EXPERIMENTAL INVESTIGATION OF LATENT THERMAL ENERGY STORAGE FOR ENERGY RETROFIT IN HIGH-RISE RESIDENTIAL BUILDINGS IN TORONTO

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ABSTRACT

High-rise apartments in Toronto are an integral part of the residential building stock, representing over 50% of total dwellings, home to approximately a third of the city's population. The recent architectural trend of high-rise apartments is moving towards more transparent facades with fully glazed exteriors. Higher window to wall ratios (WWR) entails significant discomfort due to higher solar heat gain and heat loss, causing overheating and extreme temperatures. Passive latent thermal energy storage is a possible solution to regulate indoor room temperatures. This study investigates the effectiveness of Phase Change Materials (PCMs) in apartments with 80% WWR. A composite PCM system, comprised of two PCM products with melting temperatures of 21.7 ºC and 25 ºC is introduced to provide annual thermal energy storage. The phase change cycles of the PCMs and their impact on indoor air and building interior surface temperatures are assessed using field tests. Two small scale test cells were constructed, one reference cell as a baseline and another cell enhanced with the composite PCM system positioned on walls and the ceiling. The results indicate improved performance of the test cell containing the composite PCM layer in lowering peak indoor and surface temperatures up to 6 ºC. The melting and solidification patterns showed a close correlation with peak solar heat gain and heat loss times during the day respectively.

INTRODUCTION

High-rise residential towers represented an era of change and modernization in Canadian cities in the past decades. The aim to form self-sufficient communities, in contrast to the previous urban sprawl, in addition to factors such as urbanization, shortage of suitable lands and accessibility issues, brought this model of housing to spotlight (Kesik and Saleff, 2009). In fact, high-rise apartments are still a prominent choice for housing in major Canadian cities and their dominance continues to grow as the market demands escalate. However, aging high-rise apartments are faced with crucial performance problems; deteriorating building components, leaky envelope and moisture problems are some major issues that in time degrade the living conditions for occupants (Touchie et al. 2014). Specifically, thermal discomfort is a critical issue that entails various problems and subsequent complaints in high-rise apartments as stated by RDH, (2012).

Issues such as draft, daily temperature swings, and vertical temperature stratification are among the most common causes for indoor thermal discomfort. In older apartment buildings, aging infrastructure, lack of proper insulation and poor performing windows cause large discomfort. However, in newer buildings, given

the new architectural trend shifting towards transparent facades, high window to wall ratios (WWR) or fully glazed facades lead to high solar heat gain and heat loss causing large indoor temperature fluctuations (Rodriguez-Ubinas et al., 2013; Touchie et al. 2014). Thermal discomfort in buildings implies higher reliance on mechanical systems to provide acceptable living conditions, which entails high energy demand. As shown by Alsaadani et al. (2016), space conditioning holds the highest share of energy consumption in high-rise residential buildings. Furthermore, high dependence on mechanical space conditioning decreases the resiliency of these buildings to anomaly weather events and climate change effects (Ozkan et al. 2016).

Considering the crucial importance of high-rise apartments in the residential stock of Canadian cities, it is crucial to improve their performance and enhance occupant satisfaction. Energy retrofits are a significant opportunity to reduce the energy consumption and carbon footprint of existing buildings, in addition to enhancing occupants' comfort (Touchie et al. 2014). Particularly in the context of high-rise apartments that provide affordable housing, energy retrofit measures would improve quality of life for available housing (Alsaadani et al. 2016). In this research, passive latent thermal energy storage (TES) as a retrofit measure is considered by incorporation of Phase Change Materials (PCMs) in indoor surfaces of apartment units. The aim of this paper is to evaluate the impact of integrating PCMs in highly glazed apartment units for regulating indoor temperature swings and temperature extremes.

LITERATURE REVIEW

Two main types of thermal storage applicable to buildings are sensible and latent heat storage, considering that electrochemical TES is typically unsuitable. PCMs are latent heat storage systems that store heat by undergoing a phase change -such as changing from solid to liquid states- at specific temperatures. PCMs store both sensible and latent energy; as indoor temperatures rise, a PCM stores sensible energy until the melting temperature is reached and then the latent heat storage occurs in a nearly constant temperature range and the PCMs store the latent heat of fusion in the process. The constant temperature range during the phase change process is a key factor to guarantee indoor temperature stabilization when PCMs are integrated to buildings (Soares et al. 2013).

PCMs are an appropriate choice for retrofit applications compared to materials with sensible TES for being easy to apply and unobtrusive (Ascione et al., 2014; Sharma et al., 2009). Furthermore, PCMs store heat in narrow temperature ranges and they have higher heat storage capacities in lighter density (Soares et al., 2013). Several studies have presented extensive literature reviews on PCM products, their various applications and their impacts on buildings' indoor environment. Tyagi and Buddhi (2007), Pasupathy et al. (2008), Kuznik et al. (2011), and Soares et al. (2013) have provided comprehensive background research on PCMs. It is argued that the melting temperature or temperature range in which the phase transition occurs is the most important parameter for PCM performance. In order for PCM to get activated and perform effectively, their melting range must correspond with the environment they are applied to (Evola et al. 2013).

The indoor thermal environment in buildings is primarily governed by the climate in which they are located in and how it is controlled by the occupants. Hence, indoor and outdoor boundary conditions are an important subject of study for PCM integration in buildings. For instance, Evola et al. (2014), Ascione et al. (2014) and Fiorito (2014), have investigated the impact of climate on PCM operation. Results of these

studies point to a clear link between PCM performance and climate and that the performance of PCM applications is climate specific as the correlation of melting temperature with the indoor temperatures of the building are interrelated.

Existing literature regarding TES with PCMs is mainly focused on applying PCMs for the cooling season, even though some studies such as Cao et al. (2010) and Pisello et al. (2015) have studied the impact of PCMs in the heating season. Athienitis et al. (1997) and Nikoofard et al. (2014) have assessed PCM integration in Canada, the results clearly point to the potential of TES using PCMs in the Canadian climate for both the cooling season and the heating seasons. Multiple studies such as Muruganantham et al. (2010) and Pasupathy et al. (2008) have analyzed the performance of PCMs in buildings for one year. Optimization of PCMs to operate for an entire year is quite difficult as studies have shown that PCMs with melting points selected based on the summer boundary conditions do not operate in other seasons. While the primary operation of PCMs is intended to reduce summer overheating, their impact on regulating temperatures in winter and shoulder periods must not be neglected.

To optimize PCMs for annual performance, Diaconu and Cruceru (2010), proposed a composite PCM wall system comprised of two PCM integrated wallboards with two different melting points. One PCM was positioned near the exterior side of the envelope with a melting range appropriate to control the summer conditions and a second gypsum board was positioned on the inside lining of interior walls to control the radiant heat during winter. The results showed significant total cooling and heating energy savings as well as regulated temperatures inside the building enclosure throughout the year. Pasupathy et al. (2008), Entrop et al. (2011), Ascione et al. (2014), Heim et al. (2016) and Hoes and Hensen (2015) have also addressed the insufficient effectiveness of one PCM melting point to operate for an entire year and suggested more research on hybrid PCM systems.

Considering the case specific design of PCMs in relation to climate, more research in Canadian climate is necessary to evaluate the effectiveness of PCM applications in this context. The aim of this study is to provide year around thermal energy storage using PCMs, thus optimizing PCM applications to have two melting points as a potential approach is investigated to address both heating and cooling seasons.

As outlined in the literature, due to simplifications of simulation modeling in calculating PCM performance in addition to inability to model hysteresis and sub-cooling of PCMs, it is suggested to use experimental tests for a more accurate and reliable assessment of PCM behavior (Pasupathy et al. 2008). Table 1 shows some of the main studies that have performed experimental tests on PCM building applications using test huts.

Table 1: Experimental studies on PCM building applications

Reference	PCM Properties / Application	Test Location / Test Period	Parameters of Study	Results
Pasupathy et al. (2008)	Salt hydrate T_{mp}: 26-28 °C Embedded in steel mesh for the Roof	Chennai, India, 13.1° N One year	- PCM panel thickness - Aiding PCM solidification through water heat exchangers - Validation of numerical analysis	- Roof temperature with the PCM higher for a longer period of time as a result of lower conductivity of the PCM roof - Higher PCM ceiling temperature due to lower heat removal from the PCM room -Increasing the thickness affects the solidification process of the PCM.

Kuznik and Virgone (2009)	Energain board T_{mp}: 18-22 ºC Walls	Climate chamber controlled conditions - Heating + cooling conditions	- Effect of seasonal temperature changes	- In all the cases the PCM test cell had 4.2 ºC lower indoor temperatures as result of decreased overheating. - No thermal stratification was observed in the PCM test cell as opposed to 1.3 C temperature stratification between high and mid points in the reference test cell.
Muruganantham et al. (2010)	BioPCM™ T_{mp}: 29 ºC Floor, wall and ceiling	Arizona, USA, 34.04º N One year	- PCM effect on energy consumption - Cost analysis	- A peak load shifts of 1 hour occurred in the PCM shed only in summer months. - Highest energy saving (30%) in November. Lowest saving (9%) in March
Entrop et al. (2011)	Micronal DS T_{mp}: 22-25 ºC Concrete floor	Enschede, Netherlands, 52.2º N One year	- Insulation thicknesses - Glazing types	- 16 ºC reduction of maximum room temperature and 7 ºC increase in minimum room temperature observed. - Increasing thermal insulation lowers the activation process of PCMs - The level of solar radiation coming in the cells corresponds directly with the PCM floor's effectiveness in different seasons.
Ceron et al. (2011)	Paraffinic Mix T_{mp}: 13-20.5 ºC Clay floor tiles	Madrid, Spain 45.5º N 60 days in Spring	- Direct and indirect solar exposure to the floor surfaces	- Shadow on PCM tiles facing direct sunlight reduces their efficiency by 6 ºC lowered temperature and reduced heat storage capacity. - PCM tiles not receiving direct solar radiation have smaller stored energy to discharge at night.

Whole building tests, outdoor test huts and indoor test rooms in labs or climates chambers are some of the most commonly adopted experimental test methods in the literature (Kosny, 2015). Full-scale experimental tests are an important method to evaluate building envelope components containing PCMs, to observe the performance of PCMs directly in interaction with building systems and functions. However, test huts are often preferred as they are less expensive and easier to implement, in addition to being more accessible and flexible if built in small scales. Often, including a baseline model is a common strategy to evaluate the performance of PCM integrated enclosures compared to a benchmark with conventional enclosures. Kuznik and Virgone (2009) emphasize the necessity of two cells tested under simultaneous conditions to test PCMs. The aim of field tests in this study is to analyze the behavior of the composite PCM system in detail and to better understand its daily activation.

METHODOLOGY

A hybrid PCM system for annual thermal energy storage is proposed to be integrated into walls and ceilings of high-rise apartment units. This composite PCM system is targeted for applications in direct contact with the indoor environment. In this study, commercial PCM products were selected to form the composite PCM system. Most reviewed studies have focused on pure PCMs or reference PCMs introduced with theoretically high latent heat values or high PCM percentages for maximum effectiveness. However, as commercially available PCMs get applied to building materials such as gypsum, they are mixed with flame retardants and other elements which changes their thermophysical properties and therefore affects their performance.

Thus, it was considered to investigate real available products.

Therefore, it was determined to investigate the potential of PCMs commercially available in the market. Several commercial products suitable for wall and ceiling applications were identified and reviewed based on their physical and thermal properties. The focus was specifically, on organic microencapsulated PCMs were selected as they are often preferred for their longer lifespan, structural stability, and congruent melting (Sharma et al. 2009; Bruno et al. 2015). Finally, two products; BioPCM™ and Energain™ were selected as the PCM options for this study, for their high latent heat values and their appropriate melting ranges for indoor applications in the climate of Toronto. The applicability of the products to retrofit projects and their availability in the Canadian market were other considerations. Table 2 reports the properties of the selected PCM products.

Table 2: Thermophysical properties of the selected PCM products

PCM Product	Thickness (cm)	Melting Temperature Range (ºC)	Latent Heat Capacity (KJ/Kg)	Specific Heat (KJ/Kg.ºC)	Conductivity (W/m.K)
Energain™ PCM (Gilbert and Koster, 2010)	0.5	18- 21.7	70	2.5	0.18 - Solid 0.14 – Liquid
BioPCM™ (Phase change energy solutions, 2016)	1.5	21 - 25	200	2.1	0.2

Regarding thermal characteristics of the two selected products, Energain™ PCM panels have melting points approximate to indoor temperatures in winter months. BioPCM™ panels with a nominal melting point (T_{mp}) of 25 ºC are compatible to indoor conditions in summer months in Toronto. Combining these two products in a composite PCM system could show a high potential for indoor temperature with only 2 cm additional thickness as shown in Fig. 1a. Higher thermal energy storage in a small density and thickness in Energain™ and BioPCM™ is due to their high latent heat and specific heat values leading to large sensible and latent heat storage (Fig. 1b).

The configuration of the composite PCM system is primarily based on the thermophysical properties of each PCM, specifically the heat conductivity. Both PCMs have low conductivity values, however, the conductivity of Energain™ is 0.18 W/m.K when solid and 0.14 W/m.K when liquid, while this value is 0.2 W/m.K for the BioPCM™ panel. If Energain™ panel was positioned in the first layer it would melt faster than the BioPCM™ in summer and would result in slower heat transfer to the BioPCM™ layer which is intended to regulate the indoor summer temperatures.

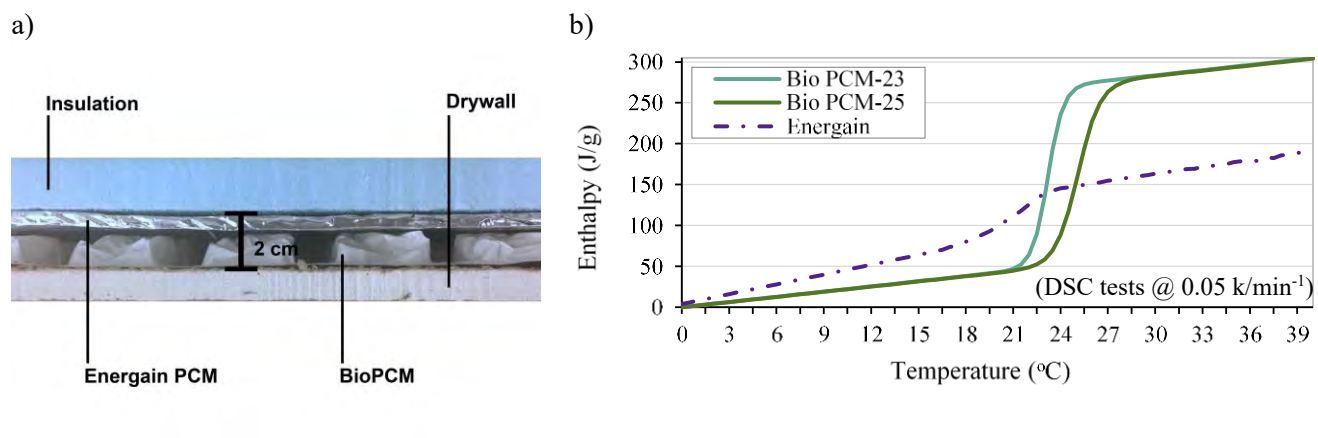

Figure 1: a) The composite PCM system b) Temperature-enthalpy curves for the PCM products

Experimental Test Methodology

In this study, the experimental tests rely on passive solar gain and ambient temperatures to activate the composite PCM system as no mechanical intervention was used. The objective was to monitor the behavior of the composite PCM system for several months. Including seasonal temperature variations and longer test period allowed for a comprehensive analysis of PCM performance.

Two small scale test cells were constructed, one reference cell as a baseline and one cell with PCM-enhanced walls and ceiling as shown in Fig. 2. Test cells were constructed to replicate typical apartment units on a scale of 1:10, furthermore, they have one glazed wall which covers 80% of one wall similar to highly glazed apartment units. The test cells were constructed with an aluminum structural frame covered with white rigid polyethylene plastic sheets. Water resistant plywood sheets (Form Ply) were positioned on the ceiling and the floor of both test cells. To insulate the units, extruded polystyrene (XPS) insulation was used on all the walls, floor and ceiling surfaces from the inside. For the glazing, a clear glass single pane was installed on the cells' façade.

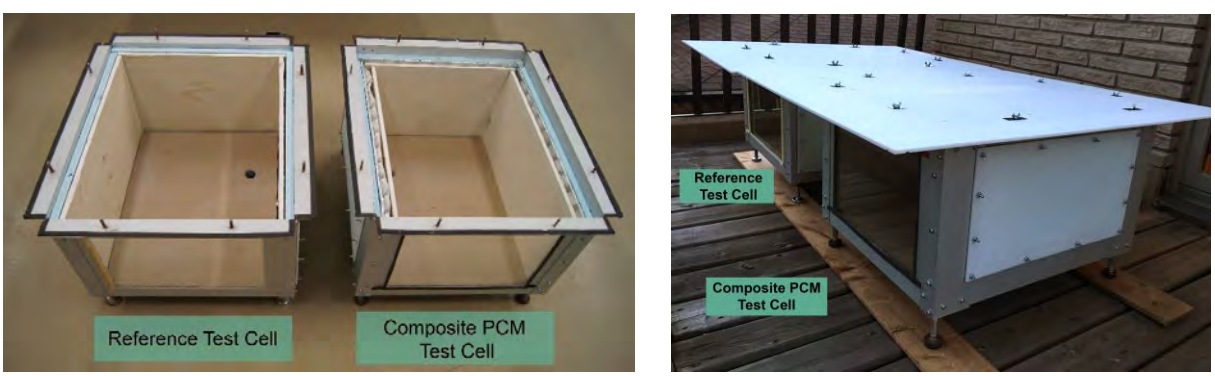

Figure 2: Experimental test cells

The main enclosure assembly includes gypsum boards facing the interior spaces on all walls and ceiling surfaces, with XPS insulation located behind it. The PCM boards are integrated into this assembly between the gypsum board and the XPS insulation. The composite PCM system is applied to three walls and the

ceiling of the composite PCM test cell. The arrangement of the PCM boards in the composite PCM wall and ceiling is detailed in Fig. 3. For simplification, the test cell integrated with PCMs is referred to as the "Composite PCM test cell" and the test cell without PCM application as the "Reference test cell".

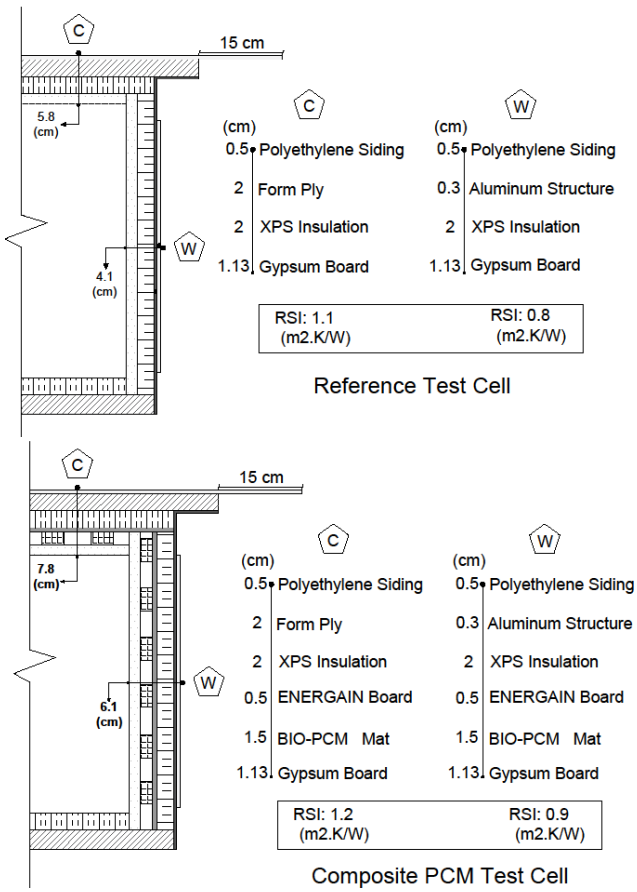

Figure 3: Enclosure assembly in the test cells

Data were collected from the test cells' indoor room and the wall and ceiling surfaces. Each test cell was equipped with one HOBO U-10-003 Data Logger to measure indoor air temperatures. 8 thermocouples and 2 heat flux transducers were installed on the walls and the ceilings of the cells to measure the surface temperatures and heat flow rates. The heat flux sensor used for this study was an HFP01 Hukseflux heat flux plate which is a ceramic disc installed between the wall and ceiling surface layers. The sensors were attached to the drywall and Energain™ PCM using a conductive paste. The data were recorded using a Graphtec data logger with direct connection of thermocouples as well as direct voltage measurements. Surface and indoor air temperatures and surface heat flow values were measured continuously with a time step of one minute for accurate monitoring of PCM activation patterns. To measure outdoor temperatures a Netatmo weather station was positioned two meters behind the test cells.

The test cells were positioned in Toronto with access to three orientations of south, east, and west. Tests were conducted from July to October to observe variations between summer and fall month temperatures and how the behavior of the composite PCM system changes.

Parameters of Analysis

The performance and effectiveness of the composite PCM system are quantified in relation to ambient weather and solar gain variations. The prominent variables for the experimental study are orientation and shading, while inclusion of night cooling is also investigated. In total, five different tests were conducted, each focusing on specific variables based on a comparative assessment between the reference test cell and the composite PCM test cell. The impacts of the composite PCM system are assessed on room and surface levels. The main comparison in the experimental tests is between the two test cells, thus the term "rate of change", is referred to the changes perceived in the composite PCM test cell as opposed to the reference test cell. The following parameters were quantified:

- *Room Level:* The analysis included the monitoring of room air temperature swings, and the rates of heat loss and heat gain inside the cells in relation to the time of day.
- *Surface Level:* The analysis allowed to investigate the exact performance and activation pattern of PCM products incorporated in the walls and ceiling in each layer. In addition to surface temperatures, evaluation of heat flow through each surface indicates the mechanism of heat gain and heat release. The temperatures are analyzed based on the melting range of the two PCM products.
- *Comprehensive analysis:* This final evaluation is focused on connecting the main variables with the measured data.
    - The influence of orientation on indoor temperature fluctuations;
    - The influence of shading on indoor temperature and surface temperature;
    - The influence of natural ventilation on indoor room temperatures

Test	Test Period	Tested Properties
Testing the impact of orientation	1 Jul- 7 Jul	Orientation: South
	8 Jul- 14 Jul	Orientation: East
	15 Jul- 21 Jul	Orientation: West
	22 Jul - 15 Aug	Orientation: South
Testing the performance of ceiling surfaces	19 Aug - 25 Aug	Surface analysis: Ceiling only
Testing the individual PCM products	26 Aug - 7 Sept	Individual PCM Test
Testing one wall and ceiling + orientation	8 Sept - 14 Sept	Surface analysis: One wall + Ceiling Orientation: South
	15 Sept - 21 Sept	Surface analysis: One wall + Ceiling Orientation: East
Testing the impact of shading and natural ventilation	24 Sept - 12 Oct	Shading + Natural Ventilation

Figure 4: Timeline of the experimental tests

RESULTS

The Impact of Orientation

In a 45-day period, data were collected from sensors positioned on two walls, one side wall and one window facing wall. Test cells were rotated to three orientations of south, east, and west for a minimum period of seven days to assess the influence of solar radiation on PCM performance. The weekly average high and low peak indoor air temperature values in each orientation shows that the maximum rate of change in the composite PCM test cell occurs when the two highest and lowest peak temperatures are recorded.

Figure 5 shows the higher effectiveness of the composite PCM system in extreme situations by regulating peak temperatures. The influence of the composite PCM shows a 9% reduction of high peak temperatures in the west and 22% increase in low peak temperatures in the south orientation. However, as each orientation test was conducted in a different week, the ambient conditions are not directly comparable. Nevertheless, the average outdoor weather conditions in the west facing and south facing periods in July are quite similar, on average the daily outdoor temperature is 23.5 ºC in both weeks. Thus, it could be suggested that the impact of solar heat gain in the west orientation is larger on indoor air temperatures which consequently entails the highest rate of change caused by the composite PCM system.

The test cells were exposed to the south for four weeks between July and August. As Fig. 6a shows, the sinusoidal temperature changes are attenuated in the composite PCM test cell. Overall, the air temperature swings are reduced by 6.8 ºC. In particular, the effectiveness of the composite system at night is significant in maintaining indoor temperatures as air temperatures of the reference cell drops 2 ºC below the ambient weather. An apparent peak temperature shifting of one hour happens in the composite PCM test cell. The maximum air temperature is shifted to later afternoon due to thermal lag in the composite PCM test cell.

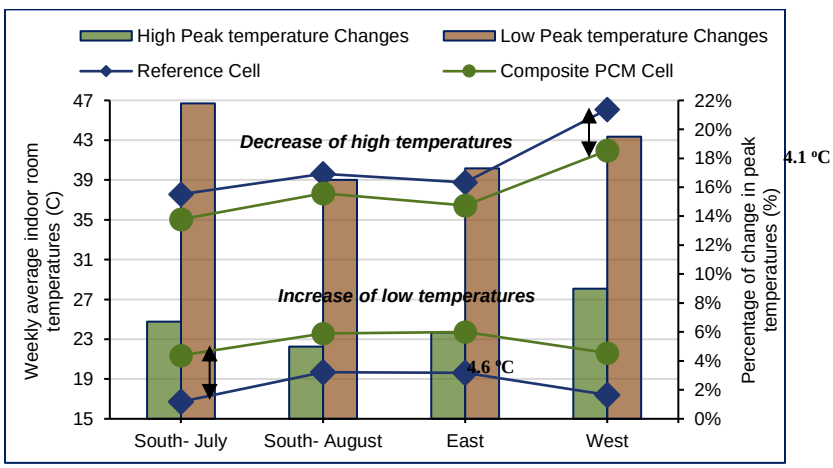

Figure 5: Correlation of orientation and peak indoor room temperatures

As the test cells face the east orientation, indoor air temperatures start to increase rapidly from 6 am in both test cells, however the overall rate of change in the composite PCM test cell is similar to the south facing scenario. Conversely, by rotating the test cells towards the west orientation, significant changes are observed as demonstrated in Fig. 6b. Unlike south and east facing orientations, highest temperatures in the test cells occur close to the sunset period from 5 to 7 pm.

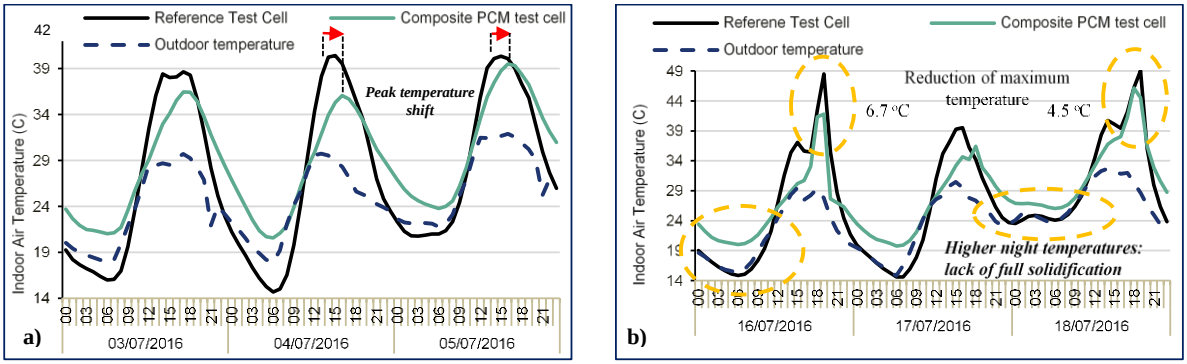

Figure 6: Hourly indoor room temperatures; a) South orientation – b) West orientation

Another distinctive pattern in July is the rapid transition of temperatures at night without solar radiation. In the east and south orientations, the night temperatures in both test cells decrease over time at a slower rate. However, in the west orientation, the large swing observed on the 16th and the 18th are as much as 33 °C in the reference test cell and 21 °C in the composite PCM test cell through the night.

Finally, by comparing the window facing wall and the side wall, the results show that in all orientations, window facing walls experience higher temperatures in both test cells. Interestingly, the effectiveness of the PCM system is also higher in reducing the surface tempera rues of the window facing wall. For instance, when the test cells are facing the west, the composite PCM system reduces the maximum surface temperatures of the PCM integrated window facing wall by 7.8 °C, while this effect is 6.7 °C for the side wall.

The Impact of Shading and Night Cooling

To further observe the influence of solar gains on PCM performance, the shading part of the test cells was removed to allow direct solar exposure in the test cells. This test was performed from September 24th to October 12th, while the test cells faced the south. The reference test cell showed high dependence on outdoor weather conditions ultimately leading to average colder indoor temperatures. Whereas in the composite PCM test cell, due to increased thermal inertia and storage capacity, indoor air temperatures were kept constantly above the outdoor temperatures.

Figure 7 compares the average room temperatures and rate of change caused by the composite PCM surfaces with and without shading. Removing the shading negatively affected PCMs' performance in reducing excessive heat gain in the spaces. In the no shading scenario, the reduction of high peak indoor temperatures in the composite PCM test cell is only 1%. By removing the shading, the increase of low peak temperatures at night is 20% higher than when the composite PCM test cell is shaded. However, more accurate results in one similar ambient condition while testing the shading could show different results.

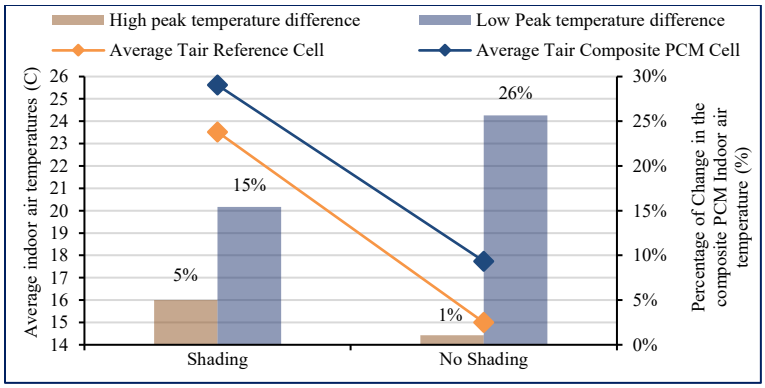

Figure 7: Correlation of indoor temperature changes in the composite PCM test cell with and without shading

A typical day in the no shading scenario in October and a day in the shaded scenario in September are compared. Outdoor temperature variation is between 11.4 to 37.6 oC in September and 7 to 22.6 oC on October. Hourly ambient temperature variations in both September and October days occur gradually with an average 0.1 oC change. Considering the rate of indoor air change in the composite PCM test cell in September with available shading, similar gradual temperature increase could be seen. Indoor temperatures in the composite PCM test cell rise slowly and reach the melting range of both PCM products in a 4-hour period. In contrast, on the October day with no shading, indoor air temperatures in the composite PCM test cell rises by 11 oC from 17 to 28 oC at the peak of solar radiation in the south orientation. This sharp increase in the indoor air of the test cell leads to melting of both PCM layers in only one hour which moves to sensible gain after they are melted further increasing indoor temperatures. This is directly linked to solar radiation and the role of shading in controlling exposure.

In conclusion, the primary difference between the shaded and not shaded scenario is that by removing the shading, the effect of solar radiation is visible in a specific period during the day with sharp temperature rise in both test cells. A spot effect which causes the PCMs to melt rapidly and as the excessive heat exceeds the latent heat storage capacity of the PCMs, their temperatures rise through sensible storage.

Higher exposure to solar radiation without shading results in higher night temperatures in the composite PCM test cell which also affects room temperatures in the next cycle. One of the key problems associated with PCMs is the inability of full solidification process at night due to high night temperatures not reaching the freezing point. When PCMs do not discharge the stored energy at night, they lose their ability in the next cycle as they stay melted and are unable to reduce the effect of the heat gain. This factor is evident in this study on very hot days or in case of extreme solar exposures as shown in Fig. 7 when the test cells are facing the west or when the shading part of the composite PCM test cell is removed.

One of the prominent solutions stated in reviewed studies is the inclusion of night cooling to facilitate the solidification process of PCMs preparing them for sufficient heat storage in the coming day. Therefore, night ventilation was applied for several nights by creating a 2 cm opening along the length of one wall to provide external airflow to the cells. Figure 8 presents the surface temperature and heat flow variations for three days, with night ventilation applied on October 9th for 10 hours until 7:30 am on October 10th. It must be noted that based on the parameters of the installed heat flux transducer, negative heat flow values indicate heat gain in the wall which means heat loss from the room. (Positive values show heat loss from the wall meaning heat gain in the room.)

The benefit of using natural ventilation is evident on reducing the high surface peak temperatures on October 10th. This is a reduction of maximum temperatures up to 7.8 oC in the composite PCM wall compared to the peak in the reference wall. This value is 3.4 oC more than the same change perceived on 8th and 9th considering a similar trend of surface temperature variation. The surface analysis demonstrates the impact of natural ventilation in reducing the surface temperatures well below the melting range of both PCM products.

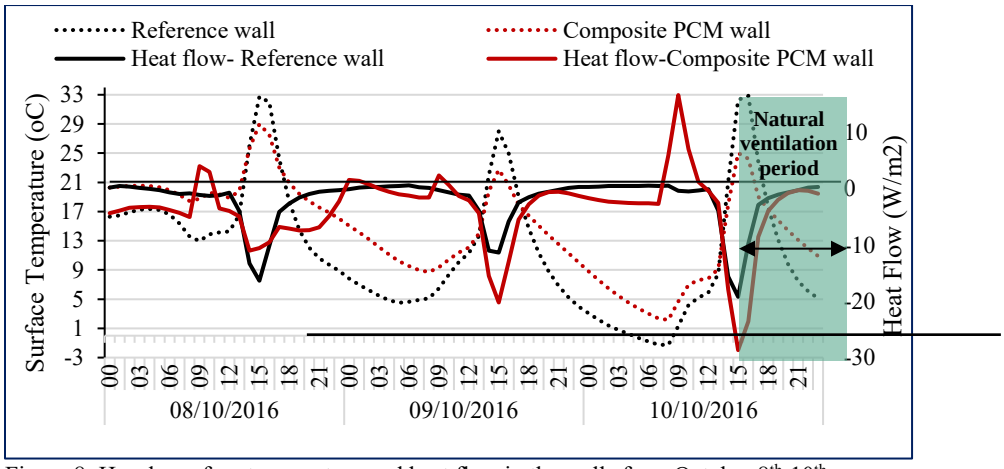

Figure 8: Hourly surface temperature and heat flow in the walls from October 8th-10th

The low temperature experienced at night results in the highest heat release from the wall to the room at 9 am on October 10th. The results obtained from other tests in this study without night ventilation show that higher night temperatures delay the solidification process of the composite PCM layers to early morning periods or even after sunshine hours. By allowing natural ventilation into the test cell, a faster solidification and heat loss from the surfaces occurred that would show improvements in the summer period as well in reducing the recharge time of the composite PCM system.

Performance of the PCM Integrated Surfaces

To simultaneously monitor the ceiling and wall surface temperature variations, one side wall and the ceiling in the two test cells were investigated from September 7th to 14th. The primary parameter of analysis is the difference between the wall and ceiling surface temperature changes in relation to the room temperature.

The hourly surface temperatures in the composite PCM wall show a faster response to ambient and indoor room temperature variations compared to the ceiling. During the day, the wall heats up more rapidly and at night it loses heat faster as temperatures start to decrease compared to the composite PCM ceiling.

Figure 9 shows the hourly room (Ta) and surface temperature (Ts) variations in three consecutive days in September. Without PCMs, the indoor room temperatures of the reference cell show a close proximity to the reference wall and ceiling's surface temperatures particularly in maximum peak periods during the day. Conversely, considering the indoor air of the composite PCM cell and the composite PCM surface temperatures, a notable gap is observed. Even though the overall trend in both figures is very similar, a slight variation could be seen in the performance of the composite PCM system applied to the ceiling and walls.

Average surface temperatures of composite PCM wall and ceiling surfaces are 4 ºC lower than the indoor cell temperatures. The largest temperature difference between the composite PCM surfaces and their corresponding cell air temperature is reached on high temperature peaks during the day. Whereas during the night, the surface temperatures get closer to the indoor room temperature as a result of heat release from the PCMs Opposite behavior occurs in the reference test cell. At night, the reference surface temperatures are lower than the room temperatures and lose heat rapidly. This is a clear indication of heat loss in the night hours from the reference surfaces out of the reference test cell. However, the radiant heat impact of the composite PCM is evidently keeping the air and surface temperatures approximately in the same range, as a result PCM solidification and release of heat back to the cell. The gap between the composite PCM surface and room temperature is decreased during the night period, on the contrary, this difference starts to rise, as early as 7 am with availability of solar radiation. The room quickly starts to warm, while the surface temperatures are increased incrementally as a result of heat storage in the PCMs in the walls and ceiling.

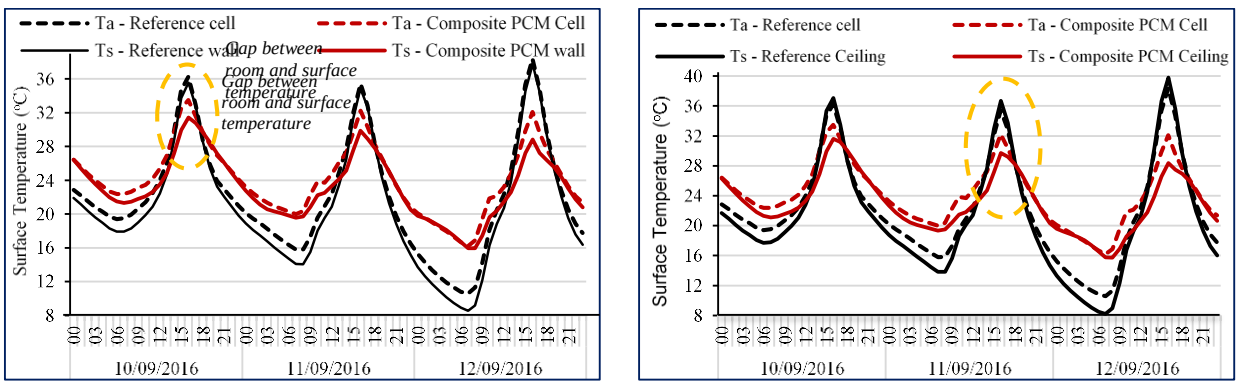

Figure 9: Hourly Indoor Room Temperature and surface temperature variations; a) Wall- b) Ceiling

The rate of increase in heat gain and heat loss in the PCM integrated wall and ceiling surfaces is compared. In the reference wall as temperatures drop, heat moves towards outwards. Heat release from the composite PCM wall to the room is clearly observed as it compensates for the heat loss from the room. However, this value is much smaller in the composite ceilings, as the average heat release to the room through the reference ceiling is also high at night entailing a smaller gap between the reference and the composite PCM ceiling. In contrast, the great difference in heat gain capability of the ceiling is more notable. The overall conclusion is that PCMs integrated into the ceiling have better performance in absorbing and storing the excess heat which could be due to natural convection and nature of heat transfer.

Test #3: Testing Individual PCM Enhanced Surfaces

This test was performed for eleven days from August 27th to September 6th, in order to separate the PCM products used in the composite PCM application to assess their performance individually. Thus, the configuration of the test cells was modified; the walls of one test cell were lined with Energain and the walls of the other test cell with BioPCM^{TM}. As shown in Fig. 10a, both PCMs are capable of moderating night temperatures individually when they start to solidify. Evidently, due to different melting ranges, BioPCM^{TM} test cell's night air temperatures are above the Energain test cell.

In contrast, the high peak temperatures in the Energain test cell are higher than in the BioPCM™ test cell. This could be related to the higher specific heat of Energain product leading to higher sensible storage in the surfaces. Detailed surface temperature and heat flow graphs presented in Fig. 10b demonstrate a similar trend of change in heat flow and surface temperatures in both Energain and BioPCM™ walls on the same day. The rate of heat release is 43% higher in the BioPCM™ wall while the rate of heat absorption in both surfaces is quite similar. The higher heat discharge observed in the BioPCM™ wall could be due to the conductivity of the BioPCM™, which is marginally higher than the conductivity of the Energain PCM.

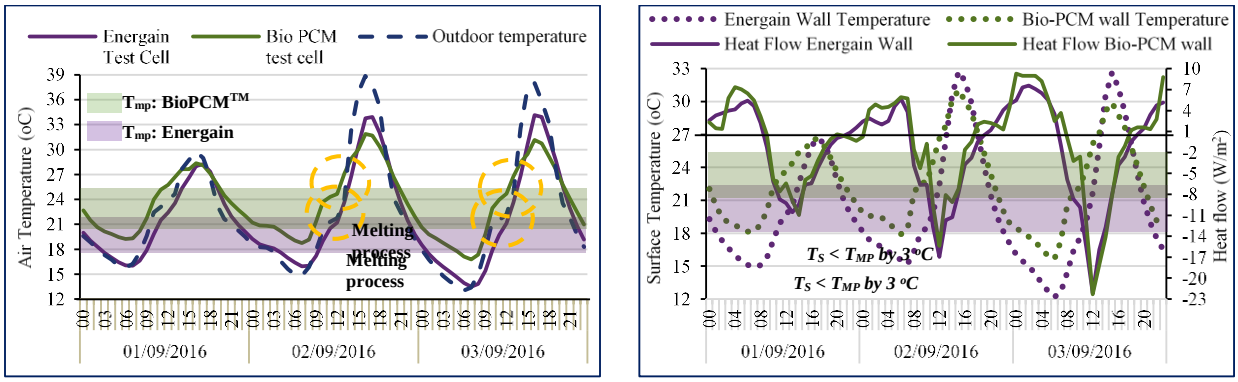

Figure 10: a) Hourly indoor temperature changes; b) Side wall surface temperature and heat flow variations

Due to the isothermal effect of PCMs, they maintain the surrounding temperatures within their melting range. This is evident in both the surface and indoor temperature graphs. For a better illustration of daily fluctuations, temperature changes per minute are assessed on the first three days of September with average daylight period of 13 hours. BioPCM™ layer starts to melt on these three days at approximately 10 am, 1 hour ahead of the Energain layer in the other test cell. The overall melting process of the Energain board is shorter than the BioPCM™, whereas the solidification process of BioPCM™ on average in these three days takes only two hours. During the isothermal process of melting, the rate of surface temperature is slowed down as expected. During the melting of BioPCM™, the surface temperature of this wall is fixed at 22 °C from 10:16 am to 12:37 pm. In the Energain, however, the process takes less time, thus shorter constant period for the surface temperatures. Nevertheless, as the Energain melts, the surface temperatures are constant at 18 °C from 11:10 am to 12:48 pm. In general, considering the entire melting range of each PCM layer, the constant period for each temperature point takes on average from 30 to 60 minutes during the phase change process.

Another main factor observed is the time lag caused by the PCMs. Even though this is generally a positive factor specifically for peak temperature shifting and maintaining constant temperatures for longer periods, the time frame of the solidification period and sunshine hours may not match. For instance, in both test cells at night, air temperatures start to decrease rapidly in the room from 7 pm, but in August nights, the Energain wall reaches 18 °C in early morning at 7 am. This factor is reduced completely in September, indicating that the PCMs are more likely to have discharged the stored energy by morning.

DISCUSSION

The initial research focus in this study was to assess the impact of solar gain and ambient weather variations on PCM performance. Pertaining to the experimental test results it is demonstrated that the impact of ambient weather is more significant as temperature variations control the entire transition of the composite PCM system during the day. Nevertheless, exposure to solar radiation enhances the melting process, while this influence is periodical specifically at times of highest solar intensity. A previous study done by Muruganantham et al. (2010) with experimental tests performed in mechanically conditioned test cells show that the effect of solar radiation becomes more prominent when the room has a constant temperature through active space conditioning.

Regarding different orientations, the experimental tests could not draw a direct link between the **impacts** of solar gains from each direction as ambient conditions in each testing week varied. The behavior of composite PCM system in performing the phase transition and heat storage is more constant when test cells are facing south. The highest and sharpest fluctuations were experienced when the test cells were rotated to the west and furthermore high-peak temperatures in both cells coincided with the peak solar times.

Another parameter to assess the relation of solar radiation to PCMs was testing the effect of shading. Even though removal of the shading occurred in October with lower ambient temperatures, the effect of the composite PCM system in reducing overheating due to high solar gain in the test cells was decreased. In contrast, higher average temperatures in the composite PCM test cell without shading led to higher night temperatures. Excess heat being exposed to the cells causes fast melting of PCMs. This excessive heat surpasses the latent heat storage capacity of the composite PCM system which turns into sensible temperature rise. Thus, it was observed that a direct link exists between sensible temperature rise and higher solar gains. Finally, due to lower temperatures, the availability of solar radiation is more important in fall months to ensure activation of the PCMs. Whereas, in summer, the excessive heat could lead to a longer period in which the PCMs stay melted, thus having a shading would be beneficial.

To better explain the impact of ambient weather on PCM performance, average data in each testing period in the span of four months are compared. Table 3 summarizes different parameters in each testing period where the test cells are facing the south orientation and the wall surface temperatures are recorded.

By looking at the trend of outdoor temperature variations and the PCM activation, the highest percentage of PCM's being activated is recorded in the month of July. Correspondingly in this month, the composite PCM system reduces indoor temperature swings and high peak temperatures significantly compared to other months. The effectiveness of having a hybrid PCM system with two melting points is evident as in July and August, the Energain™ PCM is mostly in liquid form; in contrast, the BioPCM™ is often in the solid state in September and October. The low percent of decrease in maximum temperatures in October is due to the excessive heat gain in the cell with removal of shading. The higher rate of increase in minimum temperatures in September and October is a result of full solidification due to colder nights.

Table 3: The impact of the composite PCM on indoor air temperatures

Parameters	Average Ambient Conditions (ºC)	Decrease of T_{Max} (%)	Increase of T_{Min} (%)	Decrease in Temperature Swings (%)	Frequency of PCM Activation			
					PCM Layer	Solid	Phase Change	Liquid
July	19.2 - 31.1	6%	18%	46%	BioPCM™	29%	28%	43%
					Energain™	6%	30%	64%
August	19.9 - 35.7	4%	16%	37%	BioPCM™	7%	18%	74%

					Energain™	0%	9%	91%
September	15.2 – 31.1	6%	19%	35%	BioPCM™	57%	18%	25%
					Energain™	41%	21%	38%
October	11.2 – 25.6	1%	24%	18%	BioPCM™	86%	7%	6%
					Energain™	60%	28%	12%

CONCLUSIONS

The overall impact of the composite PCM system demonstrates constant temperatures for longer periods, and slower transition times which resulted in peak shifting and reduction of extreme temperatures. The experimental tests showed that the proposed composite PCM system could easily be activated in passive conditions when the cells are only exposed to solar radiation and ambient weather. Another positive outcome of this research proved that longer testing period is beneficial in showing how the PCMs' behavior changes with ambient temperature fluctuations. Specifically, as the proposed composite PCM system in this study is intended to perform in diverse yearly temperature variations. The performance of this system will be further analyzed using computer simulation to support the present findings with annual performance analysis of the composite PCM system in different climates.

The capability of this system is clearly displayed as each PCM targets the fall and summer months as expected, Energain™ layer addresses the indoor temperature range of fall months while the BioPCM™ is effective in reducing overheating in July and August. The composite PCM system undergoes one full cycle each day; this diurnal cycle consists of one full melting cycle in the day and a solidification cycle at night in the case of favorable low ambient temperatures, which could further be adjusted by modifying ventilation and shading features.

Notable results derived from the experimental tests:

- The main outcome of implementing the composite PCM to surfaces is the significant reduction in the vulnerability of the composite PCM test cell to ambient weather changes;
- Implementing natural ventilation at night is beneficial in accelerating the solidification process and leading to an earlier solidification before sunrise hours. However, more detailed analysis is required by measuring the amount of heat flow and time of exposure to find the most effective natural ventilation scenario for the effective discharge of PCMs;
- Comparison between composite PCM ceiling and wall surfaces showed a higher percentage of heat absorption in the ceiling and thus higher reduction of high peak temperatures;
- The impact of PCMs in reducing high and low peak temperatures is higher in extreme conditions with sharp temperature swings in the test cell; such as periods in which the cell is exposed to the west, or high daily temperature variations occur during the days as in fall.

The highest advantage of the composite PCM system in this study is the inclusion of two different melting points in one system, which allowed for high latent heat storage capacity in a thin layer. With only 2 cm thickness, it is an unobtrusive addition, suitable for retrofit projects that provides significant thermal

storage. In conclusion, multiple PCM systems, using two or more PCM products with different melting points have a great potential in becoming a more prominent approach for PCM application in buildings.

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