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Using PCM in two proposed residential buildings in Christchurch, New Zealand

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Abstract

A characteristic feature of lightweight constructions is their low thermal mass which cause high internal temperature fluctuations that require high heating and cooling demand throughout the year. Phase Change Materials (PCMs) is effective in providing thermal inertia to low thermal mass buildings. The aim of this paper is to analyse the thermal behaviour of two proposed lightweight buildings designed for homeless people and to investigate the potential benefit achievable through the use of different types of PCM in the temperate climatic conditions of Christchurch, New Zealand. For this purpose, over 300 numerical simulations have been conducted using the simulation software DesignBuilder®. The bulk of the simulations were carried out under the assumption that the whole opaque building envelope is equipped with PCM. The results showed significant energy saving and comfort enhancement through the application of PCMs. Thereby, annual energy saving of over 50 % was reached for some of the PCMs considered. Additionally, the effectiveness of single, PCM-equipped structure components was investigated and substantial benefits between 19 and 27 % annual energy saving was achieved. However, occupant behaviour in terms of ventilation habits, occupancy of zones etc. remains one of the biggest challenges in any simulation work due to insufficient data.

Keywords: Structure component, occupant behaviour, energy savings, lightweight building and comfort enhancement

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INDEX OF ABBREVIATIONS

Abbreviation	Meaning	Abbreviation	Meaning
ADH	Annual	NV	natural ventilation
ADR	Annual	NVSP	Natural
AES	Annual	NZ	New Zealand
AHD	Annual	PCM	Phase Change
COP	Coefficient	PT	PureTemp
D	PCM layer	PU	Polyurethane
DB	DesignBuilde	OT	operative
DH	Discomfort	OUT	outside dry-bulb
HD	Heating	SC	structure
HSB	Heating	SCT	Shading Control
HSP	Heating	Seq.	Sequence
NNV	no natural	ΔP	Difference

Highlights

- Evaluated the thermal behaviour of two proposed lightweight buildings designed for homeless people.
- Investigated the potential benefit through the use of different PCM in temperate climatic conditions of Christchurch, New Zealand.
- Numerical simulations was conducted using the simulation software DesignBuilder®.
- Relationship exist between energy performance and comfort with the application of PCM
- Optimum performance of PCM showed a relative annual energy saving of 30 to 50 %.

1. Introduction

Buildings are necessary energy sink, they constitute one of the leading sectors of energy consumption globally. Putting this in proper perspective, buildings in the temperate and sub-tropical countries, such as in Europe, North America, and Asia account for nearly 40% of the final energy consumed with a similar global warming potential due to carbon dioxide release [1]. On the other hand, China and India with a population reaching 1.4 and 1.3 billion respectively; have about 45% and 30% of their population living in the cities. According to the energy international agency (EIA) report on energy outlook for developed and developing nations, these figures are expected to keep increasing in the next decade [2].

New Zealand with a growing population of over 4.7 million people, positioned between the Antarctica and tropics (34°– 47° latitude South) is also a culprit in high energy use of buildings [3]. The location of the country is the reason for the intense fluctuations in the weather conditions from a mild winter North Island to a hash and chilled winter South Island almost like those of Europe. This condition calls for serious concerns especially in the South Island of which Christchurch is one of the worst affected. In addition, the year 2011 earthquake resulted to huge destruction of over 100,000 residential houses with 10% of those homes irredeemable [4]. The situation calls for pragmatic reconstruction of the city which is expected to take several years.

Over the years, the different building interventions witnessed, is an indication of just how important building construction means to our development. Building envelope provides comfort and protection from unfavourable conditions caused by wind, sun, cold or hot extreme temperatures. The various energy flows within and outside of a building suggest building is a thermodynamically complex envelope. Under normal condition, the inside of a building is expected to provide warmth and shields from the effects of harsh weather conditions to guarantee a feeling of well-being. However, this has not been the case in colder or hotter climates due to inefficient code complying dwellings [5]. The use of energy efficient measures in building holds potential to cut down the energy demand of buildings. Heating and air conditioning are the major sources of energy needs of building for thermal comfort. Nevertheless, the heat is later lost due to inefficient thermal mass storage capacity of both the ceiling and wall assemblies. To optimally manage the use of energy, there is need to adapt concepts that avail favourable indoor conditions. This involves the use of materials that expeditiously regulate the interplay between the indoor and outdoor energy flows.

The study of Phase Change Material and its use as latent heat storage in different applications is gaining more attention in recent times [6–8]. Various PCM intervention in buildings have been reported. The use of PCM in building component can improve the thermal inertia by storing the excess heat in the building during the day time and later releasing the stored heat at night to the indoor environment when there is a drop in temperatures below the melting point of the PCM. According to ref [1], selection of PCM for building application is expected to satisfy the following criteria: high thermal conductivity, high latent heat of fusion, the melting temperature range must fit the application, stable chemical and physical properties, and readily available at a low cost.

As remarked by Hadorn [9] PCM are divided into three groups: Organic, inorganic and eutectics compounds. Details of this division have been widely reported [7,10]. However, researchers have further classified PCM according to their phase transition state [11,12]. Solid-liquid PCM, solid-solid PCM and liquid-gas PCM. Organic PCM are known to exhibit excellent properties for building use [12]. They melt congruently and do not experience phase segregation. Furthermore, they are usually safe, non-reactive, have a moderate latent heat of fusion and self-nucleating properties. Phase segregation and supercooling are problems associated with the use of inorganic PCMs [13]. The promising stability of organic PCMs after numerous thermal cycles were pointed out in [14]. PCMs which are less stable can experience a shift in the melting range after numerous cycles which makes them unsuitable for passive use in residential applications. As a result, this study focuses on organic PCMs.

The systematic application of PCM to building for energy and cost savings have been published [15–19]. Among these studies [16], showed how PCM can be applied to underfloor-electric heating systems and achieved significant energy savings. [15] investigated the potential of a thermal activated ceiling panel and reported that the potential of the newly developed ceiling system was able to abate and regulate the excessive heat emanating from the ceiling of an office building. Kuznik et al. [19] performed experiments to study the impregnation of PCMs into different construction materials. Other areas of PCM application in buildings includes wallboards

[20,21], floors and ceiling for passive solar heating [22]. In a study by [19], the energy equivalence of an organic based PCM was compared with those of concrete. In the study, a 5 mm thick PCM plasterboard having 60wt% microencapsulated paraffin with a melting point temperature of 22℃ store an amount of thermal energy tantamount to 80 mm thick concrete.

Several modelling and numerical simulation involving PCM in building components have been undertaken to optimize energy performance in buildings [23–25]. Na Zhu et al [23] presented a summary of some studies that employed the use of experiments, numerical and simulation approaches to investigate the thermal performance and dynamic characteristics of PCM enhanced buildings. They highlighted the benefit PCM provides in terms of free cooling and peak load shifting. In a similar vein [19], carried out experimental and numerical investigation of microencapsulated perforated panel to check their performance. From their studies, results showed that the perforated panel provided an augmentation in the heat absorbed and released. In another study, Diarce et al [24] applied the use of computational simulation to study a ventilated active façade with PCM. The thermal behaviour of the façade was shown to compare favourably with different traditional construction systems.

Based on findings from various technical literature reviewed on PCM enhanced buildings, the annual energy savings can easily reach up to 38% in temperate climates. However, the studies were focused on the performance of a single zone unit; hence the results are not readily transferable to multi zone buildings. Only a few studies [26,27] were found to have accessed the performance of PCM in complex constructions. In addition, none of these studies investigated the thermal performance of lightweight PCM-enhanced buildings considered here and in climate conditions like the ones prevailing in the Christchurch region. As such, the objective of the present study is to investigate the thermal inertia and energy performance of two lightweight PCM enhanced buildings, the first being a single zone unit and the second a multizone (i.e. with internal walls) complex envelope. The choice of lightweight building materials is due to their low costs, flexibility and ease of use in architecture design. Although, the low thermal mass of such buildings usually results in large temperature fluctuations throughout the day and increased heating and cooling loads. For this reason, the application of PCM and its effect on the thermal performance of the proposed building designs is studied in this work using DesignBuilder®.

2. Methodology

2.1 Software description

This section is devoted to the description of the main procedure adapted for the development of this study. The two-building studied in this work were modelled with Designbuilder® (DB) for dynamic comparison. One of the most important features of the program is the provision and use of real hourly weather data in the simulations, based on a variety of cities all over the world [28]. Thus, the user is able to assess the performance of the building under actual operating conditions. In addition, the complex interactions inside a building, results in a highly nonlinear mass and energy balances which become time consuming and cumbersome to try and attempt solving the problem by numerical formulations [24,29]. The heating and cooling loads are calculated according to the ASHRAE-approved 'Heat Balance' method, implemented in EnergyPlus [30]. The ASHRAE Standard 55-2004 is used for the determination of the discomfort hours which were used in this work and stand for "the time when the zone humidity and operative temperature are not in the ASHRAE 55 summer or winter clothes region" [31].

The present study is part of a proposed social housing project in Christchurch (New Zealand), which intends to provide simple housing for residents who would otherwise had to live on the streets. The simulations consider multiple internal heat gains from occupants, equipment etc. and were performed under the use of real weather data. The simulation study provides a comprehensive first estimation of the benefits achievable by the application of PCM for two specific building designs, prior to employing PCM in these buildings. For the setting up of the simulation models, architectural plans and specifications regarding the construction materials have been received from the executing contractor and presented in Fig. 1 and 2 respectively for Buildings A and B.

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2.2 Zone schedule

The schedule type for each room space (zone) and other room-based schedules are listed in Table 1 and their various schedules are defined in Fig. 3. Table 1 shows the occupancy, shading control, mechanical and natural ventilation and heating schedule type for the two buildings under study. Consider row 1 of Table 1 (Bedroom A), the schedules are given in percentages, meaning from 12 am to 7 am, the bedroom occupancy is full, and only 50% of the occupants are present in the bedroom from 7 am to 8 am. A further reduction to 25% in the occupancy is observed between 8am and 9am. From 9am until 10 pm the bedroom is left unoccupied, then by 11 pm 25% of the occupants are back and between 11 pm and 12 am the bedroom is fully occupied. A similar pattern is used to describe the rest of the schedules presented for this work.

For the simulations performed in this work, the Energy Plus simulation engine 'Version 8.1.0.008' has been used. A one-dimensional conduction finite-difference solution algorithm is used in this version. This algorithm was validated in [32] against multiple test suites (analytical verification, comparative testing and empirical validation), hence is suitable for the simulation of real thermal behaviour of PCMs in buildings. In the simulations, the PCM is consistently positioned to the interior surface of the insulation layer for all structure components. Thus, the partition walls have been equipped on either side of the insulation. The wall assembly is made of four (4) different layers as shown in Table 3.

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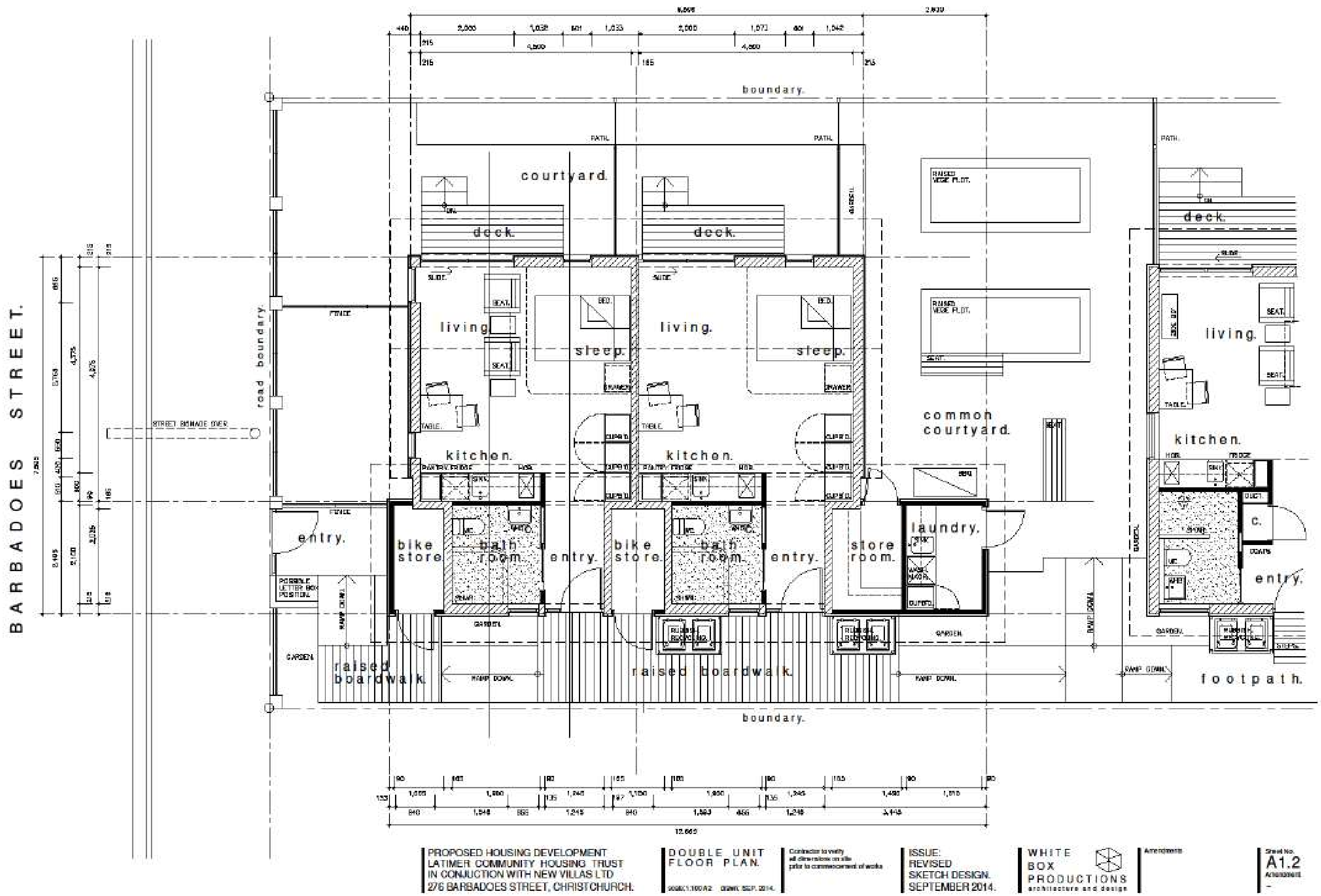

Fig. 1. Plan of the model lightweight Building A.

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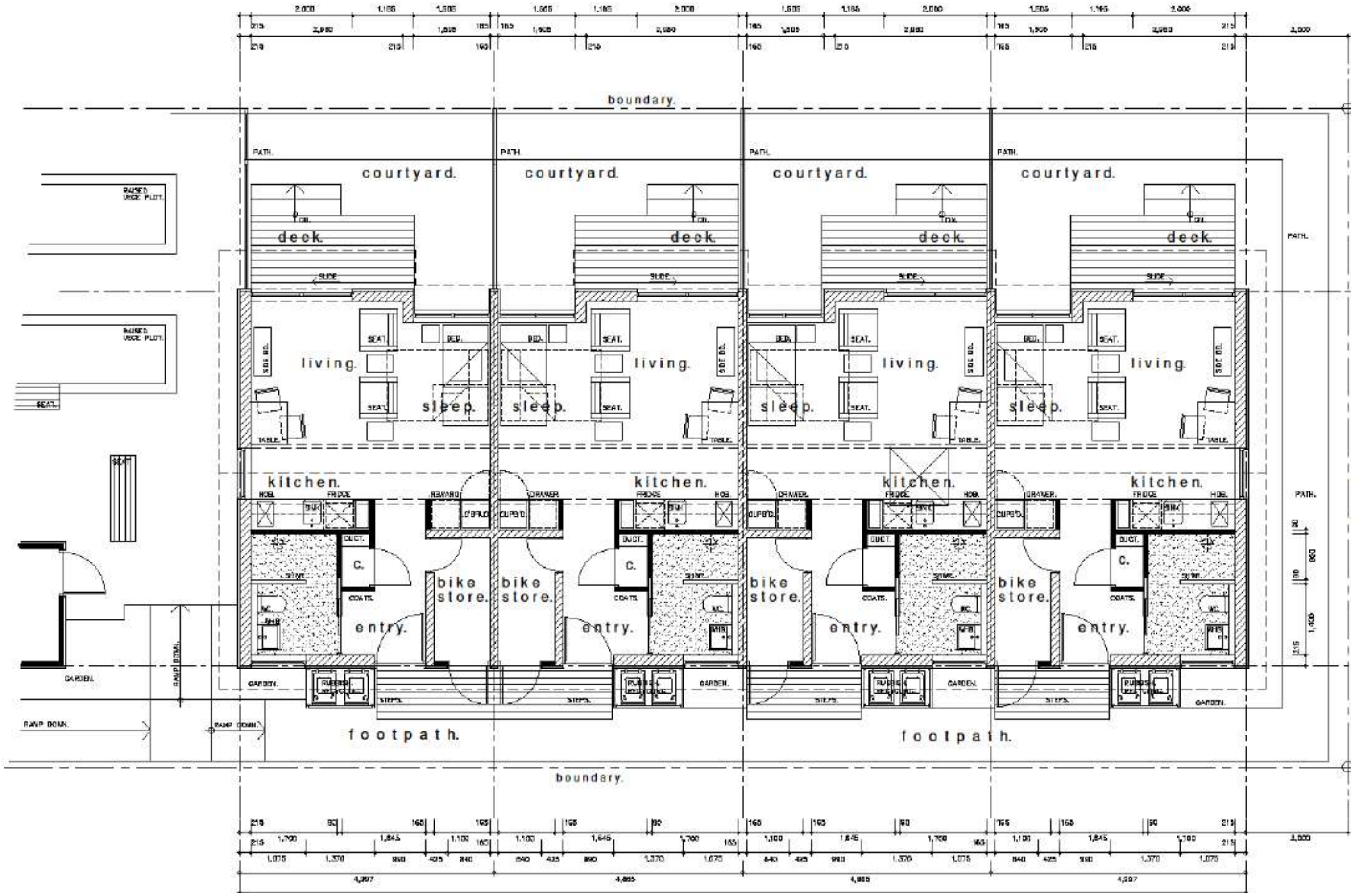

Fig. 2. Plan of the model lightweight Building B.

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Table 1

Allocation of internal load schedules for every zone.

Building zone	Occupancy	Mechanical ventilation	Natural ventilation	Heating
Bedroom A	Bedroom schedule 1	Bedroom schedule 1	Standard schedule	SH
Lounge A	Lounge schedule	Lounge schedule	Standard schedule	SH
Kitchen A	Kitchen schedule	Kitchen schedule	Standard schedule	SH
Circulation Area A	Circulation schedule	Circulation area schedule	Standard schedule	SH
Bathroom A	Bathroom schedule	Bathroom schedule	Standard schedule	BH
Storage Room A	No occupancy	No Mechanical Ventilation	No Natural Ventilation	NH
Bedroom B	Bedroom schedule 2	Bedroom schedule 2	Standard schedule	SH
Kitchen B	Kitchen schedule	Kitchen schedule	Standard schedule	SH
Circulation Area B	Circulation schedule	Circulation area schedule	Standard schedule	SH
Bathroom B	Bathroom schedule	Bathroom schedule	Standard schedule	BH
Storage room B	No occupancy	No Mechanical Ventilation	No Natural Ventilation	NH

SH: Standard Heating, BH: Bathroom Heating, NH: No Heating

Fig. 3. Daily different schedules for buildings A and B.

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Table 2

Building materials with thermal absorptance of 0.9.

Layer	Material	Conductivity $(\mathbf{W/mK})$	Specific heat $(\mathbf{J/kgK})$	Density $(\mathbf{kg/m^3})$	Thickness (m)	Solar/Visible absorptance
1	Oriented Strand Board	0.105	1880	650	0.0127	0.7
2	Expanded Polystyrene	0.040	1400	15	0.1910	0.6
3	PCM if applicable				0.005/0.0015	
4	Lightweight Metallic Cladding	0.290	1000	1250	0.0055	0.4
5	Extruded Polystyrene - CO2 Blowing	0.034	1400	35	0.2000	0.6
6	Roofing Felt	0.190	837	960	0.0050	0.8
7	Plywood (Lightweight)	0.150	2500	560	0.0180	0.78
8	Expanded Polystyrene - Lightweight	0.053	1400	12	0.0600	0.6
9	Underlay, Cork	0.050	1500	200	0.0029	0.6
10	Timber Flooring	0.140	1200	650	0.0140	0.78
11	Painted Oak	0.190	2390	700	0.0400	0.5

Table 3

Building assembly composition.

Assembly	Composition layer †	U-Value $(\mathbf{W/m^2K})$
External walls	1,2,3,1	0.191
Partition walls	1,3,2,3,1	0.245
Roofs	4,5,3,6	0.163
Floor	7,8,3,9,10	0.599
External door	11	2.125

† each layer ID represent the layer that constitute the whole assembly (For example component layer 1,2,3,1 represent Oriented strand board in the outside, Expanded polystyrene, PCM if applicable, then Oriented strand board in the building interior)

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Table 4

Properties of openings.

Layer	Material	Conductivity ($\mathbf{W/mK}$)	Thickness (m)	Solar Transmittance	Outside solar reflectance	Inside solar reflectance
1	Viracon Norther Low E on clear	1	0.00305	0.613	0.2	0.257
2	Air	-	0.013	-	-	-
3	Drapes - close weave	0.1	0.003	0.05	0.3	-

Table 5

Frame and dividers.

Layer	U-Value ($\mathbf{W/m^2K}$)	Dividers Width (m)	Horizontal dividers	Vertical dividers	Frame Width (m)
1	3.476	0.02	1	1	0.04

2.3 PCM selection

The examined PCMs employed for this study are presented. A mettler Toledo Differential Scanning Calorimeter (DSC) was used to measure the thermo-physical properties listed in Table 6. The phase change enthalpy of the selected PCMs range from 180 – 203 kJ/kg, achieved at a peak melting temperature range of 18 to 25 °C.

Table 6
Thermo-physical properties of various Organic PCMs.

PCM	Thermal conductivity (λ) ($\mathbf{W/mK}$)	Specific heat ($\mathbf{C_P}$) ($\mathbf{J/kgK}$)	Density (ρ) ($\mathbf{kg/m^3}$)	Heat of fusion ($\Delta h_{s,l}$)($\mathbf{kJ/kg}$)
BioPCMat Q21	0.2	1970	235	186
BioPCMat Q23	0.2	1970	235	186
PureTemp 18	0.2	1740	860	189
PureTemp 20	0.185	2110	860	180
PureTemp 23	0.2	1915	860	203
PureTemp 24	0.2	2945	860	185
PureTemp 25	0.2	2140	860	185

The heating rate and sample masses used for the DSC are 1 ℃/min and 4.89 to 6.58 mg. The Enthalpy-temperature (H-T) curve is a major characteristic feature of PCM that helps determine the heat storage capacity. Different methods have been reported to determine H-T relationship, some of which are the temperature history method and calorimetric method [28]. The various PCM H-T data used in this study were obtained from DSC analysis and have been identified as suitable for the passive building [33]. The optimum peak melting temperature to attain the highest energy savings is expected to be between 18 and 24 °C for colder climates. The H-T curve of PT24 at various temperature conditions with the major phase change occurring between 23 ℃ and 24 ℃ is shown in Fig. 4.

The design of the PCM sandwich panel previously reported in [34] is similar to the external wall design investigated in this paper. Therefore, it can be expected that for a small PCM layer of thickness (d) = 3 mm will have significant effects on the heating demand of the buildings. In addition, a10 mm PCM thickness was also considered in order to determine the maximum effect that PCM may have on the heating demand and comfort level.

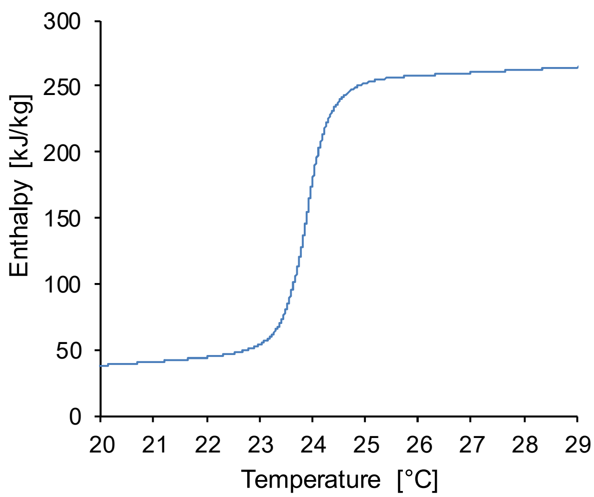

Fig. 4. Enthalpy-Temperature curve for PT24.

2.4 *Analysis of energy performance and comfort*

The annual heating demand (HD_A) and annual discomfort hours (DH_A) are important measures of the energy performance and comfort level of a building, and lead to the definition of strong comparison criteria. The annual energy saving (ES_A) and annual comfort enhancement (CE_A) achieved through the application of PCM are calculated as follows:

$$ES_A = HD_{A/NoPCM} - HD_{A/PCM} \quad (2.1)$$

and

$$CE_A = DH_{A/NoPCM} - DH_{A/PCM} \quad (2.2)$$

In terms of hourly criteria, equations 2.2 is rewritten as:

$$DR = DH = DH_{NoPCM} - DH_{PCM} \quad (2.3)$$

Where DR represent the discomfort reduction. As pointed out in section 2.1, DB enables the display of simulation results at building and zone levels. As such, the obtained DH results and floor areas for the zones are used to determine building averages. Eq.(2.4) shows the computational method of DB used to calculate building averages weighted by zone floor areas, which is done in this manner for important values like DH and HD.

$$DH_b = \frac{(DH_{z1} \cdot A_{z1} + DH_{z2} \cdot A_{z2} + \cdots DH_{zn} \cdot A_{zn})}{(A_{z1} + A_{z2} + \cdots + A_{zn})} \quad (2.4)$$

The discomfort model based on ASHRAE Standard 55-2004 and the Fanger Predicted Mean Vote (Fanger PMV), calculated according to ISO 7730, were used from the generated simulation data to evaluate the comfort level of occupants. Thereby, the discomfort hours (DH) data is equivalent to ASHRAE 'unmet load hours' [35] and stands

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for "the time when the zone humidity ratio and operative temperature is not in the ASHRAE 55-2004 summer or winter clothes region" [36]. The respective comfort areas for winter and summer clothes are illustrated in Fig. 5. Furthermore, for the calculation of the discomfort hours, the occupation of the considered zone is needed so DH are not included for times when the room is completely unoccupied.

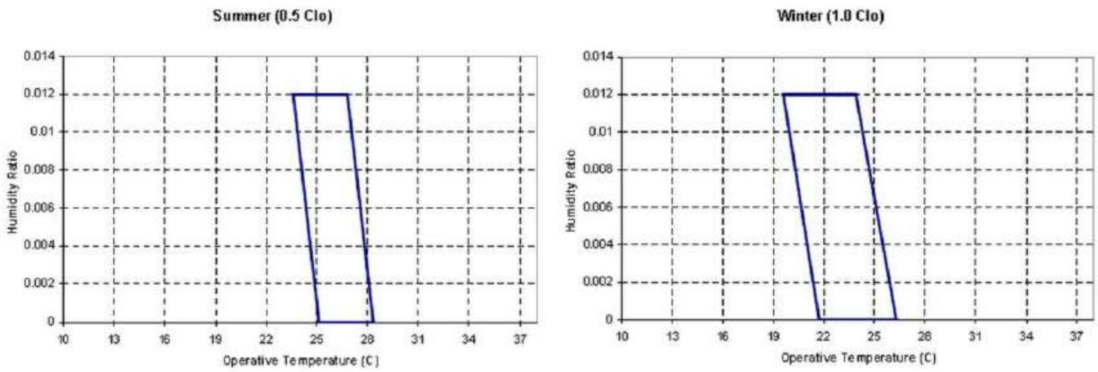

Fig. 5. Comfort area (area between blue lines) for summer clothes region (left) and winter clothes region (right) [32].

In general, the following assumptions have been made concerning the occupants:

i. Met: 1 for all occupants (meaning only men will live at the premises),
ii. The clothing insulation is assumed to be 1 clo for the winter and 0.5 clo during summer,
iii. The occupant's activity and calculation of comfort is based on room type.

Simulations have been performed for several different building envelopes containing different PCMs or, in some cases, without the application of PCM. To be able to effectively compare the simulation results, five sequences (Seq.) have been defined which generally differ in their set temperatures for heating (

Table 7). Variables contained in those sequences are:

a) The Heating Setpoint (HSP) indicates the ideal indoor air temperature (T_A) of the zone (or building) when the HVAC system is turned on.
b) The Heating Setback (HSB) defines the minimum T_A in a building when the HVAC system is turned off.
c) When the Natural Ventilation Setpoint (NVSP) is exceeded in a room, natural ventilation (i.e. the opening of windows) is induced provided that the external T_A is lower than the internal T_A and the respective zone is occupied according to its occupancy schedule.
d) The Shading Control Temperature (SCT) defines the minimum temperature for the operation of the shading devices. When this temperature is exceeded in an occupied zone the drapes are closed to reduce further solar gains.

A 2 °C temperature difference (ΔT_{NV}) between the NVSP and the HSP has been defined for all simulations in this paper. Since the heating demand is influenced negatively from a small ΔT_{NV} and the opposite applies to the occupant's comfort, a balance had to be found. Based on further simulations with different ΔT_{NV} values, it can be stated that a ΔT_{NV} of 2 °C represents a good compromise. Apart from PCM thickness and its position, all simulation model sequence of Building A and B are identical.

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Table 7

Sequence definition for both Buildings (HSP/HSB/NVSP/SCT).

Sequence	Bedroom	Lounge	Kitchen	Circulation	Bathroom
1	20/18/24/24	20/18/24/24	20/18/24/24	20/18/24/24	20/14/24/24
2	21/19/24/24	21/19/24/24	21/19/24/24	21/19/24/24	21/14/24/24
3	22/20/24/24	22/20/24/24	22/20/24/24	22/20/24/24	22/14/24/24
4	23/21/25/24.5	23/21/25/24.5	23/21/25/24.5	23/21/25/24.5	23/14/25/24.5
5	24/21/26/25.5	24/21/26/25.5	24/21/26/25.5	24/21/26/25.5	24/14/26/25.5

3. Results and Discussion

In this section of the study, an in-depth analysis of the main generated simulation results were accessed in terms of the following criteria. The benefit of the application of PCM on an annual scale based on the heating demand and the comfort level within the building. In addition, the marginal benefit, building performance and the effect of PCM in different locations of the building also formed the basis of this analysis.

3.1 PCM benefit on annual simulation

It was found that there are significant energy saving potentials, as well as a high potential to reduce discomfort through the application of each type and thickness of PCM. As expected, there is no identifiable case where one PCM has the most beneficial effects on either comfort or energy saving for every sequence analysed. An increase in PCM thickness has a positive effect on the $\mathrm{ES_A}$ and $\mathrm{DH_A}$ due to the associated increase in the thermal mass of the building envelope, when PCM was used. As will be discussed later, the limited benefit of using excessive PCM thickness may not be sufficient to overweigh the extra cost associated with the use of large quantity of PCM.

3.1.1 Heating demand

The relative annual energy savings ($\mathrm{ES_{A-Rel}}$) due to heating represent the percentage of energy saved through the application of PCM in relation to the usual heating demand i.e. without PCM. From equation 2.1, each PCM-model availed a considerable energy saving potential for both buildings irrespective of sequence or thickness (*d*). Table 1 and 3.2 presents the $\mathrm{ES_{A-Rel}}$ ranges for buildings A and B computed from equation (3.1):

$$\mathrm{ES_{A-Rel}} = \frac{\mathrm{ES_A}}{\mathrm{HD_{A/NoPCM}}} \times 100 \quad (3.1)$$

An overview about the efficiency of the PCMs is brought to bear in Tables 8 and 9. The maximum $\mathrm{ES_{A-Rel}}$ values are obtained for the Seq. 1 models. This is mainly due to the definition of the relative annual energy savings since the $\mathrm{HD_{A/NoPCM}}$ is quite low for Seq. 1 models and therefore even a small annual energy savings resulted in a high ($\mathrm{ES_{A-Rel}}$) value. The exact opposite is seen for the total $\mathrm{ES_A}$ values meaning that the total energy saved tends to rise with increasing Seq. numbers for both buildings and irrespective of the NV-setting.

Table 8
Relative Annual Energy Savings for Building A (%).

Sequence	Naturally vented (NV)		Not naturally vented (NNV)	
	d = 10 mm	*d* = 3 mm	*d* = 10 mm	*d* = 3 mm
1	43.45 - 56.49	30.85 - 52.26	35.67 - 50.00	22.77 - 45.78
2	35.71 - 54.14	26.22 - 45.07	29.06 - 46.94	20.91 - 37.43

3	29.45 - 51.81	18.87 - 44.47	21.96 - 42.26	14.22 - 34.45
4	22.65 - 45.12	12.91 - 38.63	17.72 - 37.06	10.58 - 30.12
5	19.43 - 38.54	11.25 - 33.53	13.97 - 29.55	8.38 - 24.19

Table 9
Relative Annual Energy Savings for Building B (%).

Sequence	NV		NNV	
	d = 10 mm	*d* = 3 mm	*d* = 10 mm	*d* = 3 mm
1	54.47 - 71.40	51.83 - 61.77	45.58 - 64.06	38.62 - 58.19
2	41.30 - 65.89	39.05 - 55.82	35.65 - 58.30	33.76 - 47.15
3	30.45 - 57.88	28.55 - 51.97	26.55 - 49.72	24.78 - 40.77
4	25.59 - 49.88	23.33 - 47.17	21.60 - 42.90	19.87 - 37.03
5	23.07 - 45.03	20.70 - 44.08	17.46 - 33.68	16.03 - 30.53

The lowest ES_{A-Rel} is 8.38 % and was obtained for the PT18 NNV-model with Seq. 5 setting (Building A, *d* = 3 mm). However, the average energy saving is higher than 30 % and reaches an extraordinary value of 71.4 % for the Q21 NV-model with Seq. 1 setting (Building B, *d* = 10 mm).

On the basis of the more detailed results, it can be stated that in general, the most efficient PCM for a sequence has a melting range which is close to the defined Heating Set point. This proves that the beneficial effects are dependent on how well the melting range of the PCM and the HSP matches each other. A similar situation was observed in [32] where the maximum diurnal energy storage occurred for PCMs at the melting temperature close to the average room temperature of the building. The results for the zones show that the heating demand and perceived comfort is considerably different between the zones as depicted in Fig. 6.

The biggest PCM effects on heating demand can be seen from Fig. for the bedroom zones and circulation areas with a minimum annual heating demand of less than 10 kWh/m^2 and about 40 kWh/m^2 for both PCMs considered. There is only a minor PCM effect for the kitchen and bathroom zones. Furthermore, external zones have a higher heating demand than internal zones. The results are plausible as the external zones have an additional external wall area where a more intense and larger heat transfer takes place than between partition walls. The heat exchange between the single residential units is conceivably low as it is assumed that every unit runs with the same temperature setpoints and heating schedules. The poor performance of the circulation areas can be traced back to the higher total fresh air values usually present in these zones.

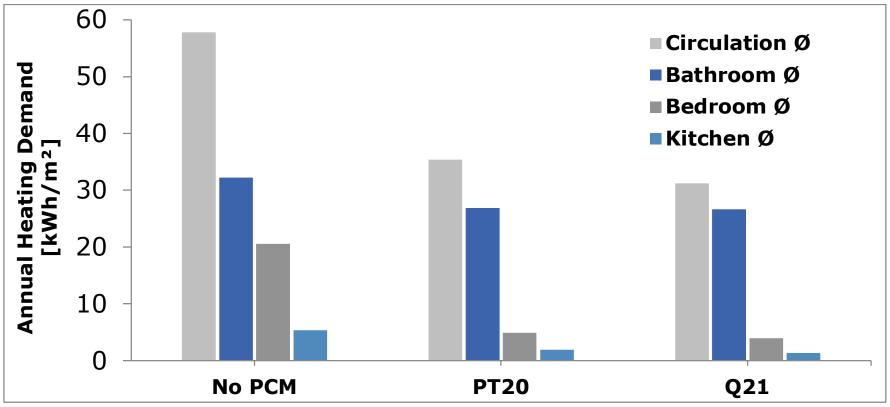

Fig. 6. Building B, *d* = 0.003, NV, Seq. 2, comparison of AHD on zone level.

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3.1.2 Comfort

During summer, the heat gains from solar radiation, air infiltration and heat conduction can raise the indoor temperatures to an uncomfortably high level (Fig. 7). Without the ability to purposely use colder external air for cooling, the internal temperatures can rise even higher. For the analysis of buildings A and B, the No-PCM models with and without natural ventilation in conjunction with sequence 4 setting (Seq. 4; NV/No-PCM and NNV/No-PCM) was chosen for analysis and result presented in Fig. 7 and 8 respectively. In addition, BioPCM mat Q23 models (Seq. 4; NV/Q23 and NN/VQ23) was chosen as it availed best performance in terms of annual energy savings and discomfort reduction.

The total number of discomfort hours experienced due to indoor overheating is fairly small for naturally vented buildings as shown in both Figs. 7 and 8 (top right) with NVQ23. However, the lack of thermal mass in the No-PCM models cause higher temperature fluctuations up to 31 ℃. Overnight the temperature is reduced in both No-PCM-models but only the NV No-PCM model reaches temperatures below the HSP of Seq. 4. Hence, the hot water radiators must heat up the building in the morning hours before the building naturally heats up through high OUTs, solar gains etc.

To quantify this, as stated for Fanger PMV models, the overheating-DH must be less or equal to 200.74 for all NV-buildings [32]. The overheating-DH for both buildings are low for naturally vented buildings whether or not PCM was applied. However, the naturally ventilated model without PCM tends to overheat more during summer, which means natural ventilation is equally important to provide comfort. In comparison with discomfort caused by reduced temperatures, discomfort due to overheating represents less than one third of the total annual discomfort hours. In the case of NNV-models this proportion can shift drastically.

In order to perform a valid comparison between building A and B, the outermost zones of both buildings were compared. Taking into account that the bedroom zones of building B accounts for the combination of bedroom and lounge in building A. The DH results showed that the occupants of building B experienced more annual DH from overheating even with higher rates of fresh air changes than the occupants of building A. This situation is valid for most of the models and especially for the No-PCM cases. Reasons for this is the occupancy behaviour (or schedule) adopted for building B due to the number of occupants, their metabolic rate, the increased number of indoor equipment as well as the higher number of partitions.

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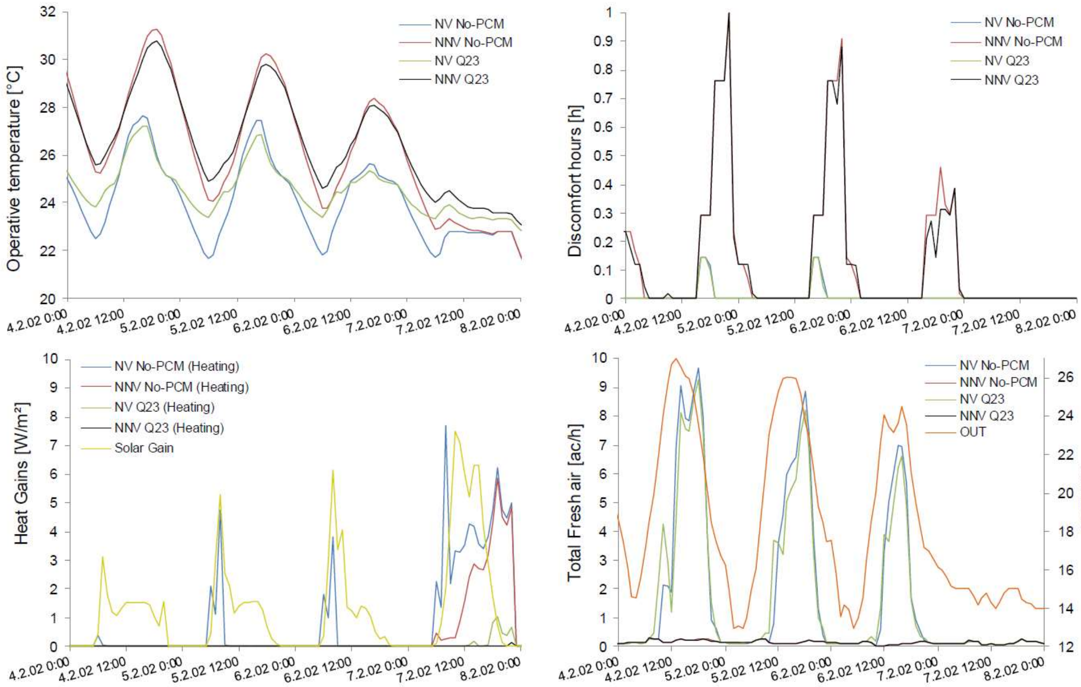

Fig. 7. Operative temperature (top left), heat gains (bottom left) discomfort hours (top right) and total fresh air (bottom right) from 4th Feb – 7th Feb summer days for building A.

In the 2013 addenda to the ASHRAE standard 55, it is explicitly emphasized that the standard is not applicable to sleeping occupants as the bed and bedding can provide substantial thermal insulation and occupants may adjust the bedding to suit their personal preferences [23]. The same situation applies to the Fanger PMV model [24]. Consequently, the real discomfort may be significantly lower. In fact, in [37] it is stated that the insulation values provided by the bed and bedding vary between 0.9 and 4.89 clo. The respective thermal neutral temperatures vary between 30.1 and 8.9 °C. The indoor air temperature of the building with a fixed lower set point never drops below 24 °C which is why it can be assumed that the overnight indoor-conditions are not highly uncomfortable in any of the investigated models. The investigation of the hourly discomfort data for the bedrooms of Building A has shown that around 82 % of the discomfort hours are detected for the sleep period (11pm to 8am) and generally the operative temperature never goes below 22.2 °C. The analysis of the discomfort hour distributions for the bedrooms of Building B shows a similar pattern. So the calculated annual discomfort hours may be reduced by 69 % to obtain the real value.

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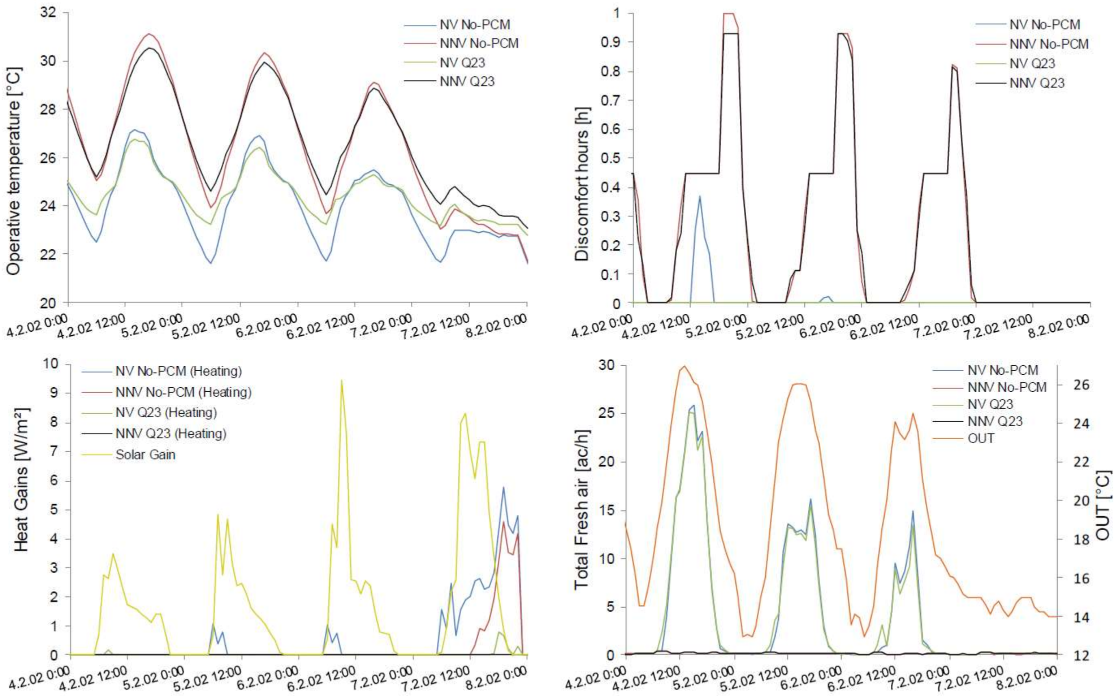

Figure 0-10: 04.02.-08.02. Results for summer days (building 2); from top left to bottom right: OT, DH, HD, TFA & OUT

Fig. 8. Operative temperature (top left), heat gains (bottom left) discomfort hours (top right) and total fresh air (bottom right) from 4th Feb – 7th Feb summer days for building B.

3.2 Marginal PCM benefit

When comparing the energy savings comfort enhancement on an annual basis, due to the application of a particular PCM type of varying thickness*,* it is striking that the differences are considerably low.

Table 10 presents result for the difference between PCM thickness of 10 mm and 3 mm for Building A, where natural ventilation of the building is present. The marginal benefit of each PCM considered in terms of annual heating demand per square metre is analysed when two different PCM thickness is compared (i.e. $\Delta P = \mathbf{AHD_{d=10}} - \mathbf{AHD_{d=3}}$).

Table 10
Influence of thickness (*d)* on annual heating demand
for building A (Wh/m²).

Sequence	ΔP_{PT18}	ΔP_{PT20}	ΔP_{PT23}	ΔP_{PT24}	ΔP_{PT25}	ΔP_{Q21}	ΔP_{Q23}
1	1727	878	2860	2261	2585	2282	2422
2	2745	1372	3437	2667	3163	2623	2872
3	4298	2361	4021	3089	3762	2952	3153
4	4979	3157	3864	3122	4058	3604	3316
5	4789	3271	3095	2475	2950	5108	4609

The marginal benefit per kg PCM reduces with an increasing total PCM mass and thus increasing layer thickness. That was expected as for infinitesimally small PCM layers, the storage capacity (enthalpy of fusion) of the PCM could be fully utilized. There is only a limited time frame (e.g. overnight) to release all heat stored in the PCM i.e. to undergo a full phase change from liquid to solid and vice versa in the daytime. A prerequisite for a full solidification is that the internal and external surface temperatures of the respective structure components (external walls, partition walls etc.) are lower than the solidification temperature of the particular PCM for a sufficient period of time. However, through the definition of fairly high Heating Setback Temperatures overnight, the necessary minimum internal surface temperatures may not be attained for most sequences for PT18, and some sequences for PT20 and Q21. Therefore, these PCMs are unable to undergo full phase change even during winter conditions for these cases. In addition, with increasing PCM thickness the time period needed for a full heat penetration of the whole PCM layer becomes larger as well [38]. Since the time period for phase change to occur is mainly dependent on weather conditions, it vary considerably. For this reason, the utilization rate of the PCM and the marginal benefit decreases with increasing PCM thickness.

3.3 Building performance

The ability of the PCM to prevent the building from cooling down fast once the electric heaters operate according to the HSB is the most important quality of the PCM in winter conditions and thus for the reduction of the annual heating demand. Therefore, the progressions of the operative temperature and heating demand (HD)-curves for No-PCM and PCM-models are illustrated in Fig. 9 and 10 for Building A and B in winter conditions (23rd June – 25th June).

The OT-curves present a distinct difference between overnight temperatures of the PCM and No-PCM models showing a significant, positive impact on the calculated comfort. Also, the stored heat released overnight can be seen from the HD-curves. The heating demand of the PCM-models is considerably smaller overnight and in the morning hours, while it increase slightly in the afternoon and evening periods.

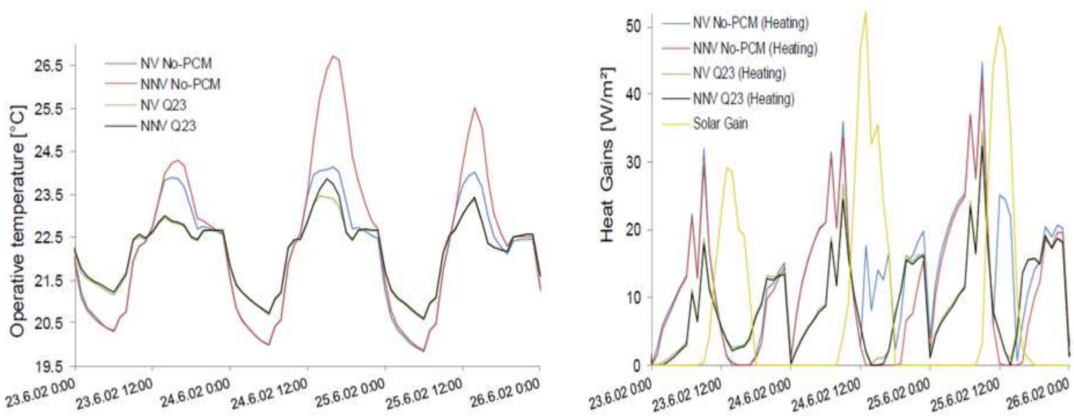

Fig. 9. Operative temperature (left) and heat gains (right) for winter days 23rd June. – 25th June (Building A, Seq. 4).

However from Figs. 9 and 10, the diurnal energy-savings are still positive by some margin for these days. This positive value results from the natural load shifting, which takes place due to the increased thermal mass. While the building receives large solar gains of up to 61 W/m^2 over the day, the excess heat is stored in the PCM, thus reduces overheating as mentioned before while the heat is released overnight. In the morning hours, when the HVAC system operates again according to the HSP, the ambient temperature is already at a higher level. Therefore, less energy is required to reach the HSP and the building soon after starts to receive increasing amounts of solar radiation. Hence, the PCM is mainly 'charged' from the solar gain and the stored thermal energy becomes available overnight when the excess heat is needed.

In addition, NV is needed in the PCM-models to avert overheating in summer conditions previously shown in Fig. 7. Although, a slight reduction in the maximum indoor temperature could be seen when comparing the two NNV-models (one with PCM and the other with No-PCM), the reduction is by no means sufficient to reach comfortable indoor conditions. As stated earlier, the lack of thermal mass in the No-PCM models results in higher indoor temperature fluctuations. Therefore, even in peak-summer, heating becomes constantly necessary in the morning hours for the naturally vented No-PCM models.

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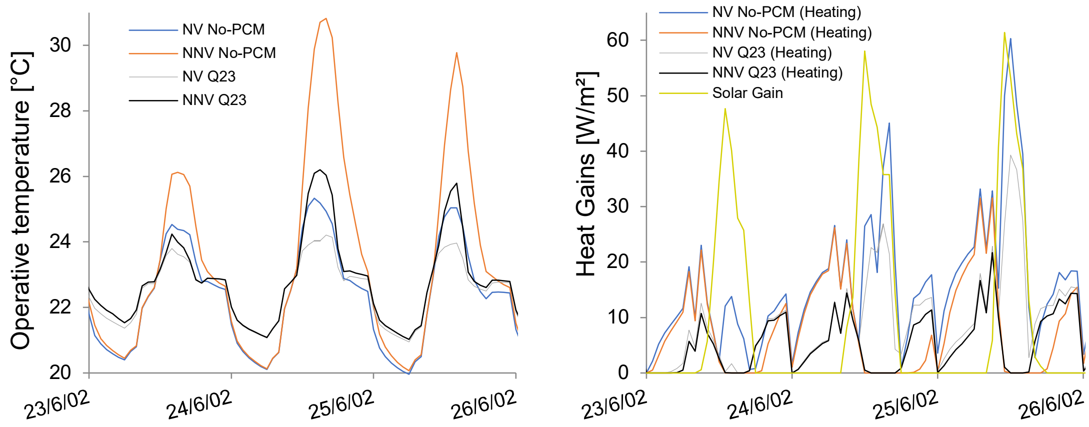

Fig. 10. Operative temperature (left) and heat gains (right) for winter days 23rd June. – 25th June (Building B, Seq. 4).

3.4 Effect of PCM in different building locations

A fraction of the investigated models was altered to demonstrate the respective energy saving potential for each structure component (SC). Due to economic considerations, the layer thickness in each SC was chosen to be 3 mm (or 2 layers of 1.5 mm for the internal partitions). Some of the results for Building B are illustrated in Fig. 11.

From Fig 9 applying PCM on the roof led to the highest annual energy savings when PCM is only applied to one SC. This applies to Building A as well. Although, the annual energy savings for the case 'All SCs' is considerably higher than that achievable by one single SC, the benefits are still significant. For instance, the maximum savings for a single SC (roof) reaches up to 11.42 kWh/m². This is equivalent to a total of 713.75 kWh energy saved per annum for the whole building. Since just over 3600 kWh are consumed per year in the associated No-PCM model, this is a significant saving of over 19%. For Building B, the percent energy saved compared to the No-PCM model is 27 %.

In terms of annual comfort enhancement, a distinct pattern can be observed as well, indicating that the application of PCM to the roof has a far greater impact on the occupant's comfort level than the utilization in other SCs. This is followed by the external walls, the partition walls and lastly the floor.

Therefore, it is expedient and necessary to normalize the annual energy savings and comfort enhancement by their associated PCM-mass, to be able to assess the beneficial effects of the different SCs correctly. Hence, the PCM-mass is kept constant among the SCs (Building A = 179.24 kg; Building B = 323.92 kg). The allocation of the resulting thickness to their associated SC is done and presented in Table 11.

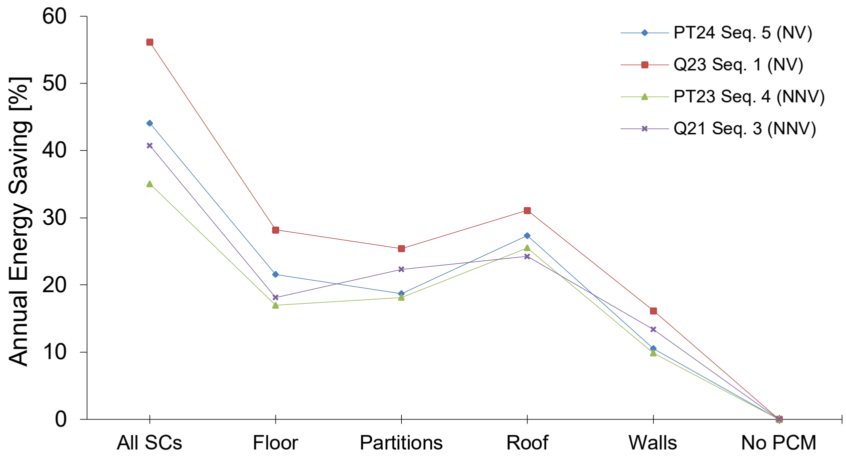

Fig. 11. Annual energy savings in % dependent on equipped surface for Building B.

Table 11
d's which result from constant PCM-masses per SC.

Building	Floor (mm)	Partition (mm)	Roof (mm)	External walls (mm)
A	3.333	1.843	2.766	2.496
B	2.801	1.195	2.713	5.287

These *d*'s were implemented in the respective models and consequently, the specific annual energy savings and comfort enhancement can be evaluated more independently of the PCM-mass. The respective specific annual energy savings obtained for Building A and B models with constant PCM mass per SC are depicted in Fig. 12 and 13.

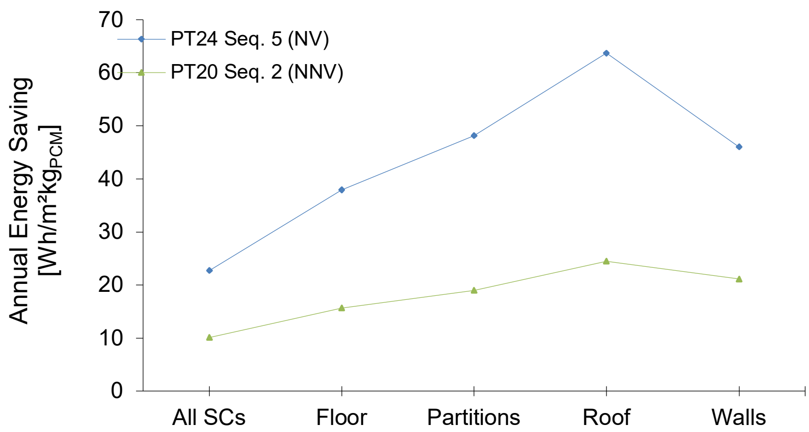

Fig. 12. Electricity saving potential per kg PCM dependent on equipped surface for Building A (const. PCM masses).

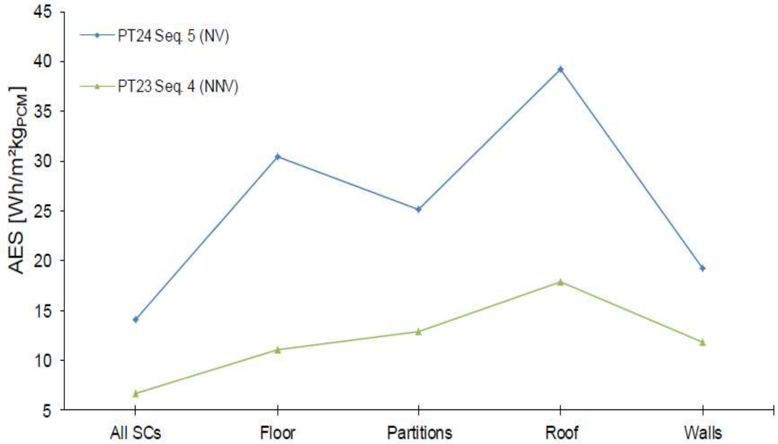

Fig. 13. Electricity saving potential per kg PCM dependent on equipped SC for building B (const. PCM masses).

The specific annual energy savings and comfort enhancement of the case where PCM is applied to all SCs are consistently lower than the results of the single SCs. This further confirms the findings that every additional kg of PCM must result in the reduction of the marginal benefit.

It can be confirmed for the specific values what was already stated for the absolute values, the roof has the biggest energy saving potential for both buildings. However, the second most efficient SC in terms of specific energy savings strongly varies among the buildings and the presence of ventilation. So, for Building A it is either the external walls or partitions and finally the floor.

However, as remarked by [1] the main idea should be to place the PCM in surfaces where the highest heat transport is expected (through radiation, conduction and convection). So for the most common buildings, the roof is the area where the highest heat transport values can be expected. The roof is exposed to high solar radiation and air stratification within the building leads to higher heat convection values. Subsequent, the external walls which receive the highest solar gains (north west and north east) should be equipped as well [19].

3.5 Error analysis

One of the biggest uncertainties is the ventilation behaviour of occupants. Only the case where NV was explicitly used to prevent the building from overheating was investigated. The real ventilation behaviour might be very different from this. Occupants will not just open the windows when the building is about to overheat but also as they have varying fresh air requirements. Additionally, the residents are not always in the building for the whole day meaning that often nobody will be in the building to operate the openings and shading devices. For this reason, preventing the overheating of the building might not work as good in reality as it was assumed in this work. It is difficult to correctly estimate the influence of the ventilation behaviour as no data is available for this particular type of occupant but it can be stated that the ventilation behaviour may increase the heating demand significantly. However, at the same time it must be stated that the heating requirements could be lower as well since the occupant will not be at home for the whole day and therefore the 'standard heating'-schedule may not be appropriate for the correct assessment of the heating demand.

Liu et al [15]. found that the heat transfer coefficient is significantly increased by the use of PCM in building walls compared to normal walls which is due to the higher energy exchange. However, the internal heat transfer coefficients, in numerical studies investigating PCM effects, are usually calculated according to correlations for normal building walls which therefore underestimate the real coefficients. The analysis of the internal heat transfer coefficients of the PCM-models has shown that they vary only little from the internal heat transfer coefficient calculated for the No-PCM walls. Therefore, it can be assumed that the energy saving potentials in the real application will be higher than the results given in this paper.

4. Conclusion

In this paper, the thermal performance of two lightweight buildings was investigated for the climatic conditions prevailing in the Christchurch region (NZ). The main purpose of the study was to show the benefits achievable by the application of PCM in these buildings. Therefore, seven (7) different PCMs were investigated. For the bulk of the simulations conducted, it was assumed that PCM was used in the whole opaque building envelope. However, for a smaller portion of the models it was assumed that only one SC at a time was equipped with PCM.

Substantial energy savings and increased comfort levels were the result of the PCM application. Most simulations showed a relative annual energy saving of 30 to 50 %. However, a maximum of 71.4 % was observed in one simulation. Generally, it was shown that the closer the melting range is to the average room temperature the higher the energy saving potential, while several simulations did not confirm this relation as PCMs with a less suitable melting range showed the highest energy savings. This led to the conclusion that the results obtained for small test rooms and single walls are not always applicable to more complex buildings.

When only a small PCM mass should be applied, the determination of the most effective surface or structure component is necessary. It was concluded that the application of PCM to the roof provides the highest energy saving potential for both buildings among all structure components (19 to 27 % annual energy savings).

In conclusion, the application of PCM improves the energetic performance and comfort levels of both buildings distinctly. Furthermore, temperature fluctuations are reduced throughout the year which is why the application of PCM can be recommended.

5. Recommendations

Most importantly, further research is essential on the typical behaviour of occupants. The behaviour influences the NVSP, the HSP and SCT considerably and hence the heating demand. This could be achieved by conduction a post occupancy study. Results from this type of quantitative study would be useful for future social housing projects which could improve the prediction accuracy for the heating demand significantly.

References

[1] Ikutegbe CA, Farid MM. Application of phase change material foam composites in the built environment: A critical review. Renew Sustain Energy Rev 2020;131:110008. https://doi.org/10.1016/j.rser.2020.110008.

[2] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8. https://doi.org/10.1016/j.enbuild.2007.03.007.

[3] Leardini P, Iliffe J, Gronert R. Building passive houses in subtropical climates? A lesson learnt from New Zealand. 17th Int. Passiv. House Conf., 2013.

[4] Tait M. www.nzherald.co.nz, n.d.

[5] Besen P, Leardini P, Boarin P. Passive Houses in New Zealand: a comparison between predicted and real performance through post-occupancy evaluation. South Pacific Passiv. House Conf. 2017, 2017.

[6] Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. Energy Convers Manag 2004;45:1597–615.

[7] Cabeza LF, Castell A, Barreneche C, De Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: A review. Renew Sustain Energy Rev 2011. https://doi.org/10.1016/j.rser.2010.11.018.

[8] Zhou D, Zhao CY, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Appl Energy 2012;92:593–605. https://doi.org/10.1016/j.apenergy.2011.08.025.

[9] Hadorn J-C. Thermal energy storage for solar and low energy buildings: state of the art. Universidad de Lleida; 2005.

[10] Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. vol. 23. 2003. https://doi.org/10.1016/S1359-

4311(02)00192-8.

[11] He B, Martin V, Setterwall F. Phase transition temperature ranges and storage density of paraffin wax phase change materials. Energy 2004;29:1785–804.

[12] Sharma RK, Ganesan P, Tyagi V V, Metselaar HSC, Sandaran SC. Developments in organic solid–liquid phase change materials and their applications in thermal energy storage. Energy Convers Manag 2015;95:193–228.

[13] Kuznik F, David D, Johannes K, Roux JJ. A review on phase change materials integrated in building walls. Renew Sustain Energy Rev 2011;15:379–91. https://doi.org/10.1016/j.rser.2010.08.019.

[14] Rathod MK, Banerjee J. Thermal stability of phase change materials used in latent heat energy storage systems: A review. Renew Sustain Energy Rev 2013. https://doi.org/10.1016/j.rser.2012.10.022.

[15] Koschenz M, Lehmann B. Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. Energy Build 2004;36:567–78. https://doi.org/10.1016/j.enbuild.2004.01.029.

[16] Barzin R, Chen JJJ, Young BR, Farid MM. Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system. Appl Energy 2015;148:39–48. https://doi.org/10.1016/j.apenergy.2015.03.027.

[17] Gholamibozanjani G, Farid M. A comparison between passive and active PCM systems applied to buildings. Renew Energy 2020;162:112–23. https://doi.org/10.1016/j.renene.2020.08.007.

[18] Gholamibozanjani G, Farid M. Application of an active PCM storage system into a building for heating/cooling load reduction. Energy 2020;210:118572. https://doi.org/10.1016/j.energy.2020.118572.

[19] Kuznik F, Virgone J. Experimental assessment of a phase change material for wall building use. Appl Energy 2009;86:2038–46. https://doi.org/10.1016/j.apenergy.2009.01.004.

[20] Errebai FB, Chikh S, Derradji L. Experimental and numerical investigation for improving the thermal performance of a microencapsulated phase change material plasterboard. Energy Convers Manag 2018;174:309–21.

[21] Kuznik F, Virgone J, Roux JJ. Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation. Energy Build 2008;40:148–56. https://doi.org/10.1016/j.enbuild.2007.01.022.

[22] Omrany H, GhaffarianHoseini A, GhaffarianHoseini A, Raahemifar K, Tookey J. Application of passive wall systems for improving the energy effciency in buildings: A comprehensive review. Renew Sustain Energy Rev 2016;62:1252–69. https://doi.org/10.1016/j.rser.2016.04.010.

[23] Zhu N, Ma Z, Wang S. Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Convers Manag 2009;50:3169–81.

[24] Diarce G, Urresti A, García-Romero A, Delgado A, Erkoreka A, Escudero C, et al. Ventilated active façades with PCM. Appl Energy 2013;109:530–7.

[25] Diarce G, Campos-Celador Á, Martin K, Urresti A, García-Romero A, Sala JM. A comparative study of the CFD modeling of a ventilated active façade including phase change materials. Appl Energy 2014;126:307–17. https://doi.org/10.1016/j.apenergy.2014.03.080.

[26] Mandilaras ID, Kontogeorgos DA, Founti MA. A hybrid methodology for the determination of the effective heat capacity of PCM enhanced building components. Renew Energy 2015. https://doi.org/10.1016/j.renene.2014.11.078.

[27] Vautherot M, Maréchal F, Farid MM. Analysis of energy requirements versus comfort levels for the integration of phase change materials in buildings. J Build Eng 2015;1:53–62.

[28] DesignBuilder. DesignBuilder EnergyPlus Simulation Documentation 2011:822.

[29] Cook P, Sproul A. Towards low-energy retail warehouse building. Archit Sci Rev 2011;54:206–14. https://doi.org/10.1080/00038628.2011.590055.

[30] ASHRAE. Thermal Environmental Conditions for Human Occupancy. ASHRAE. Am Soc Heating, Refrig Air-Conditioning Eng ASHRAE Stand 2010.

[31] DesignBuilder. DesignBuilder and Energy Plus simulation. DesignBuilder 2018.

[32] DesignBuilder. DesignBuilder, Comfort Analysis. DesignBuilder 2018.

[33] Tabares-Velasco PC, Christensen C, Bianchi M. Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. Build Environ 2012;54:186–96.

[34] Marín JM, Zalba B, Cabeza LF, Mehling H. Determination of enthalpy–temperature curves of phase change materials with the temperature-history method: improvement to temperature dependent properties. Meas Sci Technol 2003;14:184.

[35] Soares N, Gaspar AR, Santos P, Costa JJ. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy Build 2014;70:411–21.

[36] Konuklu Y, Paksoy HÖ. Phase change material sandwich panels for managing solar gain in buildings. J Sol Energy Eng 2009;131:41012.

[37] American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. 2015 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications (SI Edition). Am Soc Heating, Refrig Air-Conditioning Eng Inc 2015.

[38] Saffari M, De Gracia A, Ushak S, Cabeza LF. Economic impact of integrating PCM as passive system in buildings using Fanger comfort model. Energy Build 2016;112:159–72. https://doi.org/10.1016/j.enbuild.2015.12.006.