REDUCING THE ENERGY CONSUMPTION BY USING FLOOR HEATING WITH PHASE CHANGE MATERIALS IN THE TORONTO CLIMATE

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Bachelor of Interior Design, 2012, RCC Institute of Technology

A Major Research Project

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Building Science

in the Program of

Building Science

Toronto, Ontario, Canada, 2017

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Reducing the Energy Consumption by Using Radiant Floor Heating with Phase Change Materials in the Toronto Climate

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Abstract

This major research project focuses on reducing the energy consumption, by modelling a radiant floor heating system with phase change materials, in the Toronto climate.

Computer generated simulations were performed using DesignBuilder software, using an example of a typical condominium in Toronto .Two south facing suites and two north facing suites were investigated. Of those suites, one north facing suite had PCM below the finished floor, as well as one south facing suite. The objective of these simulations was to determine the impact of using PCM in the condo suites. Three different types of PCM were used, in order to determine which type had the biggest energy savings. The PCMs were M91/Q21, M51/Q21 and M27/Q21. The final results showed that the suites with the M27/Q21 PCM had the lowest energy usage. A cost savings comparison was performed based on the rate of energy used and the cost of the energy, provided by the Ontario Energy Board.

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1.0 Introduction

Reducing the amount of energy we use is becoming a very popular topic around the world. Some of the advantages to reducing energy are the reduction in monthly energy bills, as well as benefitting the environment. A material that is becoming very popular in the energy sector is phase change materials (PCM). Phase change materials have the ability to store energy and then release it back into the surrounding environment. One of the benefits of using phase change materials is having the ability to switch HVAC operating times from on-peak to off-peak hours. The PCMs retain energy while the HVAC system is turned on, and then release the energy back into the space when the system is not running. This can greatly reduce the heating and cooling costs.

Incorporating PCMs into the floor, sandwiched between the concrete slab and the finished flooring, is one of the ways to incorporate the energy savings into a residential application, particularly in high rise buildings. The source of the heating and cooling will be provided by a radiant flooring system. By providing heating and cooling from the floor, the entire space will have evenly dispersed air. This will allow the phase change materials to absorb energy at a fairly fast pace, reducing the amount of time the HVAC system needs to be working.

Simulations will be conducted using a typical Toronto condominium, in order to create a theoretical model that can eventually be integrated into high rise buildings. These simulations will compare north and south facing suites, in order to determine the impact of using phase change materials based on the orientation of the suites. The results of these studies will show how the phase change materials are reducing the energy consumption, when comparing south facing suites and north facing suites. Three different types of PCM will be investigated, in order to determine the best choice in the studied application. The PCMs that will be investigated are M91/Q21, M51/Q21 and M27/Q21. The enthalpies of the PCMs will be discussed further in this research. The PCMs all have the same melting temperature, but differ in Btu's per square foot. A cost comparison will also be performed, in order to achieve a better sense of how the PCM are reducing energy, based on a conceptual cost model.

2.0 Research Question

The research question for the Major Research Project is:

1) How much energy will be saved when using PCM in a typical Toronto condominium, from a theoretical perspective?

The research question was developed over a period of several months. The goal was to use a study that was already conducted in a warm climate, and see if it would perform in a cold climate. The question was developed in order to achieve an understanding of how a typical condominium in Toronto would perform when using Phase Change Materials combined with a radiant flooring system, as a means to reduce energy consumption.

3.0 Literature Review

3.1 Introduction

The use of phase change materials in building components can facilitate in increasing energy savings. Phase change materials use basic physics to absorb and release energy when matter is changing from one state to another, providing thermal storage. This allows the use of forced heating and cooling systems to be reduced. In this literature review, the topics of phase change materials, concrete flooring and radiant floor heating will be reviewed. All of this information helps to get a better understanding of the individual components that make up the system being investigated later on in this paper. The main goal of this research is to compare the energy savings when using PCM versus not using PCM.

3.2 Phase Change Materials

Phase change materials (PCMs) are materials that go through the solid to liquid phase transformation, providing thermal storage in the process. This process is also known as the melting to solidification cycle, which occurs at a temperature within the operating range of a selected thermal application (Fleischer, 2015). While remaining at a constant or nearly constant temperature, the material starts to change from a solid to a liquid, absorbing energy from its surroundings. Energy which is absorbed by the material acts to increase the energy of the component atoms or molecules, ultimately increasing their vibrational state. At the melting temperature, the atomic bonds become loose, and the material begins the transition from its solid phase, to a liquid phase. Solidification is the reverse of this process, at which time the materials transfer energy to the surroundings. The molecules loose energy, and start to transition back into their solid phase (Fleischer, 2015).

There are two main types of Phase Change Materials, microencapsulation and macroencapsulation. The concept of microencapsulation is a whole other topic in itself. For the purpose of this research, microencapsulation was chosen as the material, as it is the most effective way to keep PCMs from leaking into the surrounding environment. Microencapsulation is a process in which small, rod-shaped or spherical particles are enclosed within a thin, high molecular weight polymeric film. The development of this product involves emulsification, which is followed by the formation of membranes around each droplet by interfacial polymerization (Hawes, Banu & Feldman, 1990). The purpose of the film is to prevent PCM from leakage during their phase change process. Microencapsulated PCMs can help in reducing the overall energy consumption, which helps to maintain a comfortable indoor temperature. The PCMs are able to maintain this indoor comfort due to their ability to store and release both sensible and latent heat (Entrop, Brouwers & Reinders, 2011). Latent heat storage is one of the most efficient ways of storing thermal energy. Contrary to the sensible heat storage method, latent heat storage provides a much higher storage density, with a smaller temperature difference between the storing and releasing of heat process (Zhao & Zhang, 2011). Latent heat storage has a high energy density, resulting in a small material mass and smaller storage capacity (Fleischer, 2015). As stated in a journal article by Mishra, Shukla & Sharma (2015), the desired properties for PCMs are:

- The melting point should be in the desired temperature range. For example, if we want to incorporate PCM in building materials, then the melting point of the PCM should be around the required room temperature
- High latent heat of fusion per unit volume to store more energy in a given volume
- High thermal conductivity to aid in the charging and discharging of energy
- Low changes in volume during phase change and low vapour pressure to avoid containment problems
- Non-flammable and non-toxic
- Chemically stable
- Low cost and low containment cost

Microencapsulated techniques provide opportunities to create advanced PCMs with an area of greater heat transfer. There are also opportunities to create reduced reactivity with the outside environment as well as controlling volume changes during the phase transition (Pielichowska & Pielichowska, 2014). PCMs are a material that can be beneficial when used in accordance with building materials. They perform in both summer and winter applications. In the summer time, during the day, hot air from the outside heats up and melts the PCM, as it passes through the building. The heat that is extracted from the air is stored in the PCM as latent heat. This causes the air temperature to decrease, resulting in an optimum room temperature. During the night, when the air conditioning system is being run, the cold air will refreeze the PCM (Mishra, Shukla & Sharma, 2015). In the winter time, during the day, warm air provided by the HVAC system heats up and melts the PCM. The heat that is extracted from the HVAC system is stored in the PCM as latent heat. The advantage to this is that the HVAC system can be turned off when there are no occupants and the PCM will continue to provide warm air into the surrounding environment. PCMs help to reduce the amount of energy consumption and one of those ways is when they are incorporated into the flooring of the building. The next section will discuss the combination of phase change materials and concrete floors.

3.3 Phase Change Materials and Concrete Floors

A building integrated with microencapsulated PCMs has the potential to shift a portion of the load provided by residential air conditioners and heaters, from on-peak to off-peak time periods. This would result in a decrease of power utilities, ultimately reflecting in less expensive energy bills to customers (Khudhair & Farid, 2003). There has been a significant amount of research done on combining phase change materials with concrete. The most common research done involves the incorporation of microencapsulated PCMs into concrete, by way of direct mixing. This process of incorporating the PCM into the concrete occurs during the concrete mixing stage. The shell hardness of the PCM microcapsules must be indestructible and sustainable in order to avoid any damage occurring during the mixing and casting process (Ling & Poon, 2013).

A study was conducted by Ling & Poon (2013) in order to examine the effect of directly mixing microencapsulated PCMs on the fresh properties of self-compacting concrete. This was done by testing the sump flow, V-funnel time and J-ring properties. The results indicated that it is achievable to create good self-compacting properties using microencapsulated PCMs. The study also showed that the flow diameters of all the PCM self-compacting concrete mixtures were similar, when they were compared to the plain self-compacting concrete mixture, by only adjusting the water content and the dosage of superplasticizer (Ling & Poon, 2013). The results also found that the self-compacting concrete mixture with 3% and 5% microencapsulated PCM content displayed slightly higher viscosity, which was a result of the water content. Results from the study found that the heat storage capacity of concrete significantly increases when PCM is applied. The effectiveness of the concrete with the PCM is also dependant on the type of PCM being used, as well as the incorporation methods which are used during the production of the PCM concrete (Ling & Poon, 2013).

Based on the provided research by Ling & Poon and Khudhair & Farid, it is evident that incorporating PCMs into concrete increases the concretes heat storage capacity. This is beneficial as the combination of the PCMs with the concrete will create an efficient energy saving system. The disadvantage of this method is the inability to incorporate it into existing construction. Another option for using the PCM combined with concrete is the use of microencapsulated PCM as an “energy blanket”. This application is used when the

PCM is installed directly on top of the concrete slab, in a continuous sheet application, below the finished floor. The advantage to this application is that it can be used in both new and existing buildings. Currently, this type of product is used on walls and ceilings, but for the purpose of this research, it will be assumed to have similar effects as the previously discussed results of the PCM embedded into the concrete. An alternative to conventional HVAC systems is the use of radiant floor heating and cooling. The advantage to this system is that it is heating or cooling the floor surface directly, instead of the air in the enclosed environment. The next section will discuss the radiant system, as well as its benefits.

3.4 Radiant Floor Heating

The concept of radiant floor heating has been around for several thousand years (Jeon, Seo, Jeong & Kim). In the early stages, the radiant system was used for heating purposes, where hot air from cooking and fires was circulated beneath the floors (Kim & Olesen, 2015). Radiant heating can be made up of small pipes, ranging in size from 3/8" to 3/4", which can be embedded in concrete floors (Fontana, 2010). In the winter, hot water flows through the pipes, creating an even distribution of warm surfaces. In the summer, cold water flows through the pipes, creating an even distribution of cool surfaces. According to Kim & Olesen (2015), there are a number of steps that are required when designing a radiant heating system. These steps are as follows:

1) Based on operative temperature, calculate the design heating and sensible cooling loads which follow the standard for heating and cooling load calculations.
2) Determine the minimum required supply air quantity that is needed for ventilation and dehumidification.
3) Determine the total surface area of the radiant system, excluding areas that will be covered by any immovable or fixed objects. The areas containing immovable or fixed objects will not be included in the surface area.
4) Determine a maximum acceptable surface temperature and a minimum acceptable surface temperature, taking into account the dew point.
5) Determine the design heat flux, including the design heat flux of the surrounding areas, as well as the heat flux of the occupied areas.
6) Determine the pipe spacing and covering type, and design the heating and cooling temperatures based on the maximum design heat flux and the maximum and minimum surface temperatures.
7) Determine the thermal resistance of the insulating layer and design the heating/cooling flow rate.

8) Estimate the total length of the radiant circuit. This value is based on the surface area as well as the pipe diameter.

Radiant heating is defined as a system that has at least 50% of its heat transfer coming from radiation (Kim & Olesen, 2015). One of the main benefits to using this system is the reduction of operating costs, compared to a conventional HVAC system. The radiant system does not use any ducts, which eliminate the leaking of conditioned air, as well as decreases the amount of allergens in the air (Kim & Olesen, 2015). In the winter, the radiant system is being supplied water from a boiler and fed through the system by a pump. In the summer, the chiller is producing the cold water, which is being fed into the radiant system. The next section will discuss a previously conducted study, which incorporates phase change materials with radiant floor heating.

3.5 Modelling a Radiant Floor System with Phase Change Materials

A journal article titled "Modelling a radiant floor system with Phase Change Material (PCM) integrated into a building simulation tool: Analysis of a case study of a floor heating system coupled to a heat pump", was published in 2011 by Mazo, Delgado, Marin and Zalba. This journal article, based in Cordoba, Spain, was the original data that this research paper was initially based on. The reason being, that this study was successful in another climate. The original research question of this paper was trying to understand if this same study would be beneficial in the Toronto climate. This journal article describes a model that was developed in order to simulate a simple building, consisting of a small footprint with four walls, a roof and a floor, with a PCM radiant floor system. The PCM floor heating system is operated by a heat pump, which operates mostly at night time, in order to reduce the energy consumption costs. Heat transfer through the building envelope was calculated using a one-dimensional computer simulated model and the zone calculation model used a single node in order to determine the indoor air temperature (Mazo, Delgado, Marin & Zalba, 2011).

Test cubicles were used for this experimental data, and are located in Córdoba, Spain. The dimensions of the cubicle, as seen in figure 1, were 5.87 m (depth) X 2.38 m (width) X 2.31 m (height). There was a 1.33 m X 0.89 m single glazed window, oriented to the north (Mazo, Delgado, Marin & Zalba, 2011).

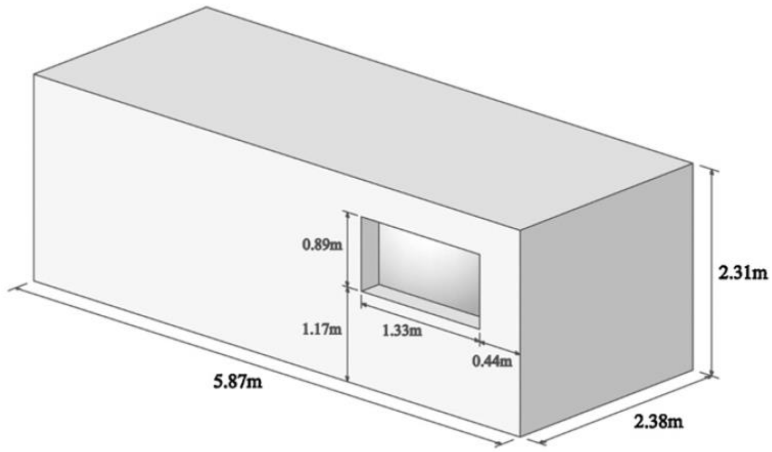

Figure 1: Experimental Cubicle (Mazo, Delgado, Marin and Zalba, 2011)

According to the Köppen Climate Classification, Córdoba is classified as a hot Mediterranean subtropical climate that is generally mild, with moderate seasonality. The summers are dry and hot, which is a result of the subtropical high pressure systems. The winters tend to have moderate temperatures with rainy weather, due to the polar front (Mazo, Delgado, Marin & Zalba, 2011). Although this climate differs significantly from the Toronto climate, the study works well for these conditions.

In the experimental model, the PCM is embedded into the concrete slab material, integrating it into the radiant floor. The simulated PCM is a granulated compound material, with its phase change temperature near 27^{o}C (Mazo, Delgado, Marin & Zalba, 2011). In order to achieve the total shift of heating energy demand from peak hours to off-peak hours, the amount of PCM in the floor has been adjusted to a 20% proportion in the mortar-PCM composite. The heat pump supplies water at a constant fixed temperature of 33^{o}C. This temperature allows the heating demand to be met, reducing the systems on-off control system. The interior air has a set point temperature of 21^{o}C. Data from the Spanish Legislation was used to determine the energy data. According to this study, the off-peak demand time is from 10:00pm to 12:00pm (Mazo, Delgado, Marin & Zalba, 2011).

In order to generate results, two different studies were conducted and compared in this journal article, one with PCM and a radiant floor system and another with a conventional radiant floor heating system. The results and performance of the system were categorized by the fluctuation of the interior air temperature and the energy consumption of the heat pump.

In order to obtain average values of performance and the cost of the energy savings, simulations of both cubicles were carried out over an entire winter period. The simulation period was selected based on the heating energy demand, which starts November 1st and goes until February 28th. The results are shown in Table 1.

	With PCM	Without PCM
Mean Daily Energy Consumption	2.62 (kWh)/cubicle	2.60 (kWh)/cubicle
Daily Operating Time	7.5h/day	7.7h/day
Daily Operating Time in Peak Period	0.3h/day	1.4h/day
Mean Daily Costs	0.17€ or $0.25/day	0.21€ or $0.31/day
Cost Savings	**17.9%**	-

Table 1: Results of the Simulations (Mazo, Delgado, Marin abd Zalba, 2011).

Both systems were able to meet each cubicle's heating requirement, with the indoor air temperature being 20-25^{o}C most of the time. Looking at the results of the simulations, some conclusions can be obtained. The energy consumption in both cubicles is relatively the same. The energy cost savings are solely due to the displacement of the off-peak electricity demand period.

4.0 Methodology

The main objective of this major research project was to determine the energy usage from a radiant floor heating system with phase change materials. This study was already conducted in Cordoba, Spain. The simulations and results are discussed in the literature review section of this report.

Using DesignBuilder as the simulation software, data was inputted and then collected for the Toronto climate Zone. Results of the temperatures, heat gains, zone sensible heating and energy outputs were gathered. These results are all discussed in detail in the rest of this paper.

Multiple simulations were performed, using different types of Phase Change Materials. These studies were designed to replicate units in what has become the typical Toronto condominium. The studies compared north and south facing suite to each other, using three different types of PCMs, in order to achieve an understanding of the impact the PCMs are having in the Toronto climate. The studies are compared in order to determine which type of PCM has the greatest impact on the reduction of energy. Cost comparisons were performed for each PCM type in order to indicate not only the most energy efficient type, but also the most cost effective. Figure 2 shows the hierarchy of work completed for this research paper.

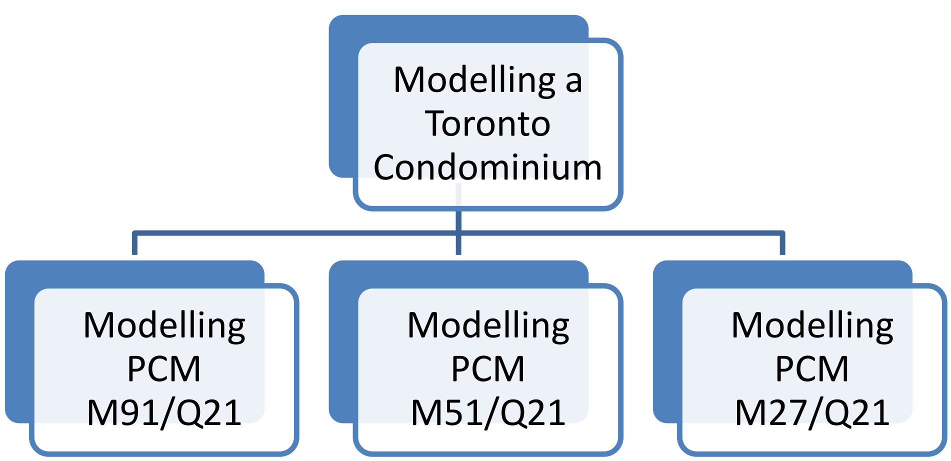

Figure 2: Methodology Hierarchy

5.0 Energy Modelling of a Typical Toronto Condominium

5.1 Narrative

The goal of this research was to study the effect of Phase Change Materials in the Toronto climate. A model of what is considered to be a typical Toronto condominium was created in order to generate simulation results. Radiant flooring was chosen as the type of heating and cooling systems. The idea for using this system was that it would work well with the large amount of concrete in the condominium building. Concrete is a very porous material and can help with absorbing excess heating and cooling, which is known as thermal mass. The idea of having the PCM's in the concrete, in addition to the concrete acting as thermal mass, formed the reasoning for using this type of system. The radiant flooring system was chosen as a way to directly activate both the PCM's and the thermal mass directly from the floor slab. Another benefit to using this type of system is solar gain. Solar gain occurs as a result of the sun infiltration into the space. The large window to wall ratio will help to increase the sun infiltration. The solar gain will provide heating energy to the space while the radiant flooring is providing energy to the flooring at the same time. These two elements will help to provide the PCM with energy, as seen below in figure 3.

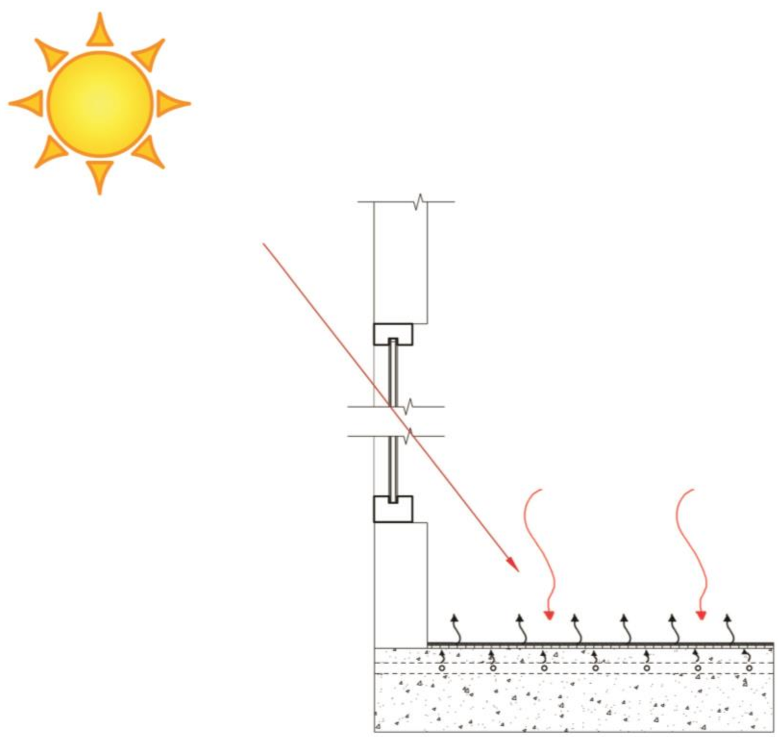

Figure 3: Solar Gain Diagram

The diagram shows how the energy in the entire system travels. Energy from the sun is being infiltrated into the space through the large windows. Some of that energy is directly heating the space, while the rest of the energy is being stored in the concrete as thermal mass. At the same time, the radiant system is providing energy to the space. The energy first goes to the PCM, and then from the PCM into the space. Using radiant floor heating and cooling systems on its own will take some more time to activate the PCM initially. The added solar gain will help to speed up the process of activating the PCM, ultimately improving the overall performance of this system as a whole.

5.2 Selection of Details

This model is a concept condominium, similar to what has become the new Toronto building normal. New, high-rise condominium towers are popping up all over the city. They typically consist of small units, with floor to ceiling windows and concrete construction. This is a theoretical model whose intention is to simulate the effects of PCMs in the Toronto climate. It should be noted that since this building was simulated without any buildings around it, the results would not be typical in reality. Other buildings modelled around would create different results, such as a decrease in solar gain due to shadows, as well as wind loads. The model was set for residential spaces, with an occupancy density of 0.0200 (people/m^2). A conceptual model of this condo tower is seen below in figure 4. The suites range in sizes from 60m^2 to 85m^2.

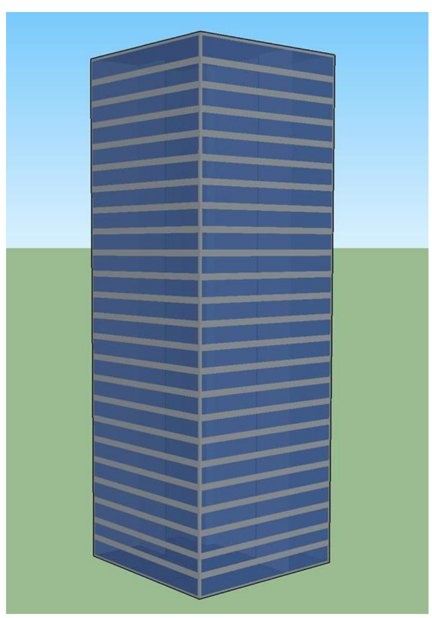

Figure 4: The Condominium Tower

The parameters set for the model are outlined in table 2.

HVAC Operating Times	7am-10am and 4pm-11pm Monday-Friday; 7am-11pm Saturday and Sunday
Heating System	Electricity from the grid to power the heat pump
Heating COP	4
Cooling System	Electricity from the grid to power the chiller
Cooling COP	3

Table 2: Model Parameters (DesignBuilder)

Figure 5 shows an example of the floor plans for this building. As this is a theoretical model, the plans were used to represent the size of the units, as well as the orientation. The two suites that are shaded are the north and south facing suites that were modelled in this section of the report. The north and south facing suites were chosen to be modelled for this paper, as they are the most effected by the orientation. The north facing suite is exposed to the least amount of sunlight, whereas the south facing suite is exposed to the most amount of sunlight. Sunlight plays a large role in energy consumption of buildings. Modelling the north and south allowed the results to show a more extreme comparison of how the PCM work in this type of environment.

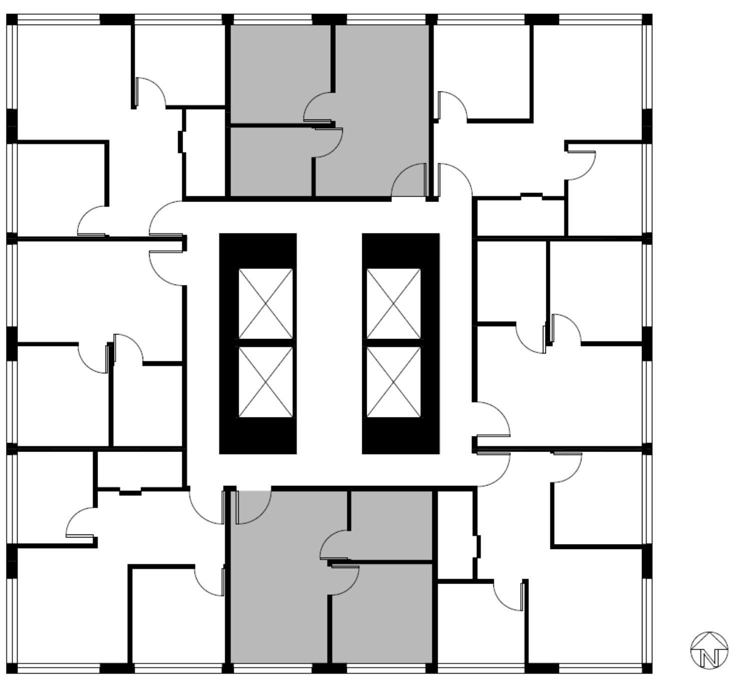

Figure 5: Floor Plan of the Condominium Tower

The weather data was selected from the EnergyPlus program, using DesignBuilder. The location was set to Toronto, Ontario. Table 3 shows the details of the weather data file. The chart shows the start month and the end month of both summer and winter, as well as the start of the extreme hot weather week and the extreme cold weather week. These are the weeks that are assumed to be the coldest and warmest of the year. These dates were used for the simulations, to get a sense of how the PCMs are working in the most extreme situations.

Latitude (°)	43.67
Longitude (°)	-79.63
ASHRAE Climate Zone	6A
Start of Summer Month	July
End of Summer Month	September
Extreme Hot Week, Starting	July 8
Typical Hot Week, Starting	August 19
Start of Winter Month	January
End of Winter Month	March
Extreme Cold Week, Starting	January 1
Typical Cold Week, Starting	February 12

Table 3: Weather File Data (DesignBuilder)

In order to generate an understanding of how the phase change materials are working in the model, four suites were chosen to collect data from. Two north facing parallel units, and two south facing parallel units were selected. One north suite and one south suite contained the PCM below the finished floor. Figure 6 shows the floor assembly for these suites with the PCM below the finished floors.

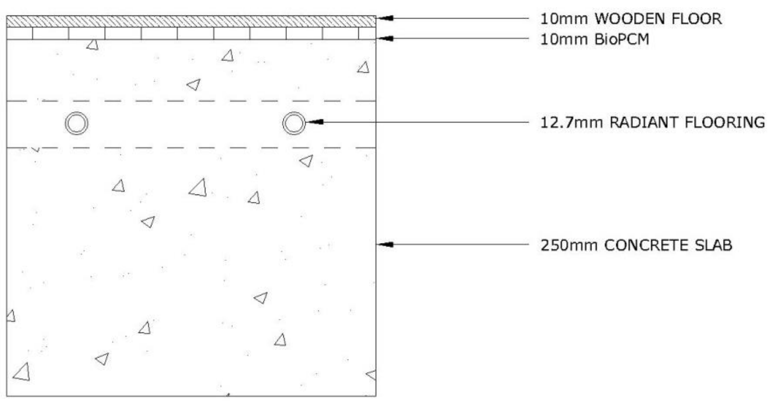

Figure 6: Floor Assembly with PCM

The remaining suites on the north and south side did not have any PCM in the floor assembly. These units only consisted of the finished floor above the concrete slab. Figure 7 shows the floor assembly for these suites.

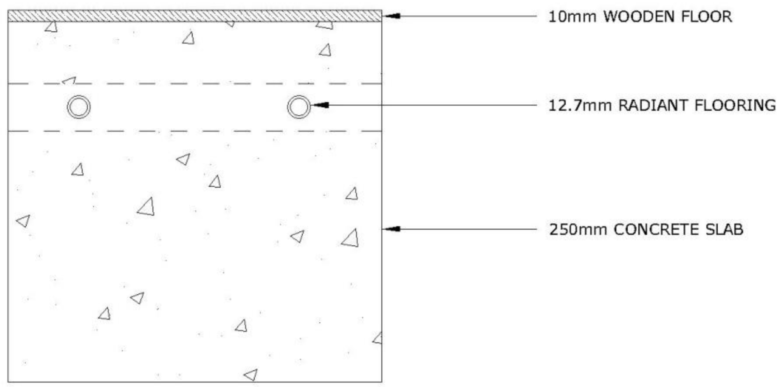

Figure 7: Floor Assembly without the PCM

The façade of the building envelope consists of a window-wall assembly, with a 65% window-to-wall ratio. In reality, an energy model would need to be created in order to allow such a high window-to-wall ratio. For the purpose of this study, it will be assumed that this ratio would be allowed by the Ontario Building Code. The reason for this would be to create a model that has a high window-to-wall ratio, in order to simulate an extreme example with an increase in solar gain. Figure 8 shows the overall exterior wall assembly.

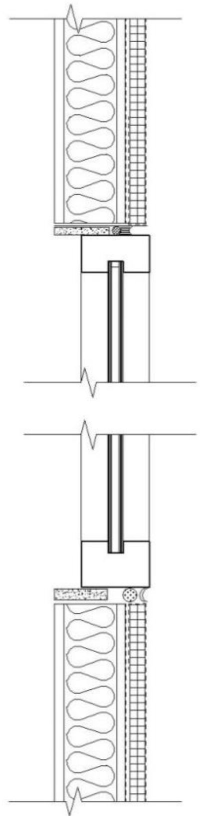

Figure 8: Building Envelope Assembly

The U-value of the windows is 0.98 (W/m^2-K). This relatively high U-value was chosen to assist the model. Since the window-to-wall ratio is so high, it was important that the windows had a greater resistance to heat flow, as well as good insulating properties. This allows the entire space to have a better overall performance. The reminder of the façade is an EIFS system, with an R-value of 17.3 (m^2*k/W). The wall assembly is shown in figure 9.

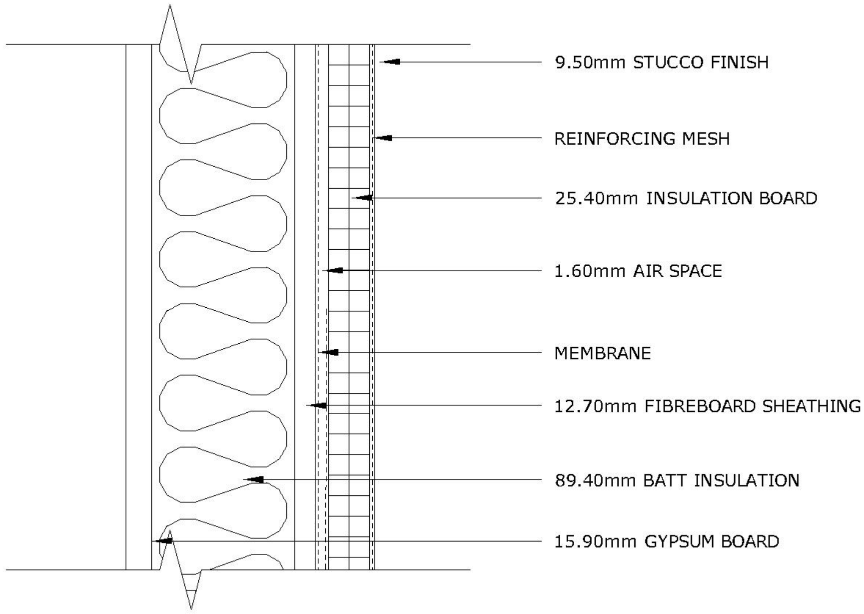

Figure 9: Exterior Wall Assembly

The material properties for the wall assembly are found in table 4 below.

Assembly	Thickness [t]	Conductivity [K]	Conductance [C]	Thermal Resistance [R]	Delta Temp.	Surface Temp.
	m	W/m*K	W/m^2*K	m^2*k/W	°C	°C
Interior Temperature						20
Interior Surface Coefficient			8.3	0.120	0.194	
						19.81
Gypsum Board	0.0095	7.75	12.500	0.080	0.129	
						19.68
Batt Insulation	0.0894	0.25	0.091	11.000	17.673	
						2.00
Sheathing	0.0127	6.25	12.500	0.080	0.129	
						1.88
Membrane	0.001	0	0.000	0.000	0.000	
						1.88
Air Space	0.0016	0.34	5.500	0.182	0.292	
						1.58
Insulation Board	0.0254	0.2	0.13	5.3	8.515	
						-6.93
Reinforcing Mesh	0.001	0	0	0	0.000	
						-6.93
Stucco	0.0095	0.72	1.96	0.51	0.819	
						-7.75
Exterior Surface Coefficient			34	0.03	0.047	
						-6.98
Exterior Temperature						-7
Total R (m^2*k/W)	17.302					
U Value (w/m^2*K)	0.057797749					
Heat Flow (w/m^2)	1.561					

Table 4: Material Properties

In order to create comparative results, three different types of PCM were chosen and modelled in the DesignBuilder simulation software. The three different types were M91/Q21, M51/Q21 and M27/Q21. The M-values represent the Btu thermal energy storage capacity of the PCM, per square foot. The Q-value represents the peak melting temperature of the product, in degrees Celsius. The melting temperature is the temperature at which the PCM become activated. The enthalpy of the PCMs change, based on their temperature. These enthalpy values are generated by the DesignBuilder software. Table 5 shows the enthalpy values and the corresponding temperatures.

Temperature (°C)	Enthalpy (J/Kg)
-20.00	1
0.00	12
10.00	25058
15.00	34799
20.00	38970
21.00	55119
21.50	80820
22.00	128509
22.50	201879
23.00	225581
24.00	231773
25.00	233328
30.00	240711
35.00	246859
45.00	254741
100.00	289545

Table 5: Enthalpy of PCMs (DesignBuilder)

The parameters for the HVAC system were set the exact same for all of the suites. The HVAC system was designed to turn on and off at specific times throughout the day. Although this wouldn't be the case in reality, the purpose was to see how the PCM were working when the HVAC system was turned off and only the PCM were providing heating and cooling to the space. Monday to Friday, the HVAC system was running from 7:00 am – 10:00 am and again from 4:00 pm – 11:00 pm. On Saturday and Sunday, the HVAC system was running from 7:00 am – 11:00 pm. The type of heating and cooling used was radiant. This consists of plastic tubing that is installed on the concrete slab. The water, both heated and cooled, is forced through this tubing, creating the warm or cold temperature in the space. A boiler, in each individual unit, was used as the main source for the hot water. Water was supplied to the radiant flooring system at a temperature of 35°C by means of a pump, in heating season. In the cooling season, water was supplied by the chiller at 12°C. These temperatures were suggested by the manufacturers of the radiant flooring. Using these settings, temperatures of the suites were gathered over the course of a full year of heating and cooling.

5.2.1 Simulations Using M91/Q21 Phase Change Materials

In order to achieve the results of the efficiency of the PCMs, simulations were carried out comparing the PCM suites to the suites without PCM, using M91/Q21 PCMs. Figure 10 shows the temperature difference in the two north suites that were investigated.

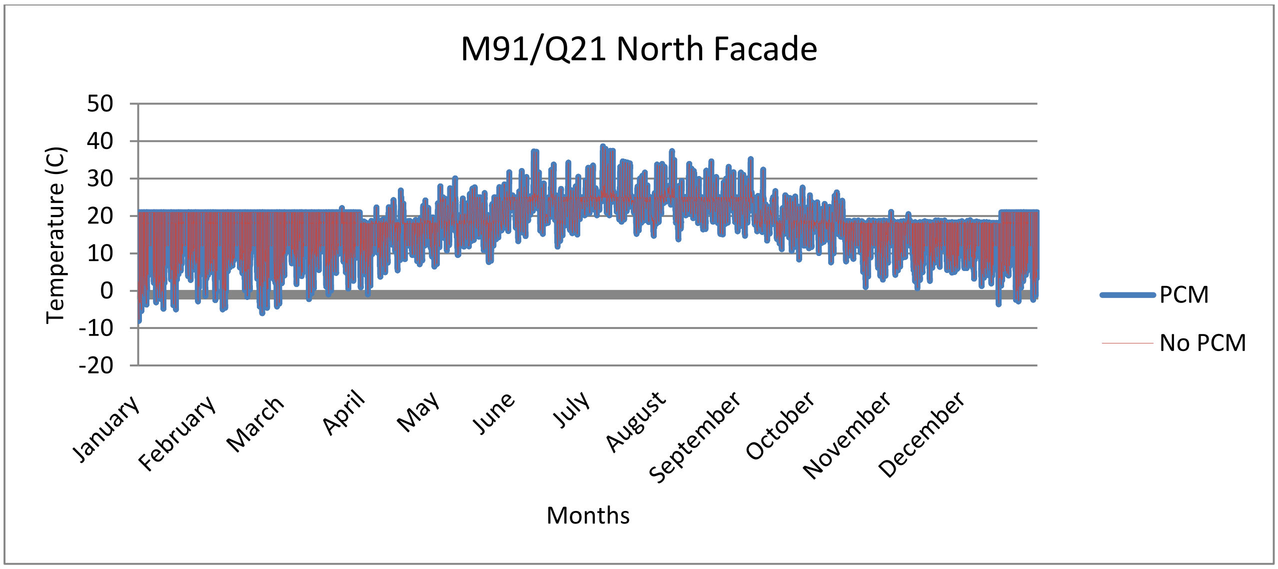

Figure 10: M91/Q21 North Façade Temperature Graph (DesignBuilder)

In order to generate the results of this chart, the simulations were run during the course of the year, with the HVAC turning on and off at its set times. Looking at this chart, the suite with the PCM is represented by the blue line and the suite without the PCM is represented by the red line. The temperatures appear to be very similar between the two suites. The main difference occurs when the HVAC system is turned off. These differences are hard to see, as this chart represents the temperature curve, over a period of one year. Figure 11 shows the temperature curve for one day in January.

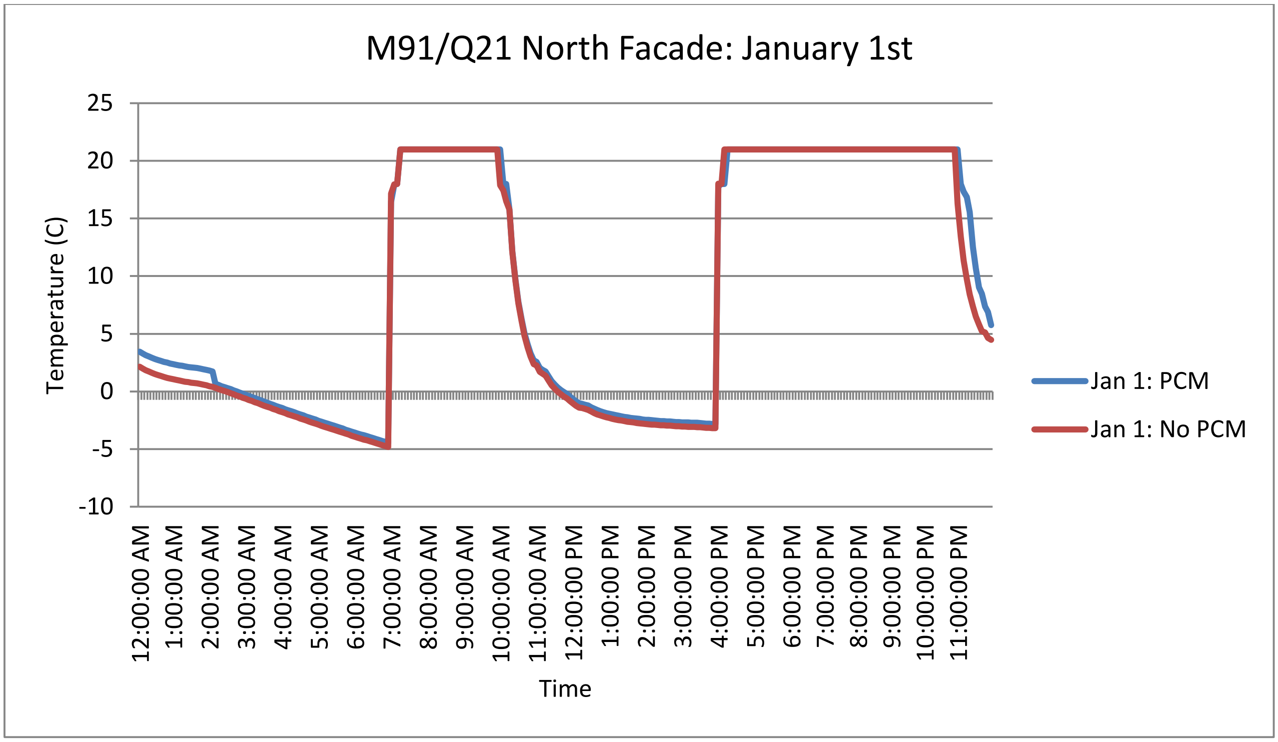

Figure 11: M91/Q21 North Façade- January 1st Temperature Graph (DesignBuilder)

The graph represents the indoor air temperature curve on a minute-by-minute timeline, for January 1st. This day was chosen to further investigate, as it is considered to be the beginning of the extreme cold week, according to DesignBuilder. In this graph, the temperatures of the PCM suite and the suite without PCM appear to be very similar most of the time. While the HVAC system is being run, the PCM are absorbing and storing heat. As soon as the HVAC system is turned off and the space begins to cool down, the PCM start to release their stored energy, heating the space. The main difference occurs between 12:00 AM and 2:00 AM. During these times, the suite with the PCM is warmer. After 2:00 AM, the temperature drops and stays just above the suite without PCM. Another time when the temperatures differ, occurs after 10:00 PM. This is when the HVAC system has been shut off. The temperature in the PCM suite drops at a slower rate than the other suite. The difference in these two suites is very minimal, meaning that the PCM does not have a great effect on the system, in this scenario. Figure 12 shows the temperature curve for one day in July.

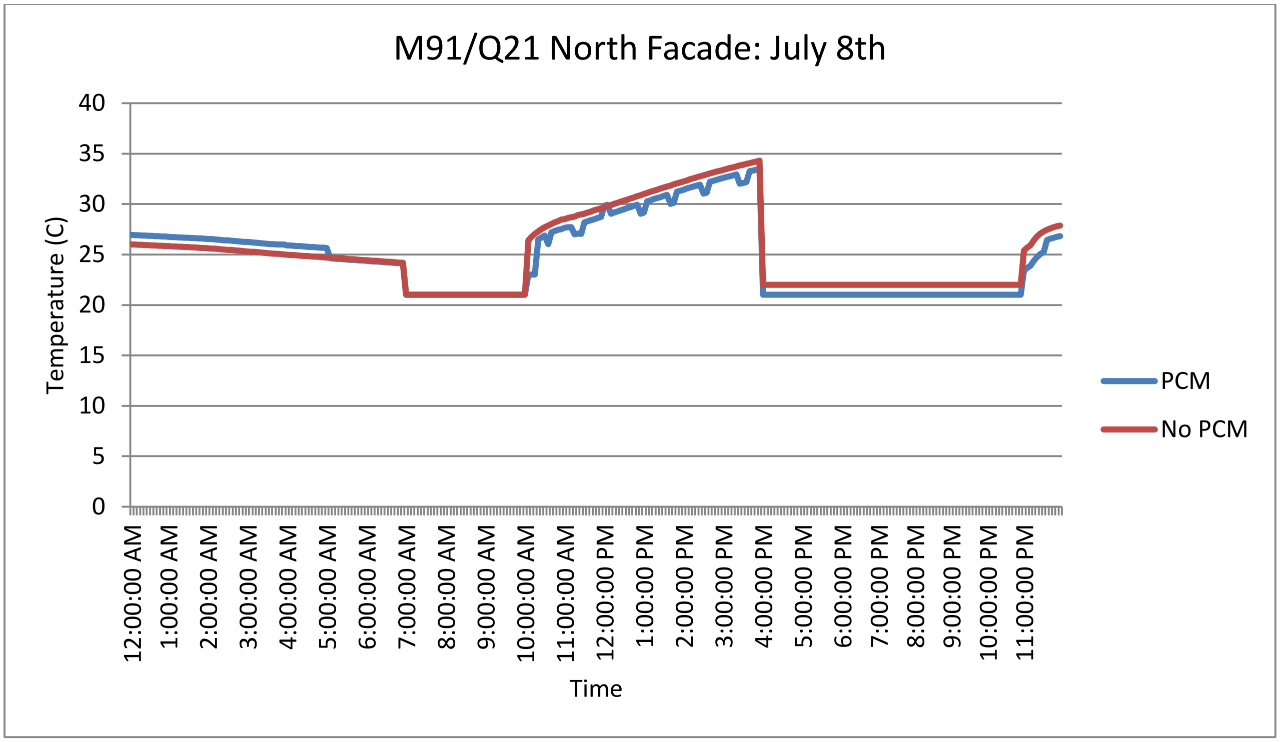

Figure 12: M91/Q21 North Façade- July 8th Temperature Graph (DesignBuilder)

This graph represents the temperature curve on a minute-by-minute timeline, for July 8th. This day was chosen to further investigate, as it is considered to be the beginning of the extreme heat week, according to DesignBuilder. The temperatures between the two suites differ at multiple points during this timeline. Between 12:00 AM and 5:00 AM, the PCM suite appears to be warmer than the other suite. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. At 10:00 AM, when the HVAC system has been shut off, the PCM suite remains at a cooler temperature. The PCM is absorbing heat from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a higher temperature. This is occurring as a result of the PCM releasing their energy, as heat, once the space begins to cool down. Once the HVAC system has been shut-off at 11:00 PM, the PCM suite remains cooler than the other suite. Figure 13 shows the graph of the south facing suites, using the M91/Q21 PCMs.

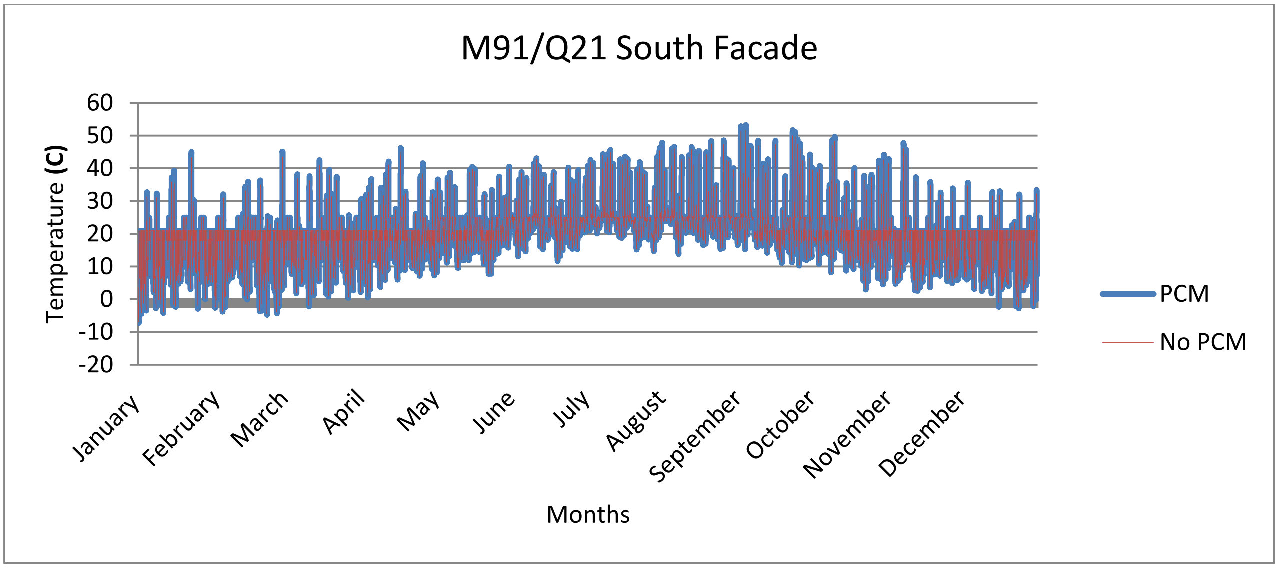

Figure 13: M91/Q21 South Façade Temperature Graph (DesignBuilder)

In these south suites, the temperatures appear to be very similar. Again, the main difference occurs when the HVAC system is turned off. These differences are hard to see, as this chart represents the temperature curve, over a period of one year. Figure 14 shows the temperature curve for one day in January.

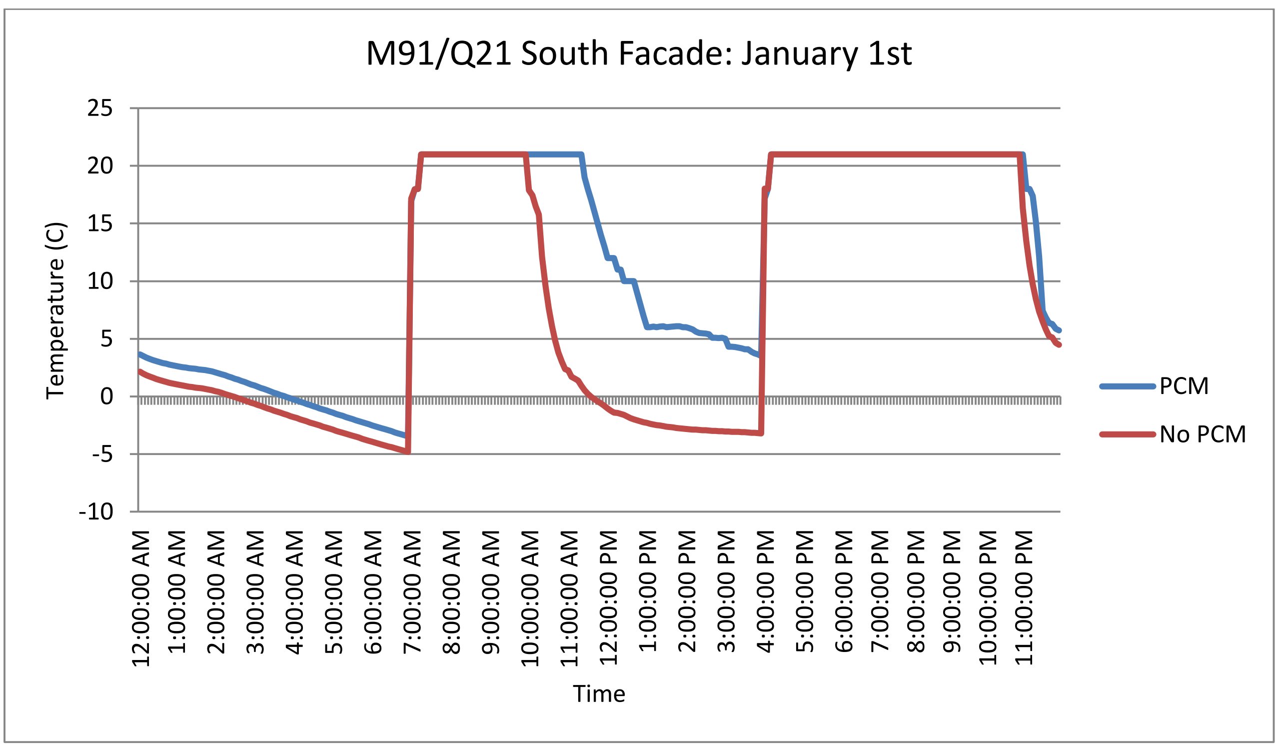

Figure 14: M91/Q21 South Façade- January 1st Temperature Graph (DesignBuilder)

The temperatures between these two suites differ. Between the times of 12:00 AM and 7:00 AM, when the HVAC system is not running, the PCM suite has a constant warmer temperature. This is a result of the PCM releasing its stored energy from the day before. By 7:00 AM, the PCM will have released all of its energy, as heat. Once the HVAC system is turned on, the PCM will begin to absorb heat from the system, while maintaining the same indoor air temperature as the other suite. The most significant difference occurs between 11:00 AM and 4:00 PM. During this time, the suite with the PCM remains significantly warmer than the other suite. Once the HVAC system is turned off, the PCM begins to release its stored heat, providing a higher indoor air temperature. As the stored energy begins to diminish, the temperature begins to drop. During this time, the PCM suite has a temperature between 20°C and 3°C, whereas the suite without the PCM has a temperature between 3°C and -3°C. By 4:00 PM, the PCM will have released all of its stored energy. Once the HVAC system is turned on, the PCM will again begin to store energy, while maintaining the set indoor air temperature. Once the HVAC system has been shut-off at 11:00 PM, the PCM suite continues to be warmer than the other suite, as a result of the PCM releasing its stored energy, as heat. Figure 15 shows the temperature curve for one day in July.

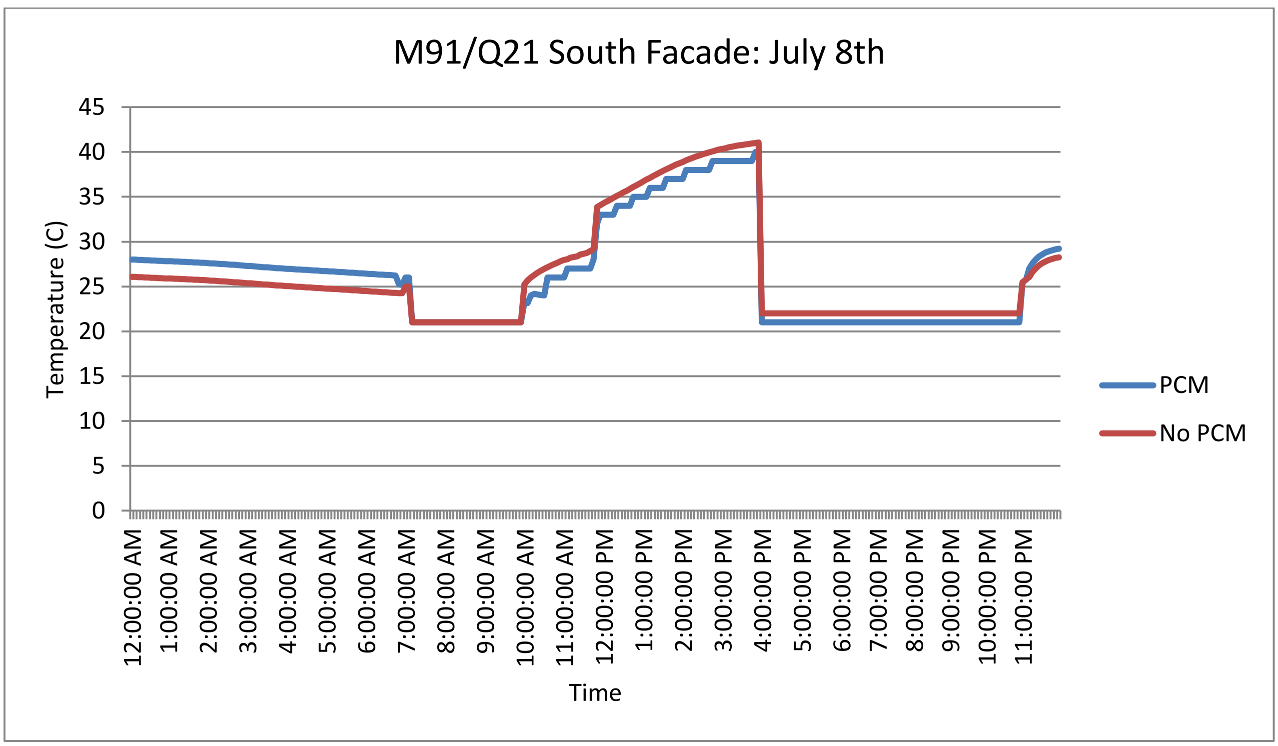

Figure 15: M91/Q21 South Façade- July 8th Temperature Graph (DesignBuilder)

Between the times of 12:00 AM and 7:00 AM, the temperature in the PCM suite remains at a warmer temperature. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. At 10:00 AM, when the HVAC system has been shut off, the PCM suite remains at a cooler temperature. The PCM is absorbing heat from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a higher temperature. This is occurring as a result of the PCM releasing their energy, as heat, once the space begins to cool down. Once the HVAC system in turned off at 11:00 PM, the temperature in the PCM suite becomes warmer than the other suite, as the PCM begin to release their stored energy.

5.2.2 Simulations Using M51/Q21 Phase Change Materials

In order to achieve results of the efficiency of the PCMs, simulations were carried out comparing the PCM suites to the suites without PCM using M51/Q21 PCMs. Figure 16 shows the graph of the north facing suites.

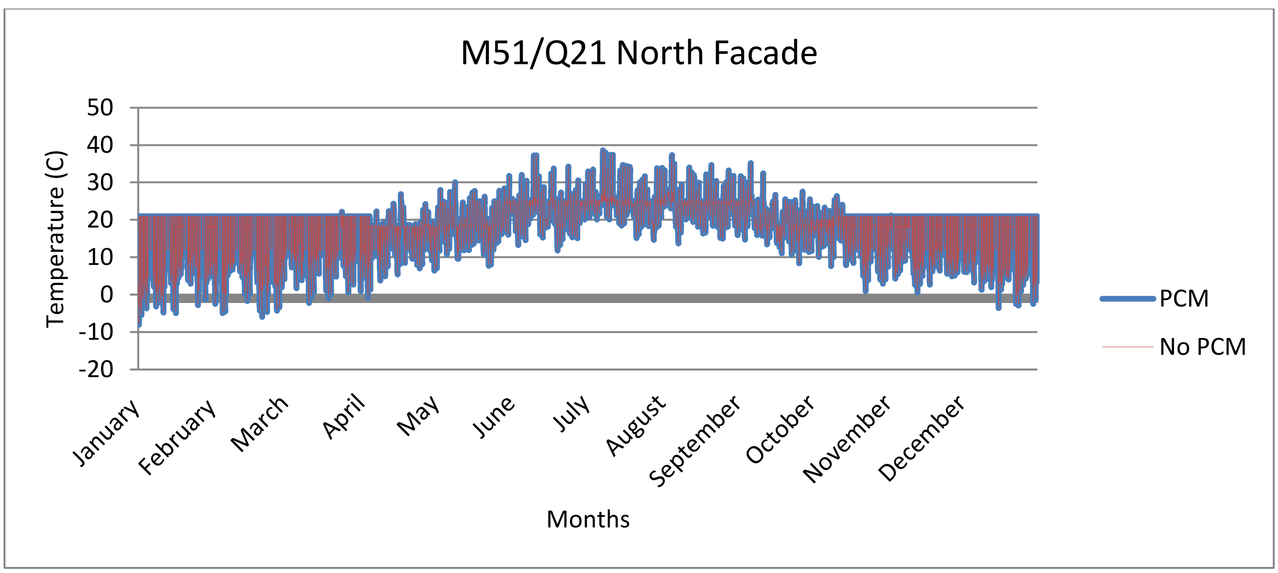

Figure 16: M51/Q21 North Façade Temperature Graph (DesignBuilder)

Looking at this chart, it is clear that the temperature graph appears to be very similar to that of the north suites using the M91/Q21 PCMs. The small difference occurs in the suite with the PCM. The temperature, when the HVAC system is shut off, is maintained for longer periods of time, as a result of the PCMs. This is hard to see, but will be further explored later in this paper. Figure 17 shows the temperature curve of one day in January.

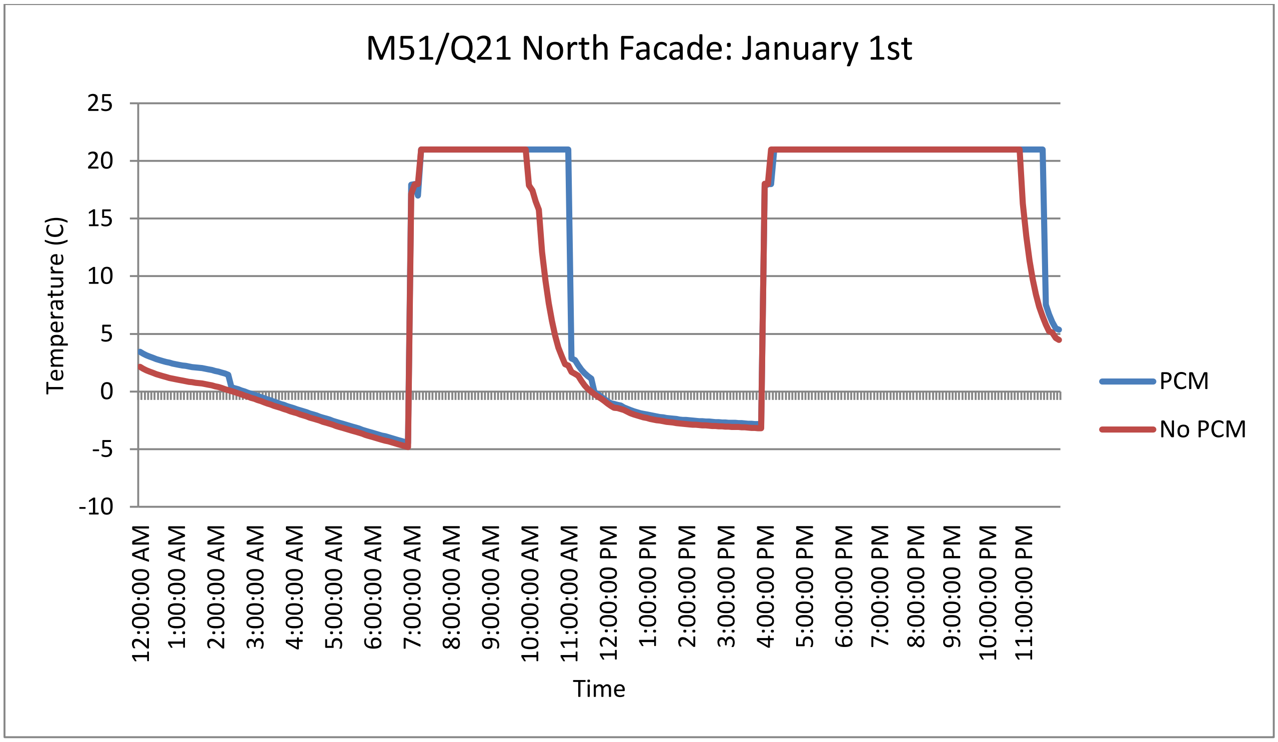

Figure 17: M51/Q21 North Façade- January 1st Temperature Graph (DesignBuilder)

In this graph, the temperatures of the PCM suite and the suite without PCM appear to be very similar most of the time. While the HVAC system is being run, the PCM are absorbing and storing energy. As soon as the HVAC system is turned off and the space begins to cool down, the PCM start to release their stored energy, heating the space. The main difference occurs between 12:00 AM and 2:00 AM. During these times, the suite with the PCM is warmer. After 2:00 AM, the temperature drops and stays just above the suite without PCM. This occurs when the PCM has released all of the stored energy and is no longer able to heat the space. At 7:00 AM, when the HVAC system is turned on, the PCM begin to absorb energy while remaining just below the set indoor air temperature. When the HVAC system is turned off at 10:00 AM, the PCM suite remains warmer than the other suite, as a result of the PCM releasing its stored energy. At 11:00 PM, the PCM suite remains at the set indoor air temperature once the HVAC system has been turned off, and begins to cool down as its stored energy diminishes. Figure 18 shows the temperature curve for one day in July.

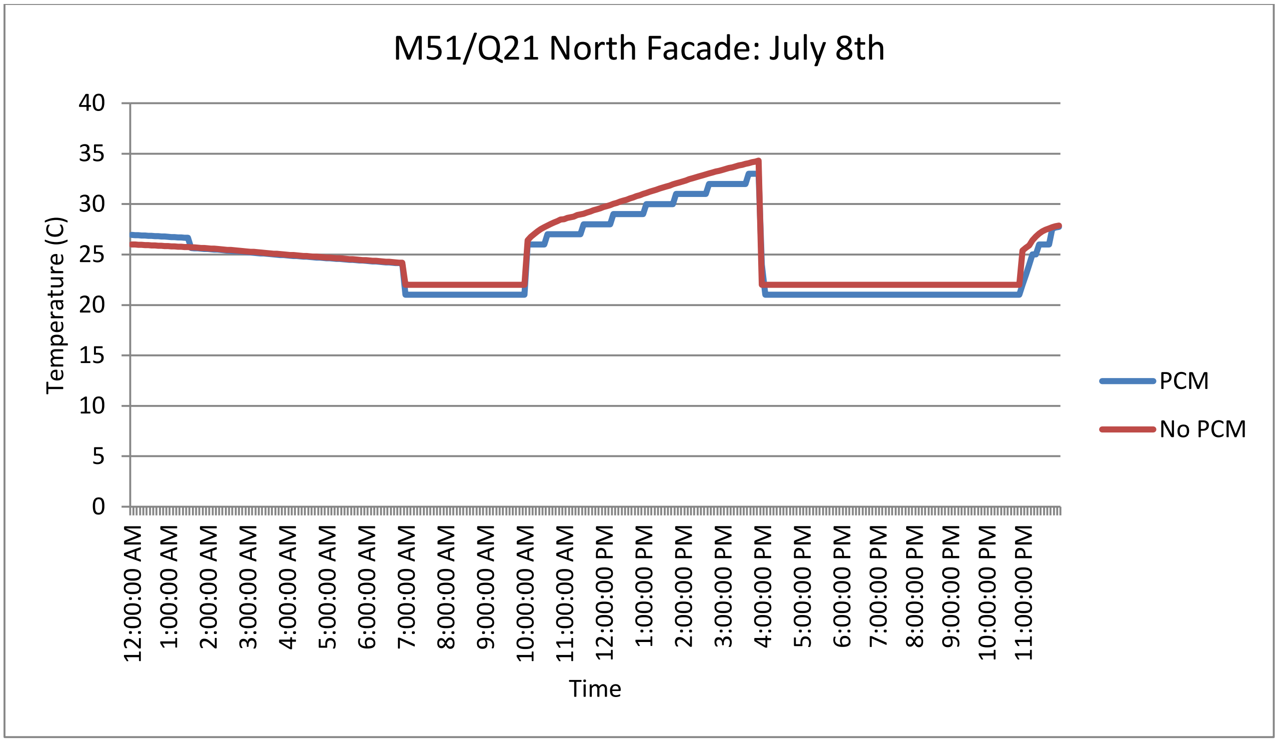

Figure 18: M51/Q21 North Façade- July 8th Temperature Graph (DesignBuilder)

The temperatures between the two suites differ at multiple points during this timeline. Between 12:00 AM and 2:00 AM, the PCM suite appears to be warmer than the other suite. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. By 2:00 AM, the PCM has released all of its stored energy, bringing the indoor air temperature to be the same as the other suite. At 10:00 AM, when the HVAC system has been shut off, the PCM suite remains at a cooler temperature. The PCM is absorbing heat from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a higher temperature. This is occurring as a result of the PCM releasing their energy, once the space begins to cool down. Once the HVAC system has been shut-off at 11:00 PM, the PCM suite remains cooler than the other suite. Figure 19 shows the graph of the south facing suites, using the M51/Q21 PCMs.

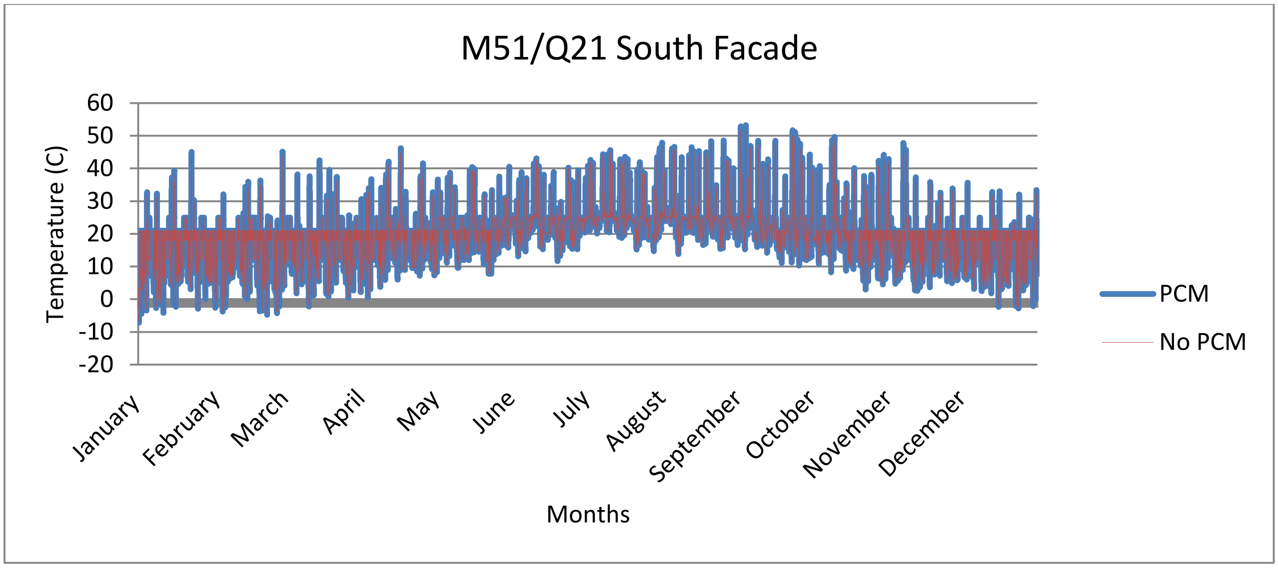

Figure 19: M51/Q21 South Façade Temperature Graph (DesignBuilder)

In these south suites, the temperatures appear to be very similar to each other, as well as to the south suites with M91/Q21. Again, the main difference occurs when the HVAC system is turned off. Since this graph is showing the temperature curve for the entire year, it is difficult to understand what is going on, on a daily basis. Figure 20 shows the temperature curve for one day in January.

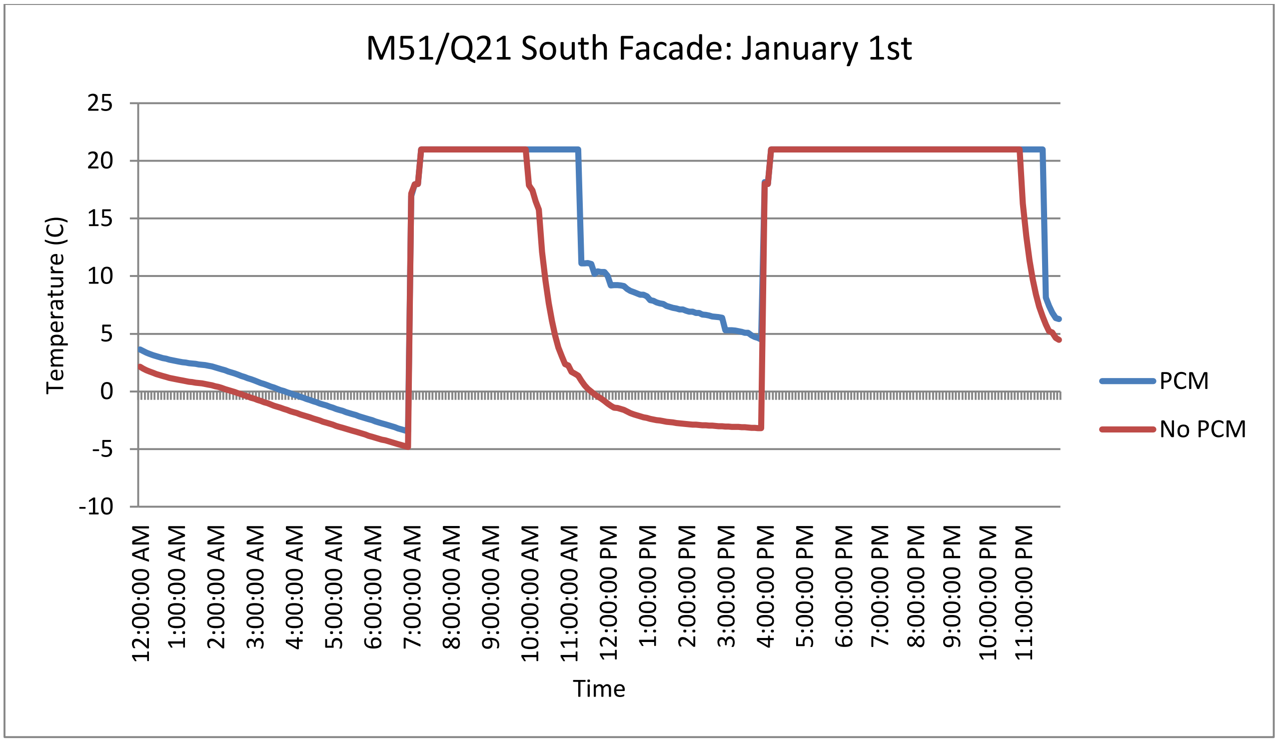

Figure 20: M51/Q21 South Façade- January 1st Temperature Graph (DesignBuilder)

The temperatures between these two suites differ. Between the times of 12:00 AM and 7:00 AM, when the HVAC system is not running, the PCM suite has a constant warmer temperature. This is a result of the PCM releasing its stored energy from the day before. By 7:00 AM, the PCM will have released all of its heat. Once the HVAC system is turned on, the PCM will begin to absorb heat from the system, while maintaining the same indoor air temperature as the other suite. The most significant difference occurs between 11:00 AM and 4:00 PM. During this time, the suite with the PCM remains significantly warmer than the other suite. Once the HVAC system is turned off, the PCM begins to release its stored energy, providing a higher indoor air temperature. As the stored energy begins to diminish, the temperature begins to drop. During this time, the temperature in the PCM suite remains between 20°C and 5°C, whereas the suite without the PCM has a temperature between 12°C and -3°C. By 4:00 PM, the PCM will have released all of its stored energy. Once the HVAC system is turned on, the PCM will again begin to store energy, while maintaining the set indoor air temperature. Once the HVAC system has been shut-off at 11:00 PM, the PCM suite continues to be warmer than the other suite, as a result of the PCM releasing its stored energy. At 11:00 PM when the HVAC system is turned off, the PCM suite remains at a warmer temperature. Figure 21 shows the temperature curve for one day in July.

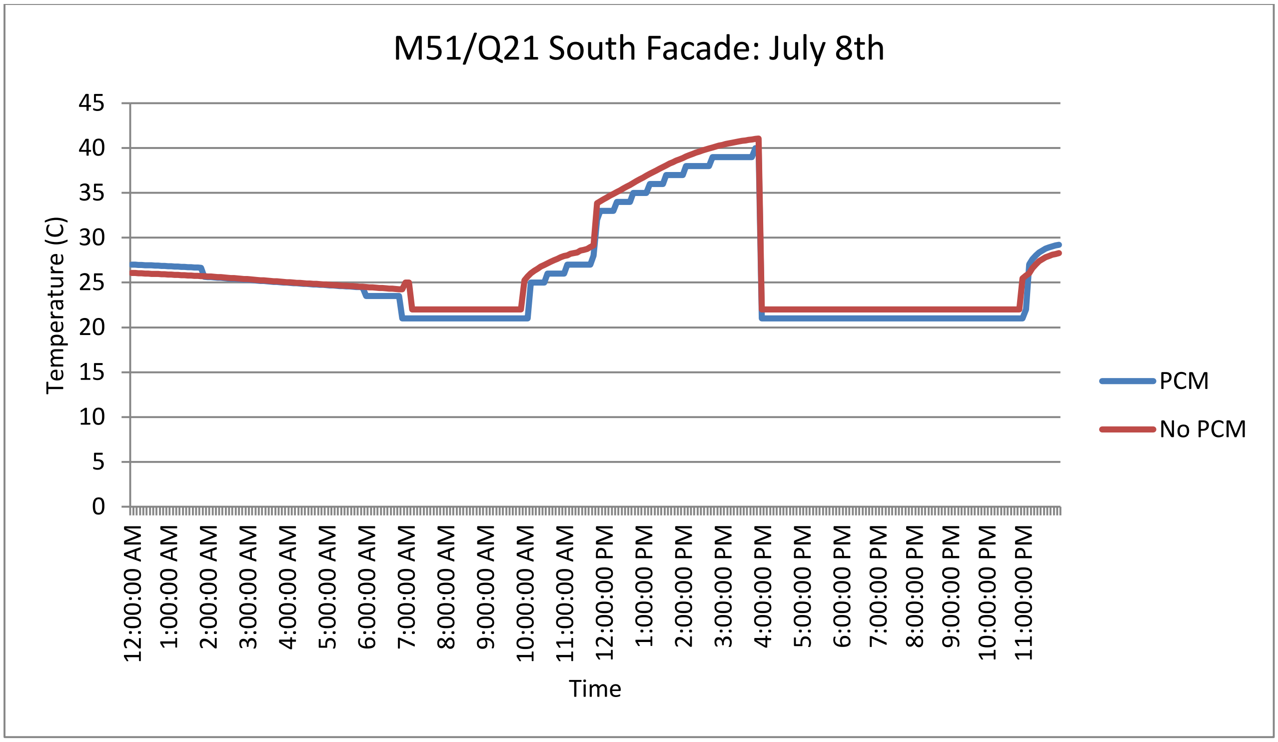

Figure 21: M51/Q21 South Façade- July 8th Temperature Graph (DesignBuilder)

Between the times of 12:00 AM and 2:00 AM, the temperature in the PCM suite remains at a warmer temperature. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. At 6:00 AM, the temperature in the PCM suite begins to get cooler than the other suite. This is due to the PCM absorbing heat from the space, allowing the temperature to become cooler. This colder temperature remains even when the HVAC system has been turned on at 7:00 AM. At 10:00 AM, when the HVAC system has been shut off, the PCM suite continues to remains at a cooler temperature. The PCM is absorbing heat from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a higher temperature. This is occurring as a result of the PCM releasing their energy, once the space begins to cool down. Once the HVAC system in turned off at 11:00 PM, the temperature in the PCM suite becomes warmer than the other suite, as the PCM begin to release their stored energy.

5.2.3 Simulations Using M27/Q21 Phase Change Materials

In order to achieve results of the efficiency of the PCMs, simulations were carried out comparing the PCM suites to the suites without PCM using M27/Q21 PCMs. Figure 22 shows the graph of the north facing suites.

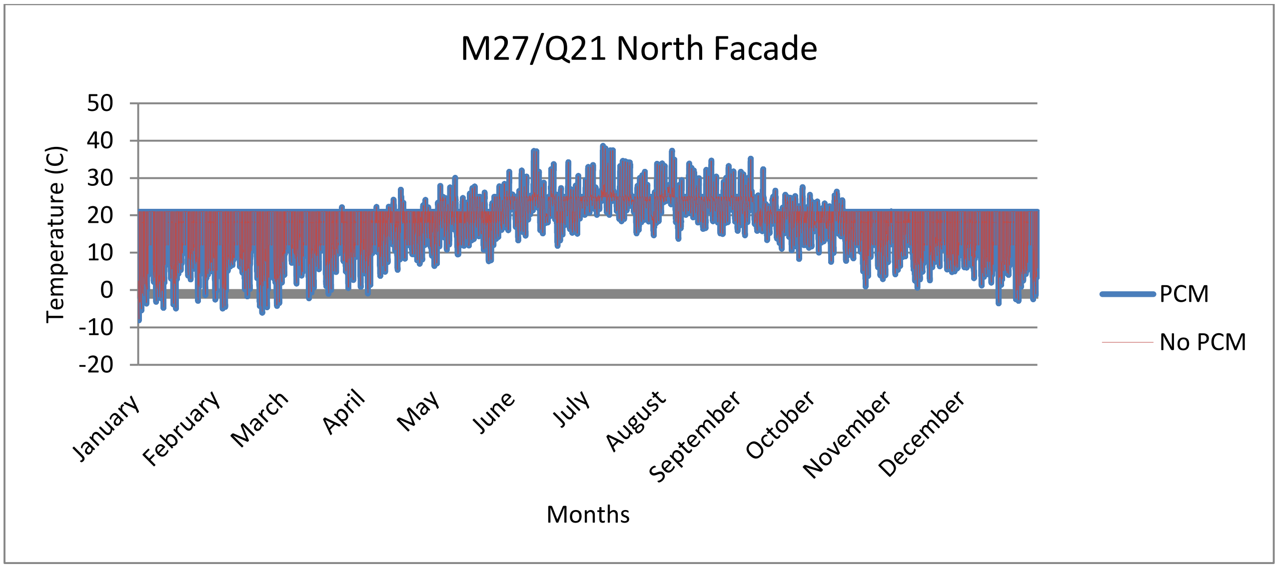

Figure 22: M27/Q21 North Façade Temperature Graph (DesignBuilder)

Looking at this chart, it is clear that the temperature graph appears to be very similar to those of the north suites using the M91/Q21 and M51/Q21 PCMs. The more significant difference occurs in the suite with the PCM. The temperature, when the HVAC system is shut off, is maintained for longer periods of time, as a result of the PCMs. Although this difference is not very noticeable, it will be further explored later in this paper. Figure 23 shows the temperature curve for one day in January.

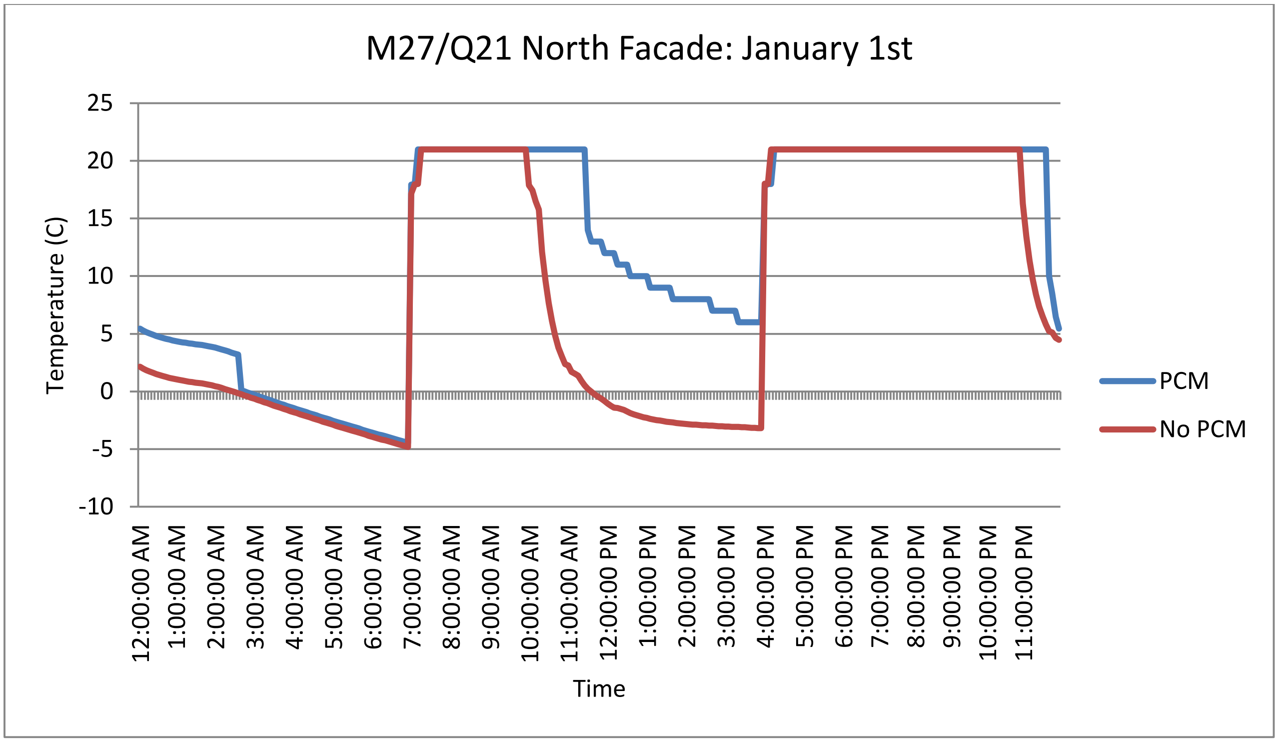

Figure 23: M27/Q21 North Façade- January 1st Temperature Graph (DesignBuilder)

In this graph, the temperatures of the PCM suite and the suite without PCM differ most of the time. While the HVAC system is being run, the PCM are absorbing and storing energy. As soon as the HVAC system is turned off and the space begins to cool down, the PCM start to release their stored energy, heating the space. The main difference occurs between 12:00 AM and 2:00 AM. During these times, the suite with the PCM is warmer. After 2:30 AM, the temperature drops and stays just above the suite without PCM. This occurs when the PCM has released all of the stored heat and is no longer able to heat the space. At 7:00 AM, when the HVAC system is turned on, the PCM begin to absorb heat while remaining at the set indoor air temperature. When the HVAC system is turned off at 10:00 AM, the PCM suite remains warmer than the other suite, as a result of the PCM releasing its stored heat. At 11:00 PM, the PCM suite remains at the set indoor air temperature once the HVAC system has been turned off, and begins to cool down as its stored energy diminishes. Figure 24 shows the temperature curve for one day in July.

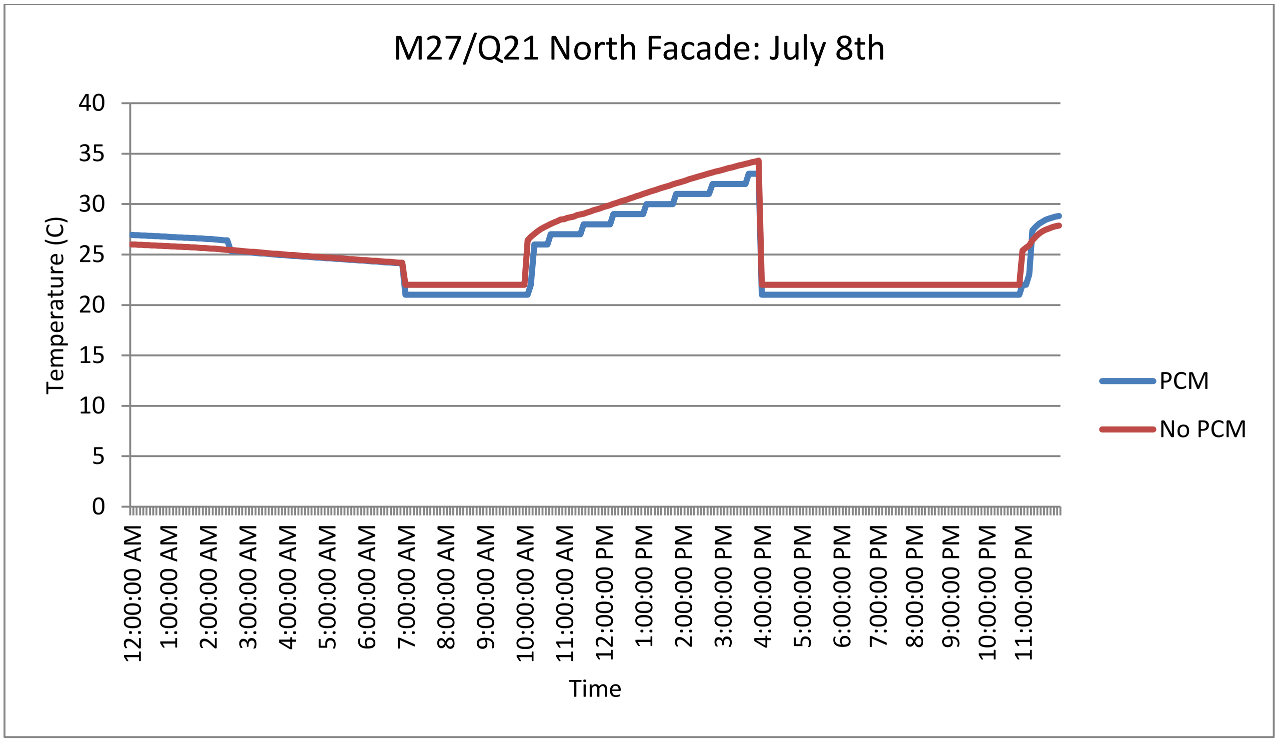

Figure 24: M27/Q21 North Façade- July 8th Temperature Graph (DesignBuilder)

Between the times of 12:00 AM and 3:00 AM, the temperature in the PCM suite remains at a warmer temperature. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. At 7:00 AM, the temperature in the PCM suite begins to get cooler than the other suite. This is due to the PCM absorbing heat from the space, allowing the temperature to become cooler. This colder temperature remains even when the HVAC system has been turned on at 7:00 AM. At 10:00 AM, when the HVAC system has been shut off, the PCM suite continues to remains at a cooler temperature. The PCM is absorbing heat from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a slightly higher temperature. This is occurring as a result of the PCM releasing their energy, once the space begins to cool down. Once the HVAC system in turned off at 11:00 PM, the temperature in the PCM suite becomes warmer than the other suite, as the PCM begin to release their stored energy. Figure 25 shows the graph of the south facing suites, using the M27/Q21 PCMs.

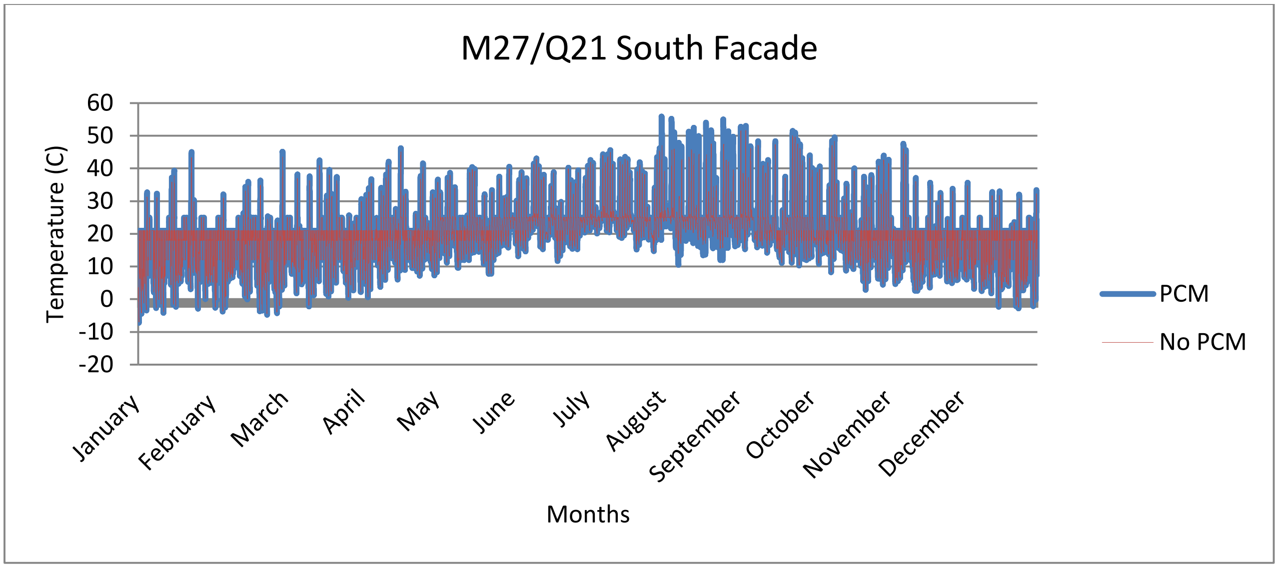

Figure 25: M27/Q21 South Façade Temperature Graph (DesignBuilder)

These south suites appear to have the most significant difference. These main differences occur between August and October. The suite with the PCM is significantly warmer when the HVAC is not running. Figure 26 shows the temperature curve for one day in January.

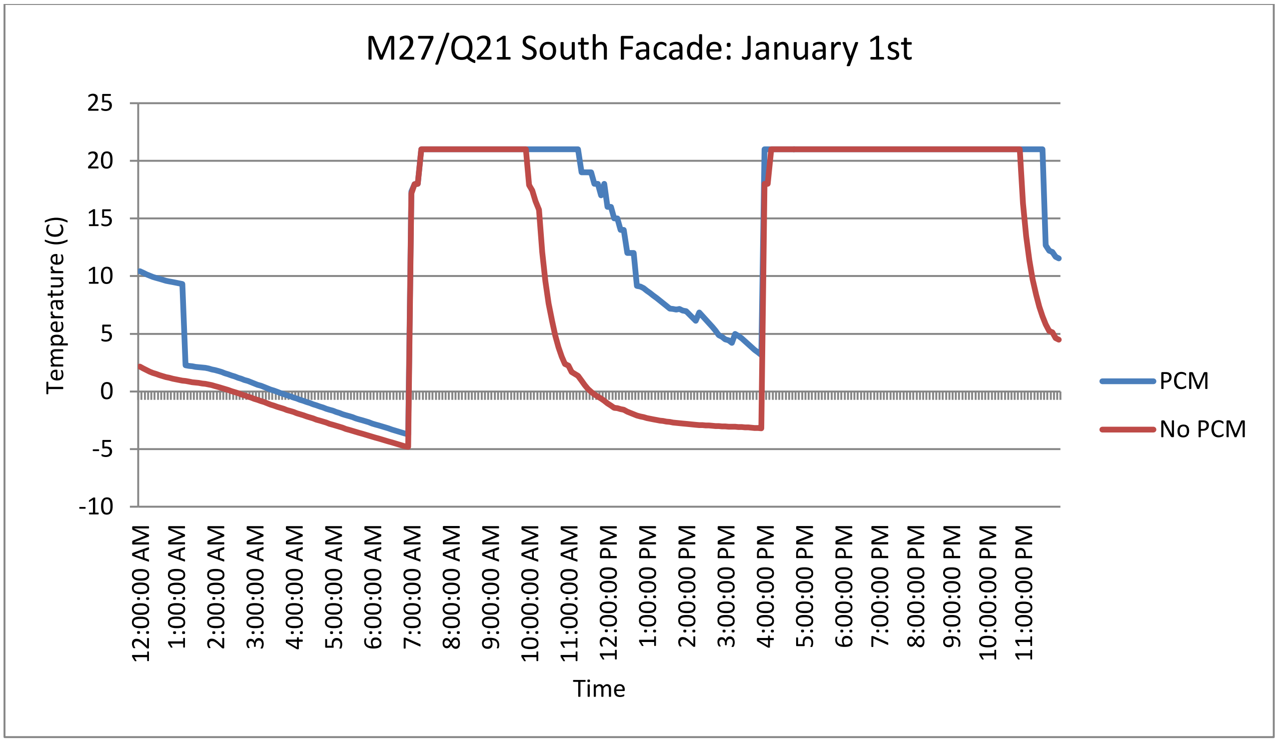

Figure 26: M27/Q21 South Façade- January 1st Temperature Graph (DesignBuilder)

The temperatures between these two suites differ. Between the times of 12:00 AM and 1:00 AM, when the HVAC system is not running, the PCM suite has a constant warmer temperature. This is a result of the PCM releasing its stored energy from the day before. By 7:00 AM, the PCM will have released all of its heat. Once the HVAC system is turned on, the PCM will begin to absorb heat from the system, while maintaining the same indoor air temperature as the other suite. The most significant difference occurs between 11:00 AM and 4:00 PM. During this time, the suite with the PCM remains significantly warmer than the other suite. Once the HVAC system is turned off, the PCM begins to release its stored energy, providing a higher indoor air temperature. As the stored energy begins to diminish, the temperature begins to drop. During this time, the temperature in the PCM suite remains between 20°C and 4°C, whereas the suite without the PCM has a temperature between 12°C and -3°C. By 4:00 PM, the PCM will have released all of its stored energy. Once the HVAC system is turned on, the PCM will again begin to store energy, while maintaining the set indoor air temperature. Once the HVAC system has been shut-off at 11:00 PM, the PCM suite continues to be warmer than the other suite, as a result of the PCM releasing its stored energy. At 11:00 PM when the HVAC system is turned off, the PCM suite remains at a warmer temperature. Figure 27 shows the temperature curve for one day in July.

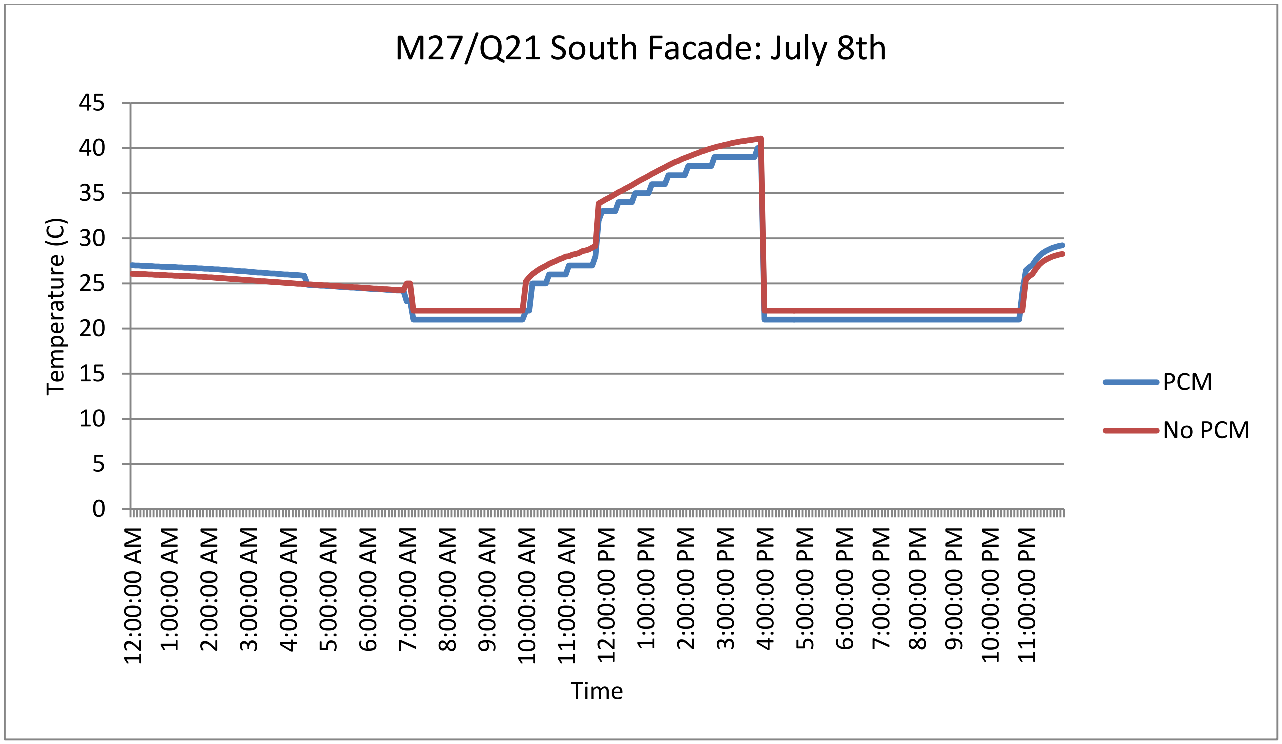

Figure 27: M27/Q21 South Façade- July 8th Temperature Graph (DesignBuilder)

Between the times of 12:00 AM and 4:00 AM, the temperature in the PCM suite remains at a warmer temperature. The PCM is releasing the stored energy, which has been absorbed throughout the daytime hours. At 7:00 AM, the temperature in the PCM suite begins to get cooler than the other suite. This is due to the PCM absorbing heat from the space, allowing the temperature to become cooler. This colder temperature remains even when the HVAC system has been turned on at 7:00 AM. At 10:00 AM, when the HVAC system has been shut off, the PCM suite continues to remains at a cooler temperature. The PCM is absorbing energy from the suite, while the HVAC system is turned off. This allows for the warmer air to be taken out of the space, lowering the indoor air temperature. The PCM temperature fluctuates according to the outside air temperature, as well as the amount of heat being infiltrated into the space. During the hours of 4:00 PM and 11:00 PM, the PCM suite has a higher temperature. This is occurring as a result of the PCM releasing their energy, once the space begins to cool down. Once the HVAC system in turned off at 11:00 PM, the temperature in the PCM suite becomes warmer than the other suite, as the PCM begin to release their stored energy.

5.3 Cost Comparison

In order to achieve a better understanding of the value of using the PCM, a cost comparison was conducted. The cost comparison provides a numerical reference in an attempt to demonstrate the cost savings of using the PCMs. It should be noted that the energy costs are based on the mid-peak value, provided by Hydro One. In the summer time, the HVAC system is turned on at 7:00 AM, which is the end of the off-peak period. The system is running until 10:00 AM which is the mid-peak period. In the evening the system is turned on at 4:00 PM, which is during the on-peak period. The system is being run through the mid-peak period until 7:00 PM and then the remainder if the energy is being used during the off-peak period, until it's shut-off at 11:00 PM. During the winter time, the HVAC system is running from 7:00 AM until 10:00 AM, which is during the on-peak time. In the evening, the HVAC turns on at 4:00 PM, during the on-peak time, and runs until 11:00 PM which the majority of the time is during off-peak. The peak energy times, found in figure 28 and are provided by the Ontario Board of Energy.

Figure 28: Peak and Off-Peak Times (Ontario Board of Energy)

The HVAC system was set to be turned on during the hours of 7:00 AM to 10:00 AM and then again from 4:00 PM to 11:00 PM. During the winter and the summer, the peak periods change, which is why the mid-peak cost was used for this cost comparison. For calculation purposes, the cost of the energy was assumed to remain constant over the 25 year calculation period. Table 6 shows the cost of running the HVAC system.

	North PCM	North no PCM	South PCM	South no PCM
Materials				
Concrete	$78.46 /m2	$78.46 /m2	$78.46 /m2	$78.46 /m2
Phase-Change material	$39.30 /m2	0	$39.30 /m2	0
	$117.76 /m2	**$78.46 /m2**	**$117.76 /m2**	**$78.46 /m2**
Cooling				
Cooling Energy	992.28 kWh	1202.57 kWh	2649.84 kWh	2902.15 kWh
Cost of Gas for Chiller	$0.13	$0.13	$0.13	$0.13
	$2.15 /m2	**$2.60 /m2**	**$5.74 /m2**	**$6.28 /m2**
Heating				
Heating Energy	8705.60 kWh	9846.78 kWh	6597.54 kWh	7676.79 kWh
Cost of Gas for Boiler	$0.13	$0.13	$0.13	$0.13
	$18.95 /m2	**$21.33 /m2**	**$14.30 /m2**	**$16.63 /m2**
Operating Costs				
Year 1	**$21.10 /m2**	**$23.93 /m2**	**$20.04 /m2**	**$22.91 /m2**
Cumulative cost after year 5	$105.50 /m2	$119.65 /m2	$100.20 /m2	$114.55 /m2
Cumulative cost after year 15	$316.50 /m2	$358.95 /m2	$300.60 /m2	$343.65 /m2
Cumulative cost after year 20	$422.00 /m2	$478.60 /m2	$400.80 /m2	$458.20 /m2
Cumulative cost after year 25	$527.50 /m2	$598.25 /m2	$501.00 /m2	$572.75 /m2

Table 6: Cost Comparison per Square Meter

The values found in the table are calculated per square meter. The costs of the materials are not included in the operating costs. This table can be applied to any project, in order to calculate the costs of running the HVAC system. Table 7 shows the cost comparison for this particular project, using the M91/Q21 PCMs. The values are based on the 60 m^2 suites that were investigated.

	North PCM	North no PCM	South PCM	South no PCM
Materials				
Concrete	$4,707.60	$4,707.60	$4,707.60	$4,707.60
Phase-Change material	$2,358.00	$0.00	$2,358.00	$0.00
	$7,065.60	**$4,707.60**	**$7,065.60**	**$4,707.60**
Cooling				
Cooling Energy	788.17 kWh	1275.88 kWh	2638.80 kWh	3183.29 kWh
Cost of Gas for Chiller	$0.13	$0.13	$0.13	$0.13
	$102.46	**$165.86**	**$343.04**	**$413.82**
Heating				
Heating Energy	6645.59 kWh	7290.91 kWh	4901.35 kWh	5503.67 kWh
Cost of Gas for Boiler	$0.13	$0.13	$0.13	$0.13
	$863.92	**$947.81**	**$637.17**	**$715.47**
Operating Costs				
Year 1	**$966.38**	**$1,113.67**	**$980.21**	**$1,129.29**
Cumulative cost after year 5	$4,831.90	$5,568.35	$4,901.05	$5,646.45
Cumulative cost after year 15	$14,495.70	$16,705.05	$14,703.15	$16,939.35
Cumulative cost after year 15	$14,495.70	$16,705.05	$14,703.15	$16,939.35
Cumulative cost after year 20	$19,327.60	$22,273.40	$19,604.20	$22,585.80
Cumulative cost after year 25	$24,159.50	$27,841.75	$24,505.25	$28,232.25

Table 7: Cost Comparison for M91/Q21, Based on a 60 m^2 Suite

These results can be used to determine the cost savings of all four of the modelled suites. The cost of construction is higher for the suite with PCM, as the materials are an added cost. First, looking at the north suites, the difference in operating costs is $147.29 per year. This means that the extra cost of the PCM will be payed-off after 16 years. Once the added costs are payed off, the operating costs of the system with the PCM will continue to save money. After 25 years, the PCM assembly will have saved $3,682.25, over the assembly without PCM. Now looking at the south suites, the difference in operating costs is $149.08 per year. This means that the extra cost of the PCM will be payed-off after 15.8 years. After 25 years, the PCM assembly will have saved $3,727.00, over the assembly without the PCM. These payback values are not considered to be economical, as 16 years to recover construction costs is quite long. Table 8 shows the cost comparison for this particular project, using the M51/Q21 PCMs. The values are based on the 60 m^2 suites that were investigated.

	North PCM	North no PCM	South PCM	South no PCM
Materials				
Concrete	$4,707.60	$4,707.60	$4,707.60	$4,707.60
Phase-Change material	$2,358.00	$0.00	$2,358.00	$0.00
	$7,065.60	**$4,707.60**	**$7,065.60**	**$4,707.60**
Cooling				
Cooling Energy	588.17 kWh	1275.88 kWh	2438.80 kWh	3183.29 kWh
Cost of Gas for Chiller	$0.13	$0.13	$0.13	$0.13
	$76.46	**$165.86**	**$317.04**	**$413.82**
Heating				
Heating Energy	6445.59 kWh	7290.91 kWh	4701.35 kWh	5503.67 kWh
Cost of Gas for Boiler	$0.13	$0.13	$0.13	$0.13
	$837.92	**$947.81**	**$611.17**	**$715.47**
Operating Costs				
Year 1	**$914.38**	**$1,113.67**	**$928.21**	**$1,129.29**
Cumulative cost after year 5	$4,571.90	$5,568.35	$4,641.05	$5,646.45
Cumulative cost after year 15	$13,715.70	$16,705.05	$13,923.15	$16,939.35
Cumulative cost after year 20	$18,287.60	$22,273.40	$18,564.20	$22,585.80
Cumulative cost after year 25	$22,859.50	$27,841.75	$23,205.25	$28,232.25

Table 8: Cost Comparison for M51/Q21, Based on a 60 m^2 Suite

These results can be used to determine the cost savings of all four of the modelled suites. The cost of construction is higher for the suite with PCM, as the materials are an added cost. First looking at the north suites, the difference in operating costs is $199.29 per year. This means that the extra cost of the PCM will be payed-off after 11.8 years. Once the added costs are payed off, the operating costs of the system with the PCM will continue to save money. After 25 years, the PCM assembly will have saved $4,982.25, over the assembly without PCM. Now looking at the south suites, the difference in operating costs is $201.08 per year. This means that the extra cost of the PCM will be payed-off after 11.7 years. After 25 years, the PCM assembly will have saved $5027.00, over the assembly without the PCM. Table 9 shows the cost analysis for this particular project, using the M27/Q21 PCMs. The values are based on the 60 m^2 suites that were investigated.

	North PCM	North no PCM	South PCM	South no PCM
Materials				
Concrete	$4,707.60	$4,707.60	$4,707.60	$4,707.60
Phase-Change material	$2,358.00	$0.00	$2,358.00	$0.00
	$7,065.60	**$4,707.60**	**$7,065.60**	**$4,707.60**
Cooling				
Cooling Energy	389.68 kWh	1275.88 kWh	2239.76 kWh	3183.29 kWh
Cost of Gas for Chiller	$0.13	$0.13	$0.13	$0.13
	$50.66	**$165.86**	**$291.17**	**$413.82**
Heating				
Heating Energy	6258.24 kWh	7290.91 kWh	4514.45 kWh	5503.67 kWh
Cost of Gas for Boiler	$0.13	$0.13	$0.13	$0.13
	$813.57	**$947.81**	**$586.87**	**$715.47**
Operating Costs				
Year 1	**$864.23**	**$1,113.67**	**$878.04**	**$1,129.29**
Cumulative cost after year 5	$4,321.15	$5,568.35	$4,390.20	$5,646.45
Cumulative cost after year 15	$12,963.45	$16,705.05	$13,170.60	$16,939.35
Cumulative cost after year 20	$17,284.60	$22,273.40	$17,560.80	$22,585.80
Cumulative cost after year 25	$21,605.75	$27,841.75	$21,951.00	$28,232.25

Table 9: Cost Comparison for M27/Q21, Based on a 60 m^2 Suite

These results can be used to determine the cost savings of all four of the modelled suites. The cost of construction is higher for the suite with PCM, as the materials are an added cost. First looking at the north suites, the difference in operating costs is $249.44 per year. This means that the extra cost of the PCM will be payed-off after 9.4 years. Once the added costs are payed off, the operating costs of the system with the PCM will continue to save money. After 25 years, the PCM assembly will have saved $6,236.00, over the assembly without PCM. Now looking at the south suites, the difference in operating costs is $251.25 per year. This means that the extra cost of the PCM will be payed-off after 9.3 years. After 25 years, the PCM assembly will have saved $6,281.25, over the assembly without the PCM.

5.4 Discussion

As is evident in this section of the paper, the results of the simulations were difficult to understand as they were presented over the course of an entire year. The full year chart causes the temperature graphs between the two different suites to be almost identical. The reason for this is that the numbers are shown over the course of an entire year and they are squished into a small space. This causes the distance between the temperatures to be very minimal, not providing an accurate graph of the temperature fluctuations. From these charts, no real information could be gathered. Looking at specific days, on a minute-by-minute basis, the difference in temperature curves was much clearer. January 1st was chosen to further investigate, as this was seen to be the start of the extreme cold weather week, according to DesignBuilder. July 8th was also chosen to further investigate, as this was seen to be the start of the extreme hot weather week, according to DesignBuilder. Figure 29 shows a comparison of all the PCM north suites, on January 1st.

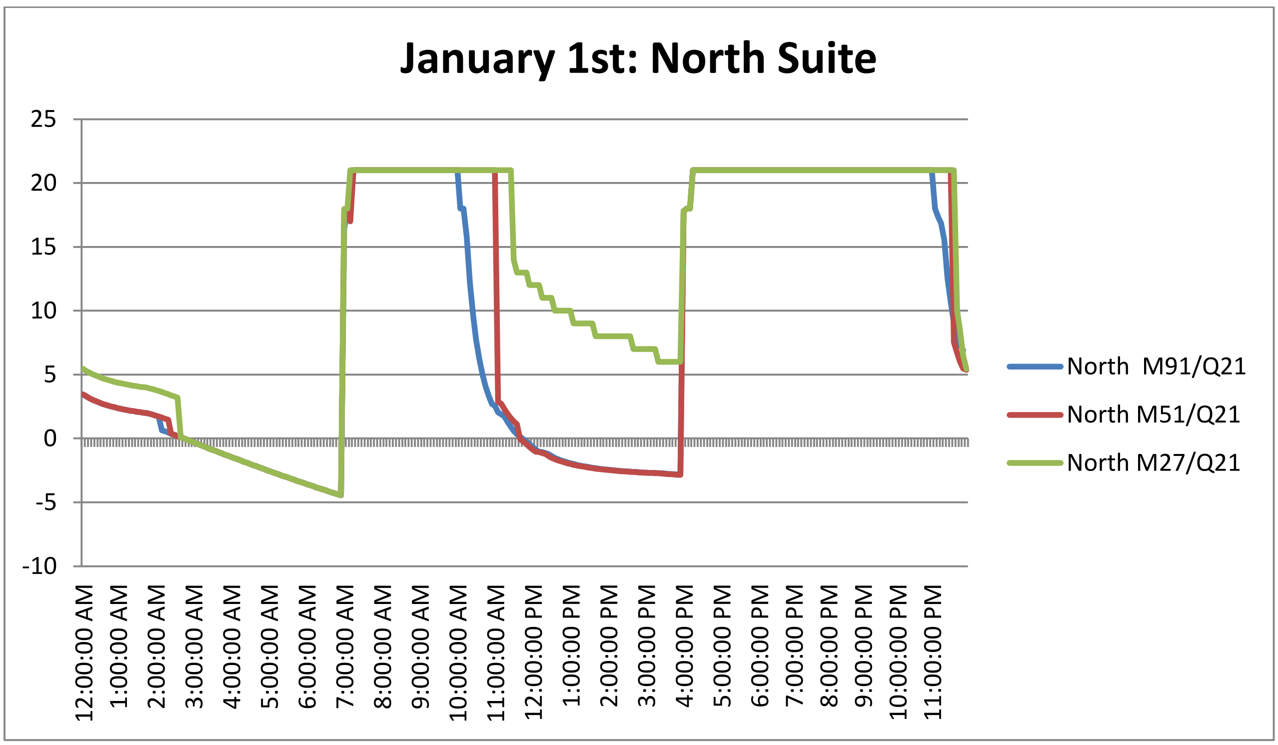

Figure 299: January 1st North Suites PCM Comparison (DesignBuilder)

Looking at this graph, it is clear that the M27/Q21 is the most effective PCM. This PCM retains the most amount of energy throughout the day, compared to the other PCM. Between the times of 10:00 AM and 4:00 PM, when the HVAC system is turned off, the M27/Q21 PCM is performing at its highest, retaining a greater amount of energy than the others. Figure 30 shows a comparison of all the PCM south suites, on January 1st.

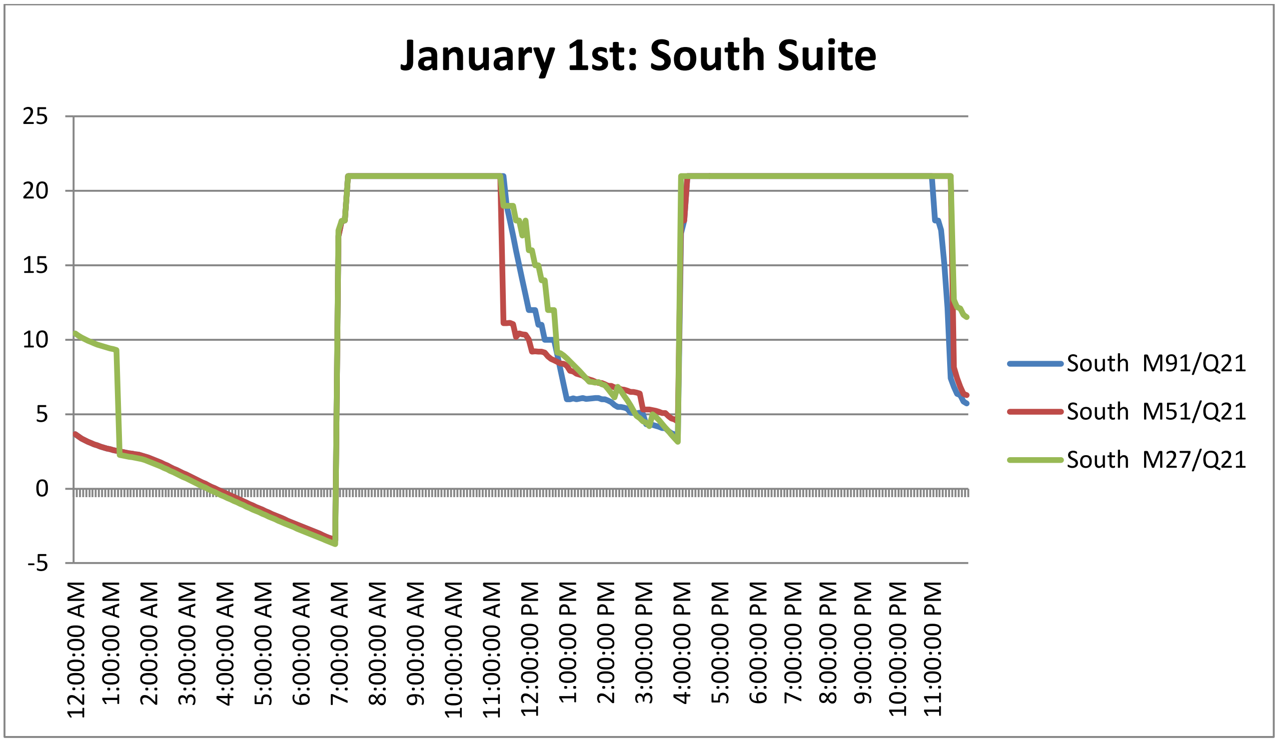

Figure 30: January 1st South Suites PCM Comparison (DesignBuilder)

Looking at this graph, it is clear that all of the PCM are performing at similar capacities. The M27/Q21 PCM does retain more energy when compared to the others. Between the times of 12:00 AM and 1:00 AM, when the HVAC system is turned off, the M27/Q21 PCM is performing at its highest, retaining a greater amount of energy than the others. Figure 31 shows a comparison of all the PCM north suites, on July 8th.

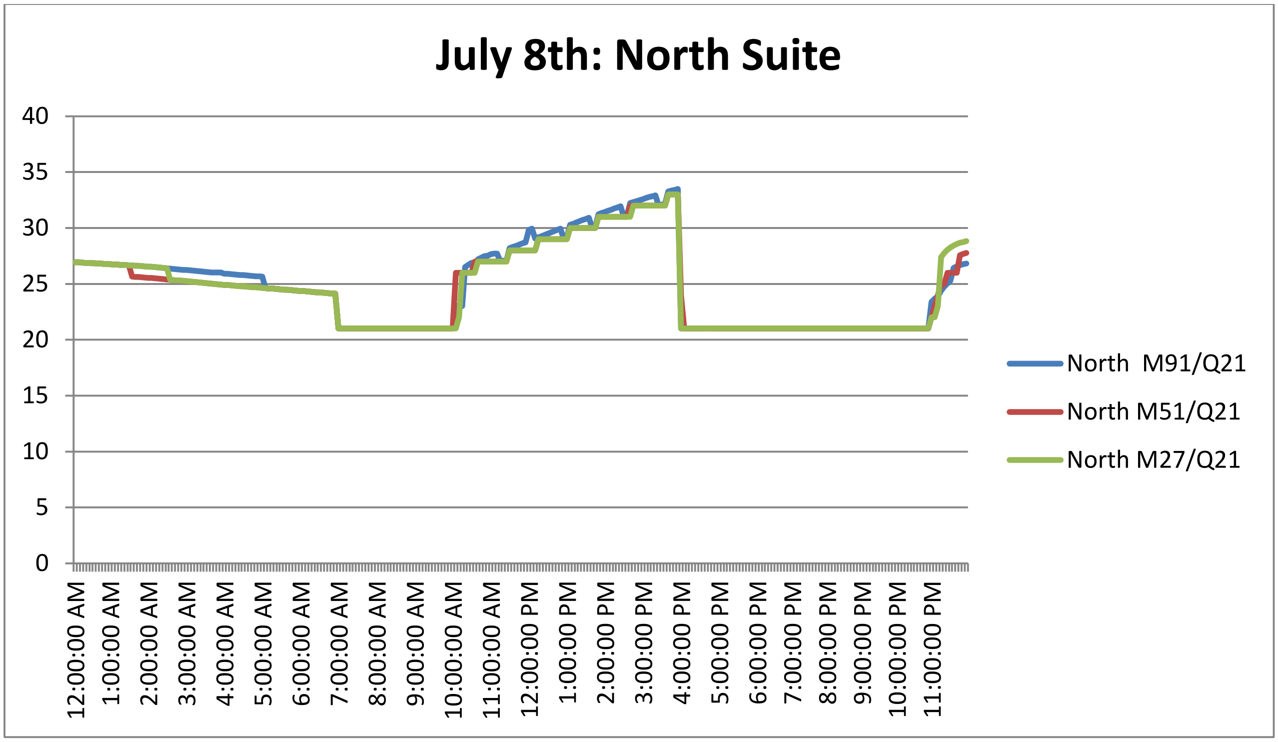

Figure 31: July 8th North Suites PCM Comparison (DesignBuilder)

Looking at this graph, all of the PCM appear to have similar energy retention. The M27/Q21 PCM is able to maintain the lowest overall temperature, when compared to the other PCM. Figure 32 shows a comparison of all the PCM south suites, on July 8th.

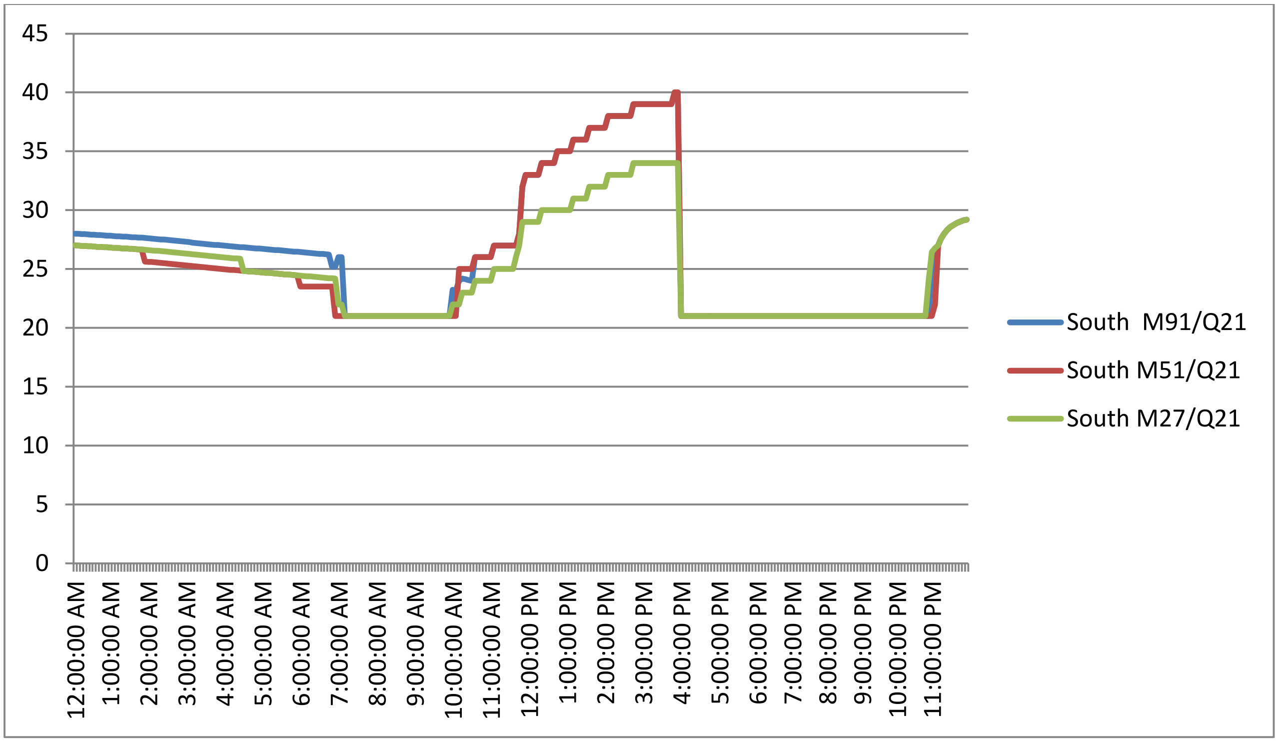

Figure 32: July 8th South Suites PCM Comparison (DesignBuilder)

Looking at this graph, it is clear that the M27/Q21 is the most effective PCM. This PCM retains the most amount of energy throughout the day, compared to the other PCM. Between the times of 10:00 AM and 4:00 PM, when the HVAC system is turned off, the M27/Q21 PCM is performing at its highest, retaining a greater amount of energy than the others.

Looking at the results from all of the studies, it is clear the PCM has an impact on reducing the energy consumption. The three different types of PCM that were studied each impacted the suites at different capacities. Table 10 shows the monetary costs of running the three different types of PCM, which will help to determine the best choice for the size of the suite investigated.

	North Facing	South Facing
M91/Q21	$24,159.90	$24,505.25
M51/Q21	$22,859.50	$23,205.25
M27/Q21	$21,605.75	$21,951.00

Table 10: Comparison of the PCM Suites

The values in this table represent the cost of running each system in the PCM suites, after 25 years. This was done to determine which type of PCM would save the most amount of money after a 25 year period. From these results, it is clear that the M27/Q21 PCM has the lowest operating cost, compared to the other types of PCM. This would be the best choice of materials to use in the 60 m^2 suite that was being studied. In order to create an accurate understanding of these results, new simulations were carried out. These new results, which are found in table 11, compare the original condominium in Toronto, with changes to the radiant system and the building envelope.

	North Facing: January 1st	North Facing: July 8th	South Facing: January 1st	South Facing: July 8th
Original Condo	17.90 kWh	9.16 kWh	22.00 kWh	10.72 kWh
New Radiant Temperatures	21.39 kWh	11.01 kWh	26.22 kWh	13.46 kWh
New U-Value	22.79 kWh	11.47 kWh	27.81 kWh	12.8 kWh

Table 11: Original Condo Compared with New Simulations

The original condo represents the north and south facing suites, without the PCM. These values show how much energy is being used to heat and cool the suites for one day, in both winter and summer. This system represents a typical condominium using only a radiant floor heating and cooling system. These values are based on the water being supplied to the system at 35°C and 12°C.

Another simulation was conducted, this one changing the ingoing water temperature to the radiant system. For the winter time, the ingoing hot water temperature was increased from 35°C to 45°C. This change resulted in a higher overall energy consumption for the day of January 1st. In the summer time, the ingoing cold water was reduced from 12°C to 5°C. This change in temperature resulted in an increase in energy usage for the day of July 8th.

One more simulation was conducted, this time with changed to the overall U-value of the building. The building envelope was changed to replicate more of a leaky building. The window-wall was changed to a U-value of 1.21 (W/m^2-K), compared to the original U-value of 0.98 (W/m^2-K). The R-value of the insulation in the exterior wall was reduced, resulting in a new overall R-value of 15.6 (m^2*k/W), compared to the original R-value of 17.3 (m^2*k/W). As a result of using these new values, the amount of energy being used in these suites increased.

The results from these new simulations show that the data used for the original condo, did in fact use the lowest amount of energy. This shows that the materials that were selected for the original condo were suitable for the Toronto climate. It also helps to show that the PCM were effective in helping to reduce the energy consumption, even when the original building was high efficient.

6.0 Conclusion

Modelling a radiant floor heating system with phase change materials was performed in this paper. The goal was to determine if this system would perform efficiently in the Toronto climate. In order for this to be done, a previous study conducted in Spain, by Mazo, Delgado, Marin and Zalba, 2011, was adapted. Using this adapted study, a new model was created and set in the Toronto area.

The main research for this paper used an example of a typical condominium in Toronto for the simulations. Two south facing suites and two north facing suites were investigated. Of those suites, one north facing suite had PCM below the finished floor, as well as one south facing suite. The objective of these simulations was to determine the impact of using PCM in the condo suites. Three different types of PCM were used, in order to determine which type had the biggest energy savings. The PCMs were M91/Q21, M51/Q21 and M27/Q21.

The results of the simulations first showed that the suites with the PCM did in fact have a lower energy usage than the other suites. This information led to further investigation, in order to establish the best choice between the PCM for energy savings. Within the section of modelling the typical Toronto condo, there is thorough research showing the temperature curves for January 1st and July 8th for each of the types of PCM. These results are showing the north and south suites as well. The many figures show the detailed difference in temperatures, as an effort to better understand what is happening within each suite, on a minute-by-minute basis.

The final results showed that the suites with the M27/Q21 PCM had to lowest energy usage. The south suite resulted in a cost savings of $251.25 per year, compared to the suite without PCM. The north suite resulted in a cost savings of $249.44 per year, compared to the suite without PCM. These cost savings are based on the rate of energy used and the cost of the energy, provided by the Ontario Energy Board.

7.0 Further Research

Further research on the topic of radiant floor heating with phase change materials in the Toronto climate can look at improving this system. The results from this study showed that the phase change materials do in fact add value to the system, but as this was theoretical research, there is a lot more work to be done on this topic. One of the areas would be to focus on the HVAC system. In this paper, the HVAC was set to turn on and off at specific times of the day. The system was not set-up to automatically turn off when the temperature in the room was at its set point. This can be changed to determine how the PCM are helping to keep the indoor temperature, by allowing the HVAC system to automatically adjust it's on and off times.

Another area for further research would be on the actual PCM product. As this research was conceptual, the product that was used isn't actually available for flooring applications. As the technology of PCM becomes more advanced, new products will become available for use in the floor. These will probably help to reduce the energy consumption even more. This would be a good place to continue to research this topic.

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