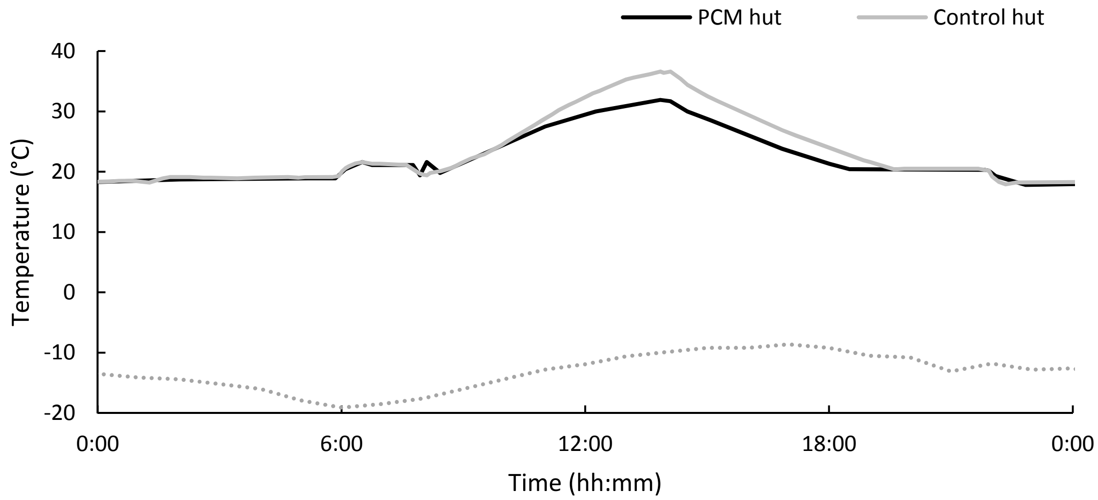


Figure 5. Behaviour of the huts for a sunny winter day (13/02/2018).

For each sunny day, the maximum diurnal temperature reached was lower for the PCM hut and a reduction of its heating consumption was measured. Such observations are presented in Table 2. Data-loggers failures on 20/03 and 07/05 did not allow recording of some temperatures.

Table 2. Huts behaviour for sunny days.

Date	Control Hut Maximum Dry Temperature (°C)	PCM Hut Maximum Dry Temperature (°C)	Outdoor Average Temperature (°C)	Heating Consumption of the PCM Hut (kWh)	Reduction of Consumption for the PCM Hut
13/02	36.6	31.9	−12.4 °C	2.5	8.0%
19/03	32.8	29.9	−8.1 °C	1.8	5.5%
20/03	-	-	−6.6 °C	1.7	14.9%
25/04	26.0	25.9	11.3 °C	0.6	73.8%
07/05	-	28.4	7.5 °C	0.3	77.0%

3.1.2. Huts Behaviour for Low Solar Gains Days

Temperature of the huts for a cloudy day (15/03/2018) is shown in Figure 6. This day, heating consumptions for the PCM and the control hut were 3.50 kW·h and 3.43 kW·h respectively. This represents a consumption 1.3% higher for the PCM hut, which is not significant.

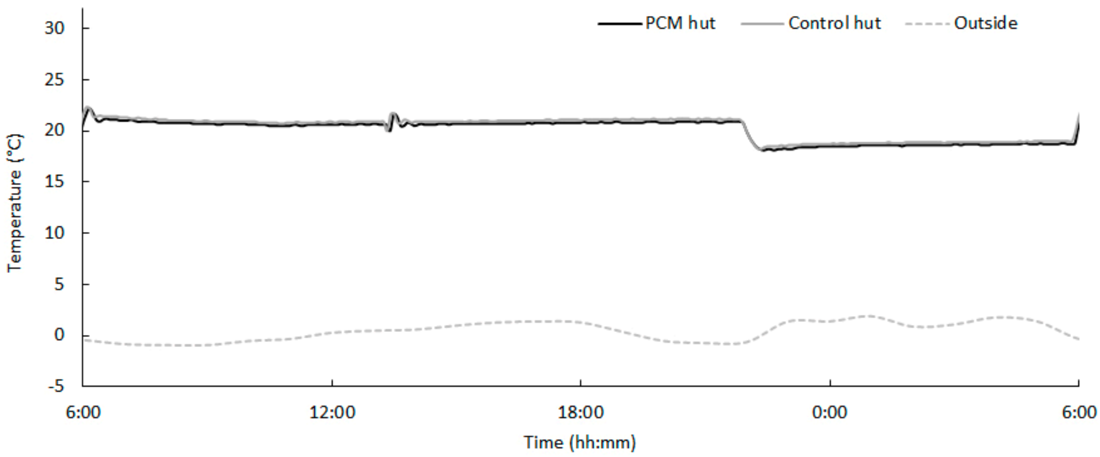


Figure 6. Dry temperature of the huts for a cloudy day of March (15/03/2018).

Similar observations, listed in Table 3, were made on other cloudy days from December 2017 to May 2018.

Table 3. Huts behaviour for cloudy cold season days.

Date	Control Hut Maximum Dry Temperature (°C)	PCM Hut Maximum Dry Temperature (°C)	Outdoor Average Temperature (°C)	Heating Consumption of the PCM Hut (kWh)	Excess Consumption of the PCM Hut
30/01	22.3	21.5	−12.2 °C	4.8	+2.4%
13/03	22.3	22.2	0.2 °C	3.5	+2.0%
14/03	22.3	22.0	−0.9 °C	3.5	+1.3%

For each day considered, the PCM hut consumption was found higher than for the control hut. However, as presented before in the methodology section, a preliminary test revealed that when both huts were tested without any panels in it, the hut that would next embody PCM hut was found to have a slightly higher energy consumption. This difference was of 3.3%. This correction factor was not applied in Table 3. According to the results presented in Table 3, it seems that the PCM had no significant impact on the huts consumption on cloudy days.

3.1.3. Huts Behaviour over Consecutive Days

The huts behaviour was revealed to be influenced by the weather of consecutive days. Figure 7 shows the huts behaviour on the 24/04/18, a highly sunny day. Such a weather allowed the PCM to melt easily. This resulted in a 2.2 °C difference for the max temperature reached between both huts for this day. However, the temperature of the PCM hut did not drop enough during this night to make the PCM go under solidification. As a consequence, when the sun rose on the 25/04/18, the PCM was still in liquid form. Therefore, for this day, there is no difference for the max temperature reached for both huts. Then, the 26/04/18 was a cold cloudy day. These conditions allowed the PCM to solidify and resulted in a 73.8% heating reduction.

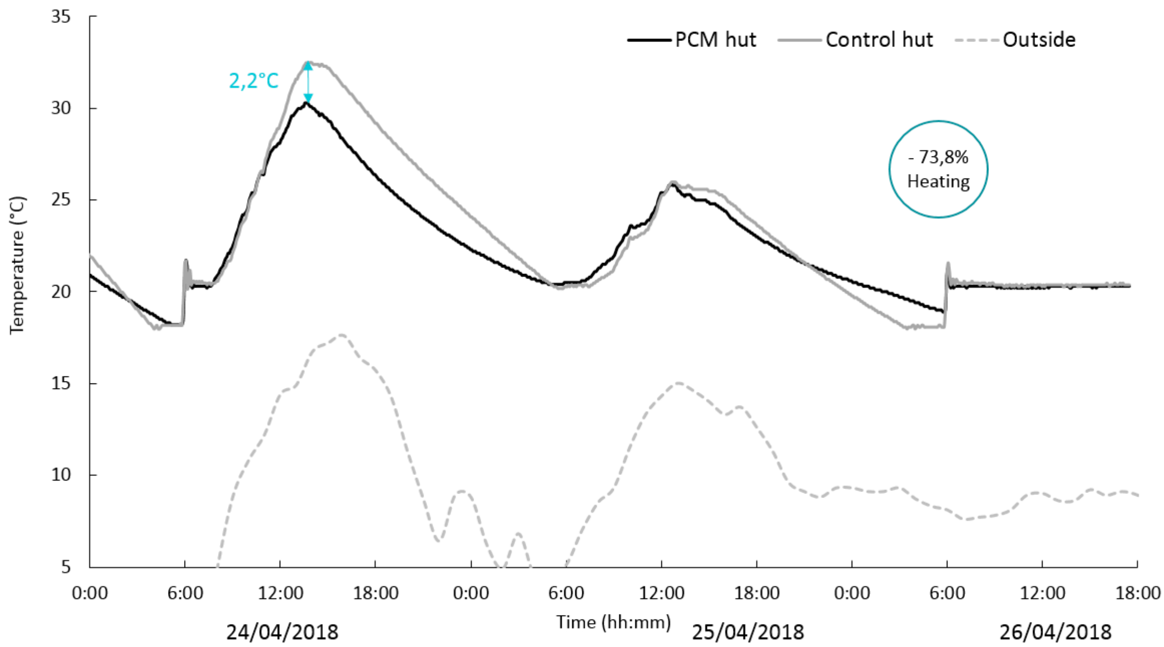


Figure 7. Behaviour of the test huts for consecutive days.

3.1.4. Average Heating Consumptions

Average PCM hut reduction of consumption from December to May is shown in Table 4. For February, the monthly heating need was low, as the monitoring was stopped during 16 days in order to run other tests, as described in the methodology.

Table 4. Energy savings and energy consumption for the PCM hut for several months.

Month	December	January	February	March	April	May
Reduction of heating for the PCM hut	2.0%	0.8%	2.8%	8.7%	9.0%	41.0%
Monthly heating need PCM hut (kW·h)	165.4	308.9	57.0	69.7	46.4	7.1

During the coldest months, from December to February, the savings were not significant. As the months are getting milder, more sunshine was available and more energy can be saved. During this winter, several days were cloudy and the PCM could not melt most of the days.

In addition, the PCM panels can store a fixed maximum amount of energy that is related to their latent heat. During the coldest months, the overall required energy to heat the control hut was important. Thus, the PCM panels were not able to release enough energy to reduce the heating consumption significantly. In January, a high percentage of days were cloudy and the total heating consumption for the PCM hut was of 308.88 kW·h. In May, a high percentage of days were sunny, the total consumption of the PCM hut was only of 7.1 kW·h and this resulted in a 41% energy savings for the PCM hut.

These results are comparable with a previous study conducted by Muruganharthama et al. in 2010, in Arizona [30]. They measured the energy savings resulting from the integration of a bio-based PCM with 29 °C melting temperature. Their experimental setup consisted of two identical test huts (4.9 m × 3.7 m × 2.4 m) made of wood-framed construction, embodying a door and a window. The PCM was integrated in arrays of plastic foil containers, in the walls, the roof and the floor. The mass of PCM integrated is unfortunately not detailed. Maximum and minimum heating energy savings were observed for November—29.3% and March—9.2%. Arizona climatic conditions are highly different than in Quebec City but similar energy savings were measured. As Arizona climate is hotter, it is expected that a PCM with a higher melting temperature is more suitable.

3.2. Summer/Hot Season

3.2.1. Days with Cold Nights

The beginning of the hot season was considered to be the 01/07/2018. Temperature of the huts for a summer day with a cold night (13/07/2018) is shown in Figure 8.

On this day, the PCM hut reached a maximum temperature 0.8 °C lower than the control hut. The night temperature, going as low as 12.9 °C, allowed the PCM to solidify, at least partially. With our experimental conditions, it was not possible to assess whether the PCM totally of partially melt. Similar observations were made for other summer days with cold nights as presented in Table 5. The PCM panels are able to reduce the overheating of the hut when the outside temperature was low enough during the night.

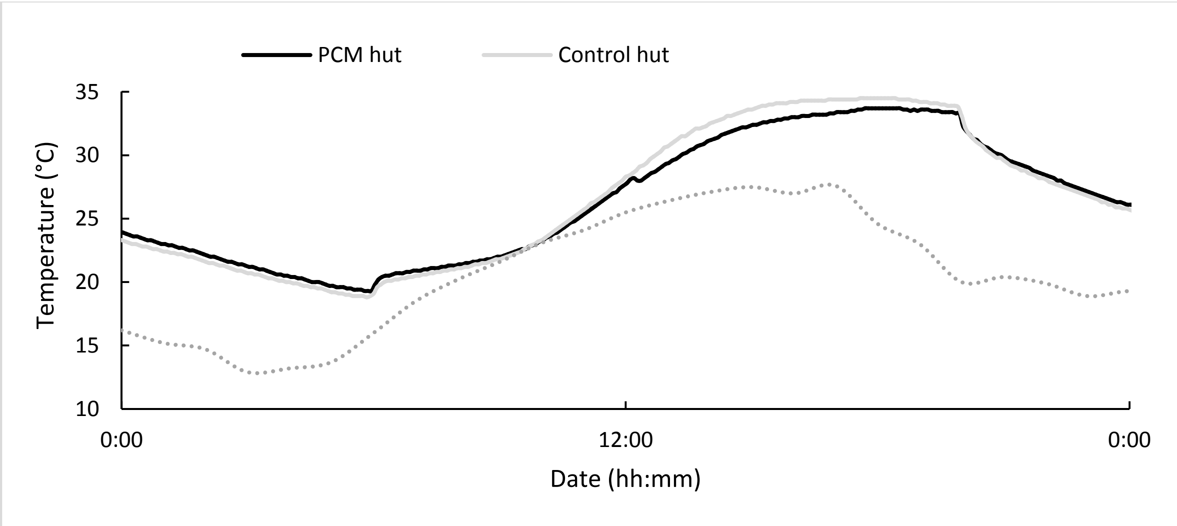


Figure 8. Temperature of the huts for a summer day with a cold night (13/07/2018).

Table 5. Maximum temperature of the huts for summer days with cold nights.

Day	Control Hut Dry Max T° (°C)	PCM Hut Dry Max T° (°C)	Δ Temperature Max (°C)	Outdoor Night Average Temperature (°C) 12 pm–6 am
13/07	34.5	33.7	0.8	14.6
23/08	31.0	29.7	1.3	13.8
31/08	35.0	33.0	2.0	10.1

3.2.2. Days with Hot Nights

Temperature of the huts for consecutive summer days with hot nights (02/08/2018) is shown in Figure 9. The night temperature, which dropped at a minimum of 16.8 °C the 03/08/18 at 5 am, did not allow the PCM to solidify in a sufficient proportion, therefore the panels are unable to reduce the overheating during these days. For these days, the maximum peak temperature reduction is of 0.3 °C for the 04/08/18, which is not a significant result.

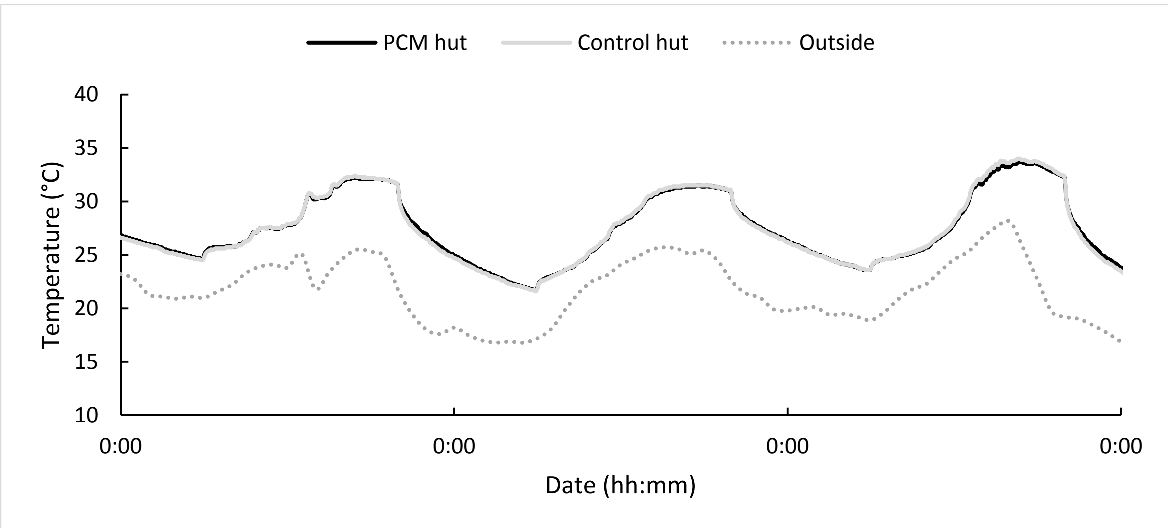


Figure 9. Temperature of the huts for consecutive summer days with hot nights.

Similar observations were made for other summer days with hot nights, as presented in Table 6.

Table 6. Maximum temperature of the huts for summer days with hot nights.

Day	Control Hut Dry Max T° (°C)	PCM Hut Dry Max T° (°C)	Δ Max Temperature (°C)	Outdoor Average Night Temperature (°C)
08/07	31.3	31.2	0.1	16.4
02/08	32.4	32.2	0.2	21.6
29/08	29.4	29.2	0.2	18.3

3.2.3. Average Performance of the Panels

Average huts temperature in summer is given in Table 7.

Table 7. Average temperatures of the huts during heating season.

Period	Control Hut Average Max Temperature (°C)	PCM Hut Average Max Temperature (°C)	Control Hut Average Diurnal Temperature (°C)	PCM Hut Average Diurnal Temperature (°C)	Outdoor Average Night Temperature (°C)
16–30 June	28.1	28.2	26.0	25.8	13.2
1–15 July	32.5	31.9	28.1	27.8	17.0
16–31 July	33.6	33.3	30.8	30.7	17.6
1–15 August	34.2	34.2	30.6	30.7	18.2
16–31 August	34.1	33.4	29.1	29.3	15.4

For the first period, from June 16 to 30, the PCM had no impact on the average max temperature. Indeed, the ventilation system was found to be inefficient because the huts were too hermetic. An air inlet was implemented from the 1 July and then the ventilation system could work properly. For July and August, higher temperature differences were recorded. The average max temperature reduction for the PCM hut from the 1st of July to the 31st August was of 0.4 °C.

Yet, the reduction of the maximum temperature reached between both huts is low compared to the differences observed in winter. In winter, the PCM hut max temperature was often reduced of about 4 °C. This may be due to the fact that the PCM cannot solidify in a sufficient quantity during summer. A first explanation is that for some nights, the outside temperature was too high to allow the PCM solidification. A lower outdoor average night temperature would increase the PCM performance, as shown in Table 7. For example, the largest reduction for the PCM hut average max temperature was of 0.7 °C for the 16–31 August, period, with a 15.4 °C outdoor average night temperature. Another explanation is that the huts had a lot of thermal energy to discharge at night due to the fact that a large window was implemented facing south, without any sunshade. This methodology allowed to gather a large quantity of solar energy during winter but induced a high overheating during summer. Before that the hut could reach a temperature allowing the PCM to solidify, several night hours were necessary to discharge the sensible heat of the hut.

Low average diurnal temperatures differences between both huts, inferior or equal to 0.3 °C, were recorded. These differences are too low to be significant, so the PCM panels apparently had no effect on the average diurnal temperature of the huts.

These results are comparable with a previous study conducted by Tardieu et al. in 2011 [31]. Their experimental setup consisted of identical wood-framed test huts, with a size of 2.60 × 2.60 × 2.60 m, which were placed on the campus of the University of Auckland in New Zealand. Windows were installed on the north facing wall and doors on the east facing walls. In one of the huts, they placed gypsum boards impregnated with 27 wt % of a PCM that had a melting range of 18–23 °C and a latent heat of fusion of 134 kJ/kg. Thermal behaviour of the huts was experimentally assessed and the seasonal energy performance of the gypsum boards was analysed using energy simulations. One of the observations was that the PCM boards were able to reduce the daily indoor temperature fluctuation by up to 4 °C on a typical summer day. This result is comparable to the maximum peak temperature reduction that was measured for the present study but for the winter period. During the winter, the wood-based panels containing PCMs were able to release much heat during the night and so to mitigate more efficiently the daily peak temperature.

4. Conclusions

This study aimed to assess the efficiency of wood-based panels integrated with PCM over different seasons within the cold climate of Quebec City (Quebec, Canada). The behaviour of two instrumented timber-frame test huts was analysed. The wood-based panels integrated with the bio-based Puretemp®23 PCM significantly affected the thermal behaviour of the timber frame test hut.

During the heating season, our experiments revealed that the PCM allows a reduction of the heating consumption. During the coldest months, from December to February, this reduction is not significant. A reason is that the huts consumed a lot of heating energy for these months. A hut is an experimental building that is constituted by a high percentage of walls compared to the floor surface. This induces a high energy consumption per square meter. In addition, climate is really cold in Quebec City. The quantity of energy stored in the PCM panels was not high enough to reduce significantly the hut high consumption for coldest months. Another explanation is that for winter 2018, weather was often with overcast sky. Indeed, average total solar radiation on a horizontal surface were of 886, 746, 794 and 686 $kJ/(m^2 \cdot h)$, for winters 2015, 2016, 2017 and 2018 respectively [32]. However, as the months are getting milder and that more sunshine is available, the performance of the panels increased and heating consumption was reduced by 8.7% for March, 9.0% for April and 41% for May.

During summer, our study shows that the PCM panels are able to slightly reduce the overheating of the hut. The panel's efficiency was found limited by the night conditions. The efficiency of the panels was maximal for days with coldest night. Night conditions are critical in order to discharge the panel's heat so it can perform the next day. As if a powerful ventilation was implemented, the PCM often could not solidify properly during the night. The daily interior maximum temperature of the huts was often superior to 35 °C. Consequently, several night hours were needed before that the hut could reach a temperature allowing the PCM to solidify. In addition, the innermost layer is made of High Density Fibreboard, with a thermal conductivity of 0.11 $W/(m \cdot K)$. Better results could be reached by optimizing with this 4mm layer that may limit the thermal exchange and thus the PCM ability to solidify.

In this study, overheating was maximized on purpose to observe the PCM panels performance over given conditions. These results are not representative of the thermal behaviour in an occupied building but renders a good approximation of such panels performance in a timber-frame building, within a cold climate. Another summer study with strategies to control the overheating, such as sunshades or a more adapted window to floor ratio, could render a better approximation of the panels performance in a building. In the present study, the inside air temperature of the huts was often higher than 30 °C. An experimental setup leading to inside air temperatures within the comfort range would bring valuable results. It could also be great to assess the performance of such panels loaded with a PCM of a higher melting temperature, such as 25 °C. A higher melting temperature would help the PCM to discharge its heat during the night. However, a 25 °C melting temperature may reduce the winter heating energy benefits, as it would be more difficult to gather solar energy during the day.

Performance of passive building strategies are linked to occupants' behaviour. Thus, the following step towards PCM panels performance in evaluation would be to assess the efficiency of such panels in a occupied building.

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