Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 111 (2017) 462 – 471

Energy Procedia

8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, ITALY

The energy saving and indoor comfort improvements with latent thermal energy storage in building retrofits in Canada

Umberto Berardi[a]*, Mauro Manca[a]

[a] Ryerson University, 350 Victoria street, Toronto, M5B 2K3, ON, Canada.

Abstract

High-rise apartment buildings in Canada are an integral part of the residential building stock, and their dominance is continuing to grow as their market escalates. Meanwhile, the refurbishment of the existing multi-unit residential building stock is becoming a fundamental step in order to address Canadian energy saving targets. The aim of this paper is to evaluate the effectiveness for energy saving of increasing the thermal capacity of the building enclosure. In particular, this paper assesses the benefits of the adoption of Phase Change Material (PCM) in lightweight constructions in the climates of Toronto and Vancouver. The main aspect investigated is the contribution of PCM systems to lower the building cooling demand and to increase the indoor thermal comfort. Building simulations aimed at comparing different PCM systems for building elements such as floors, ceilings, and walls are reported. Different orientations and internal gains are considered in order to have a complete understanding of the potential benefits of the adoption of systems with high (latent) thermal energy storage capacity in building retrofits in Canada.

Peer-review under responsibility of KES International.
Keywords: phase change materials; thermal comfort; energy simulations; passive strategies; energy efficiency; buildings.

1. Introduction

It is often stated that the building energy consumption accounts for 32% of total global final energy use, with energy consumptions above 40% and greenhouse gas (GHG) emissions of 40% in some developed countries [1-3]. The Intergovernmental Panel on Climate Change (IPCC) stated that GHG emissions from the building sector more than doubled between 1970 and 2010, reaching a value around10GtCO2eq/y nowadays, mainly resulting from the energy

* Umberto Berardi. Tel.: +1 416 979 5000 (3263);
E-mail address: uberardi@ryerson.ca

Peer-review under responsibility of KES International.
doi:10.1016/j.egypro.2017.03.208

consumptions [3]. Looking at the global trends of the energy consumptions, the IPCC has reported that significant heating and cooling energy demand increases are expected globally by 2050, growing 179% and 183% higher than the 2010 levels in residential and commercial buildings respectively [1]. Given these trends, the role of buildings in promoting energy saving is obvious. This awareness is confirmed by the increasing commitment towards zero energy buildings [4]. However, it is also evident that the refurbishment of the existing building stock is the only way to reduce significantly the building energy consumptions.

This paper aims to assess the feasibility of adopting Phase Changing Materials (PCMs) in buildings in Canada during building retrofits. The choice of studying PCMs is due to the crucial role of thermal mass in controlling the internal comfort while promoting the reduction of the peak energy demand [5-7]. In this regard, given the trend in the Canadian building sector towards fast construction systems, the latent thermal energy storage could be particularly important for energy saving. In order to prove this value it is worthy to note that Toronto is experiencing an incredibly high construction development rate; in September 2014, there were 211 new high-rise projects across Toronto, while at the beginning of 2015, the number of high-rise proposals and projects across the city increased to 470, and for the majority of the new high-rise buildings, a completely transparent envelope with high solar heat gain and low thermal mass was adopted [7]. This architectural design trends, which have been common for the last two decades, have resulted in high energy demand given by the need of continuous recourse to the HVAC systems to deal with uncomfortable indoor conditions.

2. Literature review

2.1. General aspects of PCM

The research on PCMs has become one of the major topics in the building material field, as suggested by the exponential increase in the number of papers about this topic. PCMs have the capability to store and release energy in the form of latent heat thanks to a solid-liquid/liquid-solid phase change at their melting point temperature and they may hence be used as thermal storage systems in order to store excessive heat from inside the building [8-10].When the PCMs are at a temperature below their melting point, they are solid and behave like any other material, increasing their temperature as they absorb and transfer heat according to their conductivity, density, and heat capacity. When the surrounding temperature reaches the melting point of the PCMs, these start the phase change at an almost constant temperature accumulating heat until the material is completely melted. In practice, the phase change is often spread over a temperature range which follows a Gaussian curve [11]. The main issue for the actual effectiveness of PCMs is that the indoor temperature has to span a range that enables the phase transition. For this reason, every project in which PCMs are proposed must be studied individually, and dynamic energy modeling becomes fundamental to determine the functioning of the PCM [12].

Since the activation of the PCMs depends on many factors (including the outside temperatures, the building envelope properties, the building internal loads, and the PCM melting point), the choice of a too low melting point temperature induces an under-utilization of the material in the hottest months, while a too high melting point may cause the inefficiency of the PCM during the intermediate seasons. In order to encompass a larger temperature swing and to cover a longer period, PCM systems with different melting point temperatures have been coupled [13]. A study by Kuznik demonstrated that the optimal melting temperature should be based only on the average room temperature [14]. The overall enthalpy of the PCM is also an important issue since during the charging period if the PCM thermal capacity is too high, the melting process becomes slower and eventually it could even not complete.

PCMs are usually classified in three categories: organics, inorganics, and eutectics [15]. The organic PCMs are usually available in different melting point ranges, are chemically stable and do not show super-cooling effects but have a lower conductivity (about λ=0,2W/mK), which limits their ability to exchange heat [16]. Reversely, the inorganic PCMs have a higher conductivity and a smaller volume change, although they often show episodes of super-cooling, and are corrosive. Recently it has emerged the need for PCMs having a liquid phase change (so no solid to solid PCMs) to be contained in other construction materials or envelopes to prevent leakages and contaminations [10]. However, once encapsulated, PCMs can be integrated into porous materials such as plasterboards or finishing panels has already proven to be effective [17].

Many studies have demonstrated remarkable benefits from the application of PCM in building construction for passive (in building elements) and active (coupled with the HVAC system) strategies. Feustel and Stetiu showed that the use of double PCM wallboards in all walls and ceiling can keep the room temperatures close to the upper comfort limits without using any mechanical cooling [18]. Kuznik et al. showed that the application of PCM on the walls of a test room can decrease temperature fluctuations by 4.7 ºC [19]. Another study by Schossig et al. showed that during the summer season, the temperature in the PCM test room can be reduced by up to 4 ºC [20]. Meanwhile, a study by Ascione et al. proposed a deep investigation about the application of PCMs in the retrofit of existing building to reduce cooling demand [12]; dynamic energy simulations were performed in typical European buildings of the 1950s and the authors looked at the building performances in five Mediterranean cities. The study showed that the greatest savings were achieved with 3cm of PCM plaster, while thicker layers were not resulting in significant improvements. The results showed that PCMs are able to realize summer energy savings although their behavior was strictly depending on the climate; in particular, a higher day-night temperature swing, typical of arid climates, was more favorable since it facilitated the melting-freezing cycle of the PCMs [12].

Evola et al. presented a useful methodology for choosing the most appropriate PCM according to the climatic operating conditions and the comfort requirements [11]. They took the room operative temperature as a key parameter and assessed the thermal comfort, quantifying the intensity of thermal discomfort (ITD), a measure of the difference between the room operative temperature and the upper comfort limit temperature. Another important factor is the duration of each interval of temperature above the threshold that can be perceived by the human body. Evola et al. also proposed the use of the frequency of activation (FA), a parameter to indicate the percentage of time during which the PCM undergoes a phase change. In order to calculate the FA, the authors considered active a PCM when its surface temperatures fell between the phase change intervals, although it is known that the heat capacity at the boundary points of the temperature is much lower than at the peak since the phase change is an isothermal process. Finally, the PCM storage efficiency was used to show the ratio of the thermal energy actually stored by the PCM to its maximum storage capacity. The case study of Evola et al. consisted of the installation of honeycomb PCM wallboards on the partition walls of a lightweight building with the aim of improving summer thermal comfort. The results showed a reduction in peak operative temperature of about 1˚C, an attenuation in the daily surface temperature swing of the partition of about 2-3 ˚C, and a time shift up to 2 hours in the peak surface temperature. The application of the PCM wallboards coupled to appropriate night ventilation reduced the seasonal ITD by about 35% and the thermal comfort is assured for up 60% of the occupancy time. Although previous studies, a common metric to assess the PCM behavior is still missing in literature and recently Castell and Farid suggested that FA cannot always be related to improvements in thermal comfort [21].

3. Methodology

The study presented in this paper is primarily based on energy simulations performed with Energy Plus of an ideal building designed according to lightweight construction techniques for high rise buildings in Canada [22]. Each series of simulations was represented by the following three steps: firstly, the baseline, i.e. the standard construction without PCM, was modeled; then, the floor PCM, i.e. a PCM layer applied only on the innermost layer of the floor surface, was modeled; finally, the floor and envelope PCM, i.e. all the internal opaque surfaces were designed to have an additional internal layer of PCM, was modeled. In this last case, the PCM is covered by a layer of gypsum plasterboard.

Each series focuses on two different locations, Toronto and Vancouver, and it was carried out both for the cold season (October-March) and the hot season (April-September). The U-value of the building envelope was kept constant in each simulation regardless the variation of the type of PCM in order to estimate the phase change effect without being altered by the variation of thermal transmittance. In the end, the same series of simulation were repeated for three different profiles of internal gains, as described in section 3.3.

3.1. The calculation model

The case study was assumed to be inspired by a typical multi-unit residential building. It was composed by four rooms 5x5x3 m, positioned so that each one is adjacent to each other and has two exposed facades, one opaque and one glazed 85% window to wall ratio. In this way, it is possible to simulate four different orientations (Fig.1).

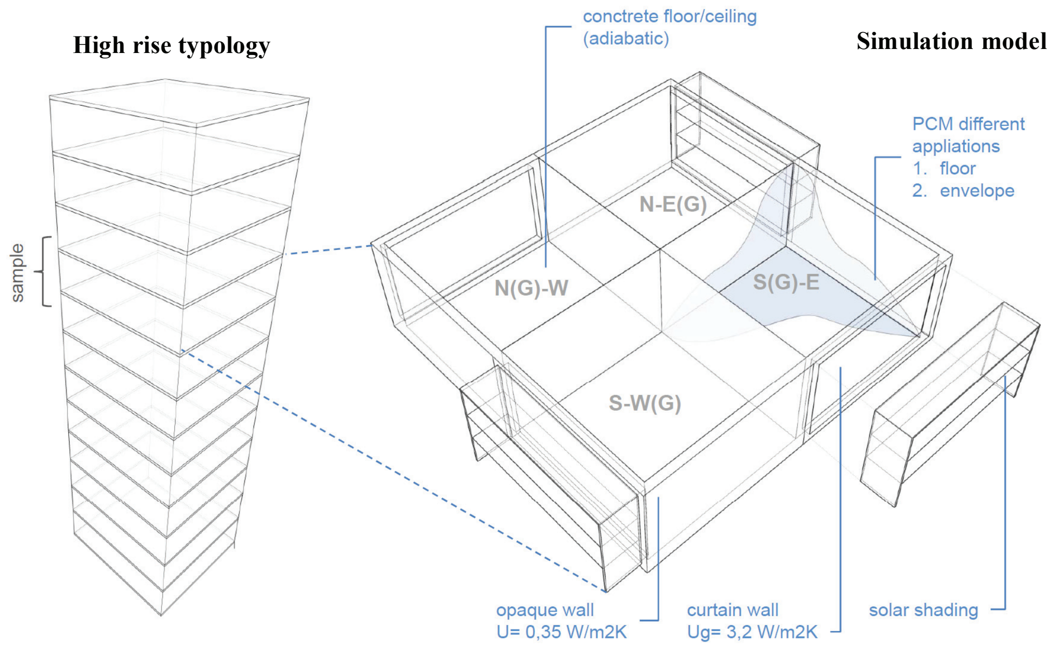

Fig. 1. Room design of the case study analyzed in this paper.

The main characteristics of the model are summarized below. Rooms N(G)W was a north-west room with north glazing façade and no solar protection; NE(G) was a north-east room, east glazing façade with solar protection; S(G)E was south-east room, south glazing façade with solar protection; SW(G) was a south-west room, west glazing façade with solar protection. The "G" in brackets stands for Glazed and identifies the glazed façade of the room.
The activity varies according to internal gains profiles: occupancy was 0.0870 people/m^2, i.e. two people on 24 m^2 studied with different occupancy schedules; equipment = 10 W/m^2(3 W/m^2 for the best case scenario), with lighting target of 150 lux.
The building construction details were:

- Wall: sandwiched XPS with U = 0.35 W/m^2K;
- Partitions: plasterboard with U = 1.923 W/m^2K;
- Floor 20 cm concrete slab (adiabatic surfaces above and below in energy calculations);
- Model infiltration settled at 0.5 ac/h;
- Windows to wall ratio settled at 85% with curtain wall façade;
- Glazing units were double clear 3mm/6mm with Ug = 3.2 W/m^2K;
- Shading system consisted of 1m boxes with three louvers, except for the north facing glazing façade.

The building climate control details were:

- Temperature set point operative fixed at 25°C in summer and 21ºC in winter;
- Natural ventilation scheduled between 3 and 12 ac/h, when T limits 22ºC<T<25ºC.

Given the high WWRs of modern Canadian constructions, buildings are highly affected by solar radiation and the inside temperature can be significantly (up to 20ºC) higher than the outside. Solar gains could be a good strategy for winter heating but the use of a shading system is required in favor of reliable results in summer. Natural ventilation at night is also important to promote PMC solidification and improve its benefits during the following day [6].

3.2. The PCM

The PCMs tested in this study are Phase Change Energy Solution-BioPCM™. This material is made from a rapidly renewable plant extract, which is harvested and then manufactured into blankets with small cells (Fig. 2).The standard values of the materials are M27, M51, M91 and M182. In the material name, the M-value refers to the heat storage capacity of the material in Btu per square foot. As an example, a product with an M-Value of 91 has the ability to store 91 Btu of latent heat per square foot (i.e. 287 Wh/m^2). A second code in the specific product name, the Q value, refers to the melting point temperature of the BioPCM.

(a)

(b)

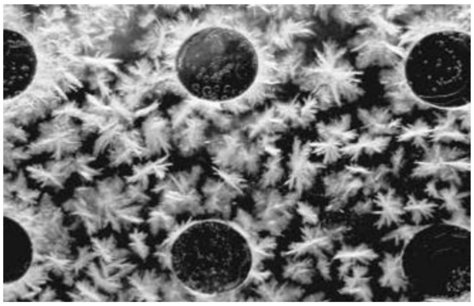

Fig. 2. Bio PCM blanket considered in this paper (a) and microscope view of the Bio PCM in its solid state (b).

3.3. Occupancy profiles and internal heat gains

Internal Gains (IG) have an important role in the study of PCMs [6]. The heat released inside a room affects the internal temperature influencing the behavior of PCMs. Especially in residential buildings, IG can have different intensity and distribution; therefore it is worth to consider at least three different scenarios: a low level of IG (best case for summer comfort), a typical occupancy scenario for residential use, and a high level of IG scenario (worst case for summer comfort). The best case considers an occupancy profile during mornings and nights, leaving out the hottest part of the day. This case would apply to people working during the whole day and coming back home just after work. The internal gains ratio was 3 W/m^2 [24]. The worst case is when people stay home 24 hours a day and the internal gains ratio is 10 W/m^2 (this value is usually attributed to office buildings equipment) [25] with scheduled variations between 30% and 70% during the day. The typical case scenario is calculated keeping the same value of IG as the worst case scenario but the occupancy schedules account for a full presence at night and variations during the day: 100% from19:30 to 9:00, 0% from 9:00 to 12:30,100%until 15:30,and 50% until 19:30. In this paper, the results for the typical case scenarios are mainly shown. In the following graph (Fig.3) the different impact of the IG profiles on cooling demand and the subsequent behavior of PCM (study case: Vancouver) is shown.

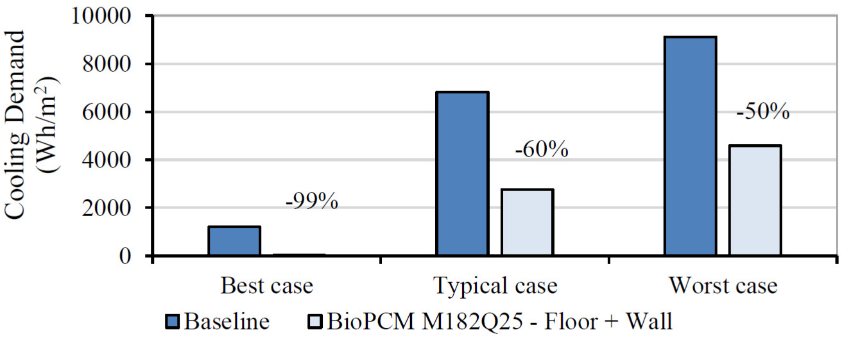

Fig. 3. Variation of cooling demand and PCM effectiveness in Vancouver.

4. Results

4.1. Cooling demand

The first set of simulations evaluates the effectiveness of the application of BioPcm M51Q25 on the floor and on the inner opaque surfaces (floor + walls) in the typical case scenario. The PCM had a phase change occurring at 25 ˚C. The results show, in the first case (PCM applied on the innermost surface of the floor element), that the PCM can reduce the energy consumption for cooling between 5% and 10%, while in the second case (floor + walls) can yield an energy saving between 15% and 21%. A second set of simulation calculates the total energy demand for cooling with BioPcm M182Q25 (with a value of latent heat storage capacity of 182 Btu/ft2 (i.e. 574 Wh/m^2).The volume of the material also changed passing from 2cm to 7cm of thickness. In this particular case, the improvements are significant. The cooling demand decreased by 8% compared to the BioPcm M51Q25 case and by 30% compared to the Baseline in the S(G)E room (Table 1). This result is mainly guaranteed by the increase of thermal storage capacity.

Table 1. Cooling demand expressed in W/m^2 for the simulations in Toronto and percentage of reduction referred to the baseline case.

Baseline				BioPcm M51Q25 - Floor + Wall				BioPcm M182Q25 - Floor + Wall			
N(G)-W	N-E(G)	S(G)-E	S-W(G)	N(G)-W	N-E(G)	S(G)-E	S-W(G)	N(G)-W	N-E(G)	S(G)-E	S-W(G)
35784	28750	16986	26799	30423	23093	13428	21347	30134	22447	12030	20227
% of reduction over the baseline case				*15.0%*	*19.7%*	*20.9%*	*20.3%*	*15.8%*	*21.9%*	*29.2%*	*24.5%*

The third set of simulations was carried out for the winter season with the application of BioPcmM182Q21 (phase change occurring at 21 ˚C). The result didn't show any particular improvement, consistently with other studies on the use of PCM in winter in cold climate. In some case the PCM, being in a solid form, with a low level of conductivity, prevented the concrete slab from absorbing sensible heat, thus reducing its thermal mass effect and causing a small increase in heating demand.

The next series replicates the same procedure but with the weather data of Vancouver. Again the simulation with a higher quantity of PCM, using BioPcm M182Q25, showed better results in terms of cooling demand (Table 2).

Table 2. Cooling demand expressed in W/m^2 for the simulations in Vancouver and percentage of reduction referred to the baseline case.

Baseline				BioPcm M51Q25 - Floor + Wall				BioPcm M182Q25 - Floor + Wall			
N(G)-W	N-E(G)	S(G)-E	S-W(G)	N(G)-W	N-E(G)	S(G)-E	S-W(G)	N(G)-W	N-E(G)	S(G)-E	S-W(G)
25946	19520	6821	25305	20976	13549	3761	18251	20934	12487	2772	17240
% of reduction vs. the baseline				*19.2%*	*30.6%*	*44.9%*	*27.9%*	*19.3%*	*36.0%*	*59.4%*	*31.9%*

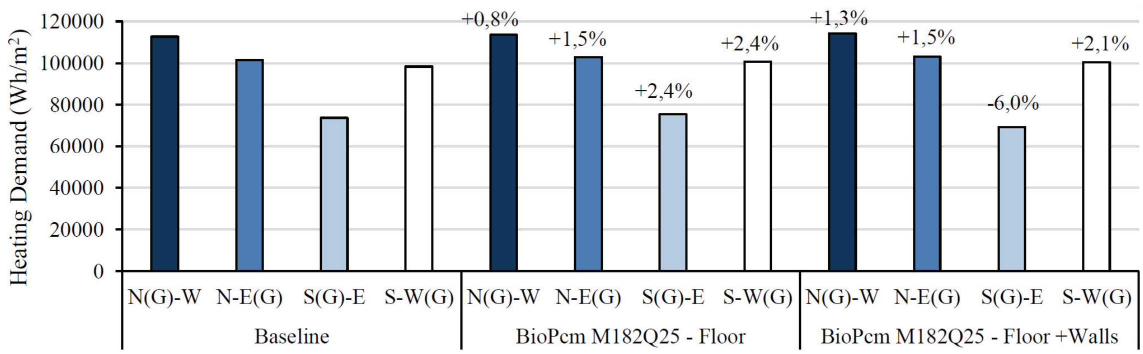

Fig.4. Variation of heating demand and PCM effectiveness in Vancouver

The case of Vancouver shows an improvement in cooling demand of more than 50%. This greater improvement is mainly due to milder temperatures in summer, the little excess of heat can then be absorbed by the PCM without overfilling its heat capacity. As well as in Toronto the use of PCM in winter did not perform as efficiently as in summer with just a little improvement in the S(G)E room of about 6% (Fig.4).

4.2. Thermal Comfort

To confirm the effectiveness of the PCM a simulation in free floating mode in summer was performed. It is reported the case of Toronto and Vancouver with the application of BioPCM M182Q25 and BioPCM M51Q25 on the floor and the opaque surfaces vs. typical case scenario. The case study of Toronto showed a temperature distribution below the comfort threshold of 28ºC for almost the totality of occupied hours in summer, with just three hours above it in the S(G)E room (Table 3). For the majority of the time, the temperature range falls between 22 and 25ºC without the activation of cooling. In the other rooms, the operative temperature is more often detected at or above the value of 28ºC. The temperature distribution with BioPCM M51Q25 accounts for a larger discomfort time with 218 hours of temperature higher than 28ºC.

Table 3.Hours at or above 28ºC – Toronto S(G)E oriented room.

	N(G)-W	N – E(G)	S(G) – E	S – W (G)
Baseline	557	436	376	434
BioPCM M51Q25	262	247	218	246
BioPCM M182Q25	238	129	3	121

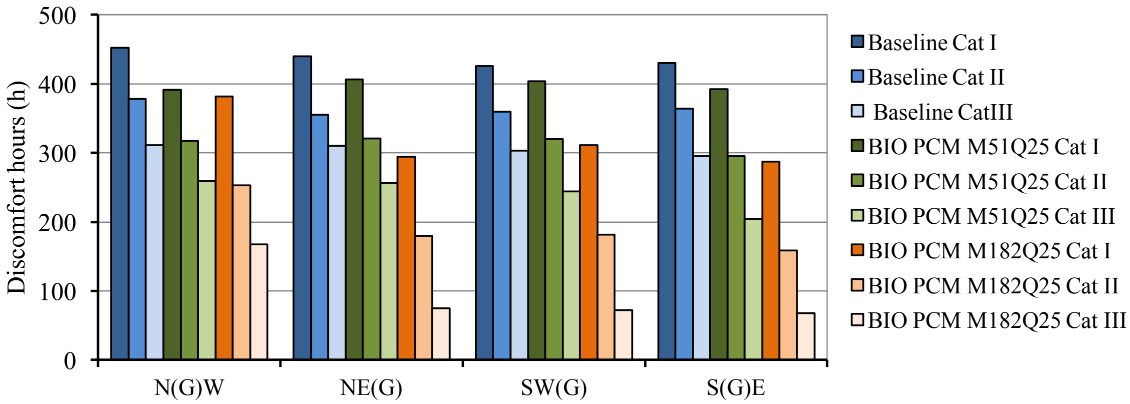

Fig. 5. CEN15251-Category I, II, III: Discomfort hours during occupancy time in the month of July – Toronto

Considering the adaptive comfort approach the threshold value is not constant in time but is a function of the daily mean outdoor temperature. The Standards CEN 15251 [26] are considered to estimate this value of threshold temperature and thus the hours of thermal discomfort for the month of July (hottest month) during occupied hours in the case study of Toronto (Fig.5). In the following chart each column represents the number of discomfort hours according to each category range; therefore a lower number of discomfort hours corresponds to a longer time when a condition of comfort is detected during occupied hours: the number of hours in Category I (23.5 ºC – 25.5ºC) will be higher than the one in Category II (23 ºC – 26 ºC) and the number of Category II will be higher than the one in Category III (22 ºC – 27 ºC).The results show a significant improvement in thermal comfort in every room. This is also verified when comparing the operative temperatures during the summer design week, 8-15 July (Fig.6).

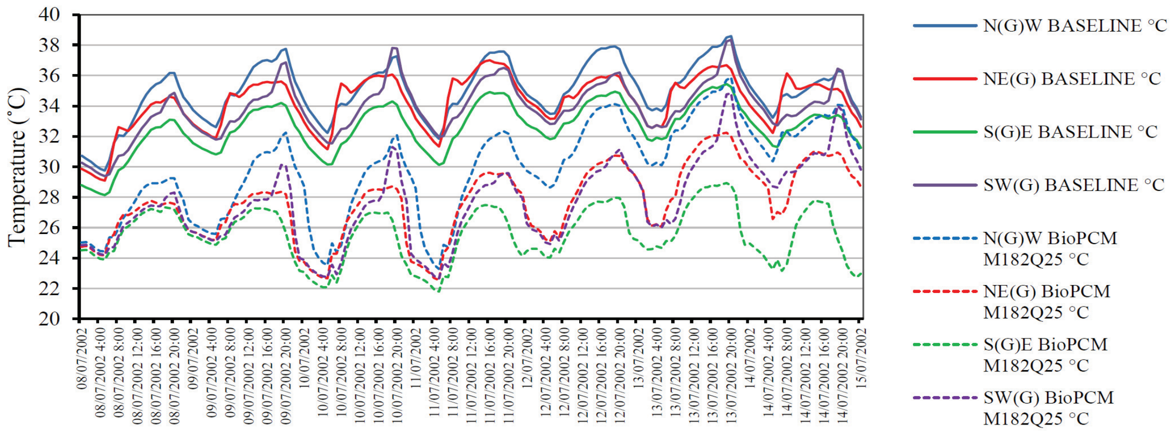

Fig. 6. Operative temperature distribution for the baseline case and the case with BioPCM M182Q25 in Toronto

The case study of Vancouver shows an acceptable level of comfort for the whole summer when the operative temperature is always recorded below 28ºC. The adaptive comfort analysis in the baseline case shows a number of hours between 406 and 391 outside the standards of CEN 15251 Category I and only 10 to 38 hours in Category II. Both in the case of BioPCM M51Q25 and M182Q25 there is a little improvement for the Category I. Some improvements are detected in Category II and III where the use of PCM could eliminate thermal discomfort in summer. However, the improvement in those latter two categories is not significant since the level of comfort is already high in the baseline case with only a few hours out of range.

4.3. Frequency of Activation

Useful information to evaluate the effectiveness of the PCM is the FA. This indicator is calculated as the percentage of time during a given period when the inside surface temperature falls inside the PCM melting point range. The temperature range considered is 24ºC< T <26ºC and the products studied are BioPCM M182Q25 and M51Q25 and the reference period is the month of July.

In Toronto typical case the BioPCM M182Q25 on the exterior wall of the S(G)E room is active for 56.5% of time; for 26.5%the PCM is in solid state whereas for the 17% is found in liquid state. On the partitions, the activation time is for each partition around 43%. On the floor surface, the frequency of activation is 63% and it is melted only for 5% of the time. In the case of the N(G)W room, a reduced frequency of activation is detected. This is consistent with the higher level of cooling demand and discomfort hours. The FA on the inside surface of the exterior wall is 38% and it is melted for 58% of the reference period. On the floor surface, the FA is 49% against a 46% of melted state (Fig.7).

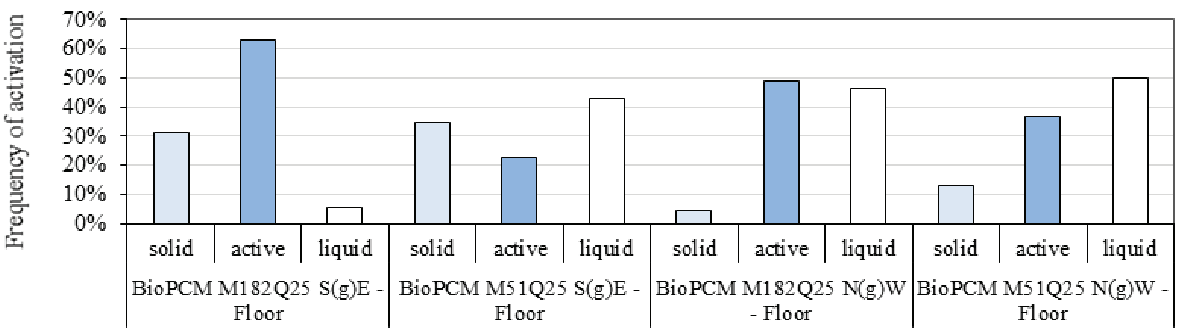

Fig. 7. Frequency of activation of the PCM systems in Toronto.

The BioPCM M51Q25 showed less activation time compared to the M182Q25. The temperature range on the inside surface of the exterior wall of the S(G)E room falls inside the phase change range for the 30% of the time. On the floor surface, the FA is 23%, 42.5% is melted and 34.5% is solid. The same decrease in performance is detected on the partitions where the activation time accounts for 24%, for 27% it is solid and for 47% is melted. The FA on the N(G)W room is also reduced, with 32% of activation time on the wall and 37% on the floor. The FA in the N(G)W is higher in the S(G)E oriented room, however, the time when the PCM is melted accounts for the 57% of the total, which causes a higher probability of discomfort even if the PCM has an higher frequency of activation.

In the case study of Vancouver - typical case the FA of BioPCM M182Q25 is 1.4% on the floor and 14% on the exterior wall of the S(G)E room. In the N(G)W room the FA is 30% on the floor and 43% on the exterior wall. The PCM is almost never in the melted state. This fact is consistent with the low values of cooling demand: The increase of room temperature is hence completely absorbed by the PCM. The results for M51Q25 are almost the same of M182Q25 with little improvements over the S(G)E room: FA is 1.4% on the floor surface and 14% on the exterior wall of the N(G)W room.

5. Discussion and Conclusions

This study showed satisfactory results testing different construction assemblies with the application of PCM systems. The improvements in terms of decrease in energy demand were mainly in summer, proving what was found in literature. However, the majority of papers show smaller benefits than the current one. The main two reasons for a so high performance (29% for Toronto and 59% Vancouver) are the chosen location and the overall design criterion of the rooms. It is important to remark that the simulation model is considered as a system of compounds where passive strategies play an important role together with the PCM. Energy simulations were carried out over a model that has a good behaviour in terms of passive design and a generic shading system was applied on the window surface. The importance of combining different passive strategy with the application of PCM is evident if each room is considered separately and then compared to each other. The N(G)W room in every configuration shows the worst results whereas the S(G)E room, with a more appropriate passive design, always showed the best results. In this room, thermal gains and losses are controlled and the further application of PCM is more effective. The case of the N(G)W is worth to be explained. The relatively higher energy demand for cooling comes from the absence of any solar shading, therefore the 85% of the north surface is exposed to the sky dome (diffused and reflected) radiation, whereas the consistent solar protection of the other rooms reduces the visible exposed area and screen solar radiation. Solar gains in the north façade are in the south façade given the proper solar shading is in use.

The climate conditions play an important role in the charge and discharge cycle. The difference of temperature along 24 hours is large enough to guarantee a correct operation of the PCM which can be fully discharged during the night and thus exploited during the day; however, summer in Toronto is characterized by considerably hot days which cause a relatively high need for cooling. In these days, the PCM is likely to be found in melted state for a high percentage of time and it is not effective. Sometimes it is also possible that the PCM in the floor assembly reduces the heat flux towards the layer of concrete underneath, decreasing the thermal inertia of the component.

The best contribution of PCM is given when climate conditions and outside temperatures are moderate. The combination of PCMs with different melting points could help encompass a wider range of temperatures, such as spring and summer or even winter and summer. The main obstacle to this will be the decrease of the total thermal conductivity of the assembly. An ideal PCM with high level of conductivity could avoid this problem. Another technical solution to that problem would be overlapping the two sheets in a way that the cells will not lay over each other. The impact over comfort is relevant for the scenario of Toronto, the values reported for Category II and III show good potentials for the BioPCM and the curve of operative temperature show a gap of about 5ºC between BioPCM M182Q25 and the baseline case. In this case, it is also shown that a higher heat capacity brings about better results. In Vancouver, the level of comfort in summer could be almost completely ensured with a good passive design without the use of PCMs, as shown in the baseline case analysis. The application of a BioPCM M51 or products with lower heath capacity could be enough to eliminate the cooling demand.

The frequency of activation showed consistent results with the other parameters of comfort and cooling demand. Sometimes higher values of activation time were not directly related to an improvement of comfort due to the overall environmental condition and the predominance of the melted state of the PCM.

Simulation results showed a better efficiency using a higher level of heat capacity like M182. This aspect deserves to be studied and could be mainly due to its increase of cost which would exceed correspondent energy savings.

In conclusion, the application of PCM in building construction has shown in many previous studies, as well as in this paper, its high proficiency. However, the material is really sensible to each climate variation and internal gains profile and it is not recommended take general assumptions. Any practical case must be studied and simulated in order to evaluate the opportunity to use PCMs and its real efficiency in terms of cost and energy performance.

6. Acknowledgements

The authors gratefully acknowledge the financial support of the ISSNAF Foundation and the CNI for supporting the research period of the second author to the Ryerson University. The support of the Homeowner Protection Office of BC Housing is also acknowledged as part of the Building Excellence Research and Education Grants Program.

References

[1] Fourth Assessment Report of the Intergovernmental Panel on Climate Change, www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html
[2] Berardi U. Sustainability assessment in the construction sector: rating systems and rated buildings, Sustain Dev 2012,20(6):411-424.
[3] Berardi U. A cross country comparison of building energy consumption and their trends. Resour Conserv Recy 2016, doi: 10.1016/j.resconrec.2016.03.014
[4] 2050 Energy strategy.https://ec.europa.eu/energy/en/topics/energy-strategy/2050-energy-strategy
[5] Naraid J, Masoud G, Berardi U, El-Korchi T, Van Dessel S. Design and application of concrete tiles enhanced with microencapsulated phase-change material. J Architec Eng 2016,22(1):05015003.
[6] Papachristou AC, Athienitis AK. The importance of thermal mass in predictive control case study: a zone with floor heating and a chilled beam. Proceedings of the eSim Buildings Performance Simulations Conference 2016.
[7] Berardi U, Anaraki H. The benefits of light shelves over the useful daylight illuminance in office buildings. Indoor Built Environ 2016, doi: 10.1177/1420326X16673413.
[8] Akeiber H, Nejat P, Abd Majid, Wahid MA, Jomehzadeh F, Famileh IZ, Calautit JK, Hughes B, Zakiet S. A review on phase change material (PCM) for sustainable passive cooling in building envelopes. Renew Sust Energ Rev 2016,60:1470–1497.
[9] Sadineni SB, Madala S, Boehm RF. Passive building energy savings: a review of building envelope components. Renew Sust Energ Rev 2011;15:3617–3631.
[10] Konukulu Y. Review on using microencapsulated phase change materials (PCM) in building applications. Energ Building 2015;106:134–155.
[11] Evola G, Marletta L, Sicurella F. A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings. Build Environ 2013;59:517–27.
[12] Ascione F, Bianco N, De Masi R, de Rossi F. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. Appl Energ 2014;113:990–1007.
[13] Pasupathy A, Velraj R. Effect of double layer phase change material in building roof for year round thermal management. Energ Building 2008;40:193–203.
[14] Kuznik F, Virgone J, Noel J. Optimization of a phase change material wallboard for building use. Appl Therm Eng 2008;28:1291-1298.
[15] Zhou D, Zhao CY, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Appl Energ 2012;92:593–605.
[16] Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Build Environ 2007;42:2197–2209.
[17] Kuznik F, David D, Johannes K, Roux JJ. A review on phase change materials integrated in building walls. Renew Sust Energ Rev 2011;15(1):379-391.
[18] Feustel HE, Stetiu C. Thermal Performance of Phase Change Wallboard for Residential Cooling Application. Ernest Orlando Lawrence Berkeley National Laboratory.
[19] Kuznik F, Virgone J, Roux J. Energetic efficiency of room wall containing PCM wallboard: a full-scale experimental investigation. Energ Building 2008;40(2):148-156.
[20] Schossig P, Henning HM, Gschwander S. Micro-encapsulated phase-change materials integrated into construction materials. Sol Energ Mat Sol C 2005;89:297-306.
[21] Castell A, Farid MM. Experimental validation of a methodology to assess PCM effectiveness in cooling building envelopes passively. Energ Building 2014;81:59-71.
[22] Design Builder Software Ltd. Design Builder v4. Template: Canadian Energy Code.
[23] Phase change energy solutions. http://www.phasechange.com
[24] UK National Calculation Method for Residential Buildingshttp://www.uk-ncm.org.uk/
[25] Wilkins C, Hosni MH. Heat Gain from Office Equipment. ASHRAE Journal. June 2000.
[26] EN Standard 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2007.