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Experimental research on the use of micro-encapsulated Phase Change Materials to store solar energy in concrete floors and to save energy in Dutch houses

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Abstract

In this paper an experimental research is presented on a new use of Phase Change Materials (PCMs) in concrete floors, in which thermal energy provided by the sun is stored in a mix of concrete and PCMs. When this thermal energy is being released – in moderate sea climates during the evening and early night – it is aimed to reduce the need for thermal energy of conventional heating in houses. The temperatures of four concrete floors in closed environments were monitored to reflect on the influence of PCMs and type of insulation in relation to ambient temperatures and solar irradiation. The application of PCMs in concrete floors resulted in a reduction of maximum floor temperatures up to $16 \pm 2\%$ and an increase of minimum temperatures up to $7 \pm 3\%$. The results show the relevance of an integral design in which the thermal resistance of the building shell, the sensible heat capacity of the building and the latent heat capacity of the PCMs are considered simultaneously.

Keywords: Phase Change Materials (PCMs); Concrete floor; Insulation; Experiment

1. Introduction

In many countries reducing the energy use of the built environment receives much attention. Within the European Union (EU) the energy use by the built environment is more than 40% of the total energy consumption (EC, 2002). It is shown that Phase Change Materials (PCMs) can help in reducing the energy use for maintaining a comfortable indoor temperature (Zalba et al., 2003; Huang et al., 2006; Sharma et al., 2009), since they have the ability to store and release both sensible and latent heat. The latent heat capacity of a material is in general much larger than the sensible heat capacity. In the case of water the sensible heat capacity is 4.2 kJ/(kg K). The latent heat capacity is 334 kJ/kg in case of solidification and 2260 kJ/kg in case of vaporisation (Verkerk et al., 1992). The liquefaction of ice or evaporation of water for cooling purposes both form ancient techniques, but PCMs with transition temperatures for specific purposes were introduced in the 19th century (Kürklü, 1998).

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Nomenclature

C_p	sensible heat capacity (kJ/(kg K))
C_l	latent heat capacity (kJ/kg)
h	height (mm)
I	irradiance (W/m^2)
l	length (mm)
Lt	light transmittance (%)
M	mass (kg)
R	thermal resistance (m^2 K)/W
RR	rain rate (mm/h)
RH	relative humidity (%)
T	temperature (°C)
Ts	solar direct transmittance (%)
U	thermal transmittance W/(m^2 K)
V	velocity (m/s)
w	width (mm)
Greek letters	
ρ	bulk density (kg/m^3)
θ	angle (°)
Subscripts	
c	resistance solid material
PCM	Phase Change Material
t	resistance flexible material
w	wind

Nowadays multiple materials are offered that have their melting temperature between 18 and 23 °C (Zalba et al., 2003; Baetens et al., 2010), which can be considered to be around comfortable indoor temperatures. An ambient temperature below this temperature will ascertain that the latent heat in the PCMs will be or is emitted to the surroundings. When the ambient temperature rises, the thermal energy necessary for liquefaction will be provided by the surroundings. The PCMs will act as a battery storing thermal energy. This makes it possible to increase the thermal capacity of buildings and to reduce peak temperatures.

Pasupathy et al. (2008a) mention three different ways to use PCMs in buildings, namely:

1. in walls (e.g. Peippo et al., 1991; Cabeza et al., 2007; Chen et al., 2008);
2. in other building components (e.g. Nagano et al., 2006; Pasupathy et al., 2008b) and;
3. in separate heat or cold storages (e.g. Esen and Ayhan, 1996; Esen et al., 1998; Esen, 2000; Zhu et al., 2009).

Bentz and Turpin (2007) specified potential applications of PCMs in concrete by analysing the calorimetry of PCMs embedded in porous light-weight aggregates. They addressed the necessity for further research and field testing. Hunger et al. (2009) showed that micro-encapsulated PCMs can be applied in self-compacting concrete mixes reducing the peak temperatures during hydration. Cabeza et al. (2007) offered the important figures of a field test considering micro-encapsulated PCMs in concrete walls. Li et al. (2009) used micro-encapsulated PCMs in floor elements made out of a composite of high density polyethylene and wood. However, no research seems to have been conducted on the direct application of PCMs in concrete floors. In this case a direct application means without using mechanical systems that transport heat between the concrete floor and a reservoir containing PCMs. Zhang et al. (2007, p. 654) already mentioned that the "*combination of buildings materials and PCM is an effective way to enlarge the thermal energy storage capacity of building components for the purpose of direct thermal energy storage in buildings*". Furthermore they stated that "*…porous building materials have advantages of low cost, ease of fabrication and widespread application in building industries*" (ibid, p. 654). As a counterexample research of Esen and Ayhan (1996), Esen et al. (1998) and Esen (2000) reflects, instead of incorporating PCMs in building materials, on the use of PCMs in an advanced mechanical heating system, in which solar collectors provide thermal energy to a heat pump for space heating via a storage tank containing PCMs.

In moderate climates one can imagine that concrete floors having PCMs can store thermal energy provided by solar irradiation that directly enters dwellings by the windows during the day. Storing this solar energy during daytime and releasing it in the evening can help in reducing the energy need for thermal comfort during the relatively cold night. Depending on the specific transition temperature, that needs to be around a comfortable room temperature of 21–23 °C[1], the PCMs can be expected to be most effective during spring and autumn. In these seasons daylight and ambient temperatures can be sufficient to charge PCMs during daytime. During the evening or night the ambient temperature can be low enough to discharge PCMs.

Over the last 10 years a Dutch meteorological spring – starting at the 1st of March till the 1st of June – shows average hourly temperatures of 9.5 °C with a maximum of 19.4 °C and an average hourly irradiation of 155 W/m^2 with a maximum of 661 W/m^2 (KNMI, 2010). A Dutch

[1] The authors are aware that comfort is rather subjective. However, Van der Linden et al., 2006; van Hoof and Hensen, 2007, and Peeters et al., 2009 suggest temperature ranges based on standardized methods and depended of outside temperatures that can be considered as highly acceptable.

meteorological autumn – starting at the 1st of September till the 1st of December – shows in the region of Twente average hourly temperatures of 10.6 °C with a maximum of 21.1 °C and an average hourly irradiation of 77.3 W/m^2 with a maximum of 570 W/m^2 (KNMI, 2010). During winter in moderate climates ambient temperatures (on average 2.9 °C) and solar irradiation (on average 31.8 W/m^2) will probably be too little to charge this thermal battery. During summer with an average hourly temperature of 17.4 °C and an average hourly irradiation of 200 W/m^2, overheating – the case in which the latent heat capacity of PCMs is exceeded during day and night – needs to be prevented by applying awning or shutters for example.

Given these foreseen possibilities of PCMs in storing thermal energy provided by the sun and elaborating on the mix design of Hunger et al. (2009), this paper shows the effects of applying micro-encapsulated PCMs directly in concrete floors. An experimental setup has been developed to test two concrete floors with micro-encapsulated PCMs and for comparison two without micro-encapsulated PCMs with different glazing systems and insulation. The main objective is to gain insights in how PCMs embedded in concrete floors can help in heating living rooms during the evening and early night in a moderate climate by only making use of solar irradiation as a source for thermal energy. The Netherlands have a moderate climate with an average ambient temperature of 9.7 °C and an annual incoming solar radiation of 1003 kW h/(m^2 year) for the time period 1971–2000 (KNMI, 2002). The following questions form the basis of our research in gaining insights:

1. What are the effects of micro-encapsulated PCMs in concrete floors on indoor temperatures compared to concrete floors without micro-encapsulated PCMs when using solely solar energy to heat the indoor environment?
2. What are the effects of the type of insulation on the temperatures of concrete floors with and without micro-encapsulated PCMs when solar energy is the only heat source?
3. What melting point of the micro-encapsulated PCMs can be considered to be most effective in a moderate climate, when using solar energy for heating purposes during the evening and early night?

The next section explains the experimental setup that was developed. Section 3 shows the results regarding the monitored weather conditions and thermal behaviour of the boxes. The analysis of the derived data takes place in Section 4, before closing the paper with discussions and conclusions in Section 5.

2. Experimental setup

Like in many other research projects focusing on the use of PCMs in building components, e.g. Kissock et al. (1998), Cabeza et al. (2007), Pasupathy et al. (2008a), and Voelker et al. (2008), this research also makes use of volumes representing scaled living space in dwellings. Advantages are the manageability of the setup, the size of the test field, costs and time restraints related to developing the setup.

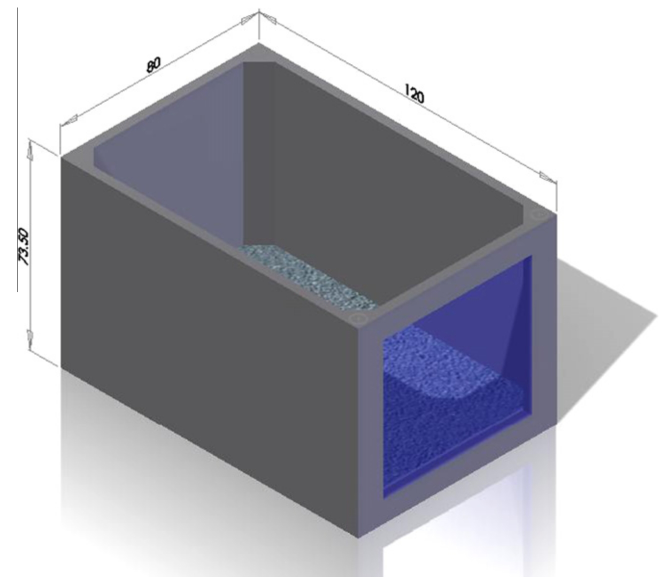

Fig. 1. Dimensions of the frame providing the basis of the boxes (sizes in cm).

The experimental setup encompasses four boxes, equipment for data acquisition and the test site. The test site is the location where the boxes are exposed to the environment and where data acquisition takes place. In order to understand which effects micro-encapsulated PCMs in concrete floors can assort in dwellings in a moderate climate on the northern hemisphere, four boxes are fully insulated and have a window located to the south through which the solar irradiation can enter.

2.1. Materials and dimensions of the boxes

Each box is based on a synthetic frame with a inner volume of 1130 mm × 725 mm × 690 mm ($l \times w \times h$). This basis is shown in Fig. 1. Within this volume a concrete floor of 104.2–104.7 kg[2] is placed to provide thermal storage capacity. In two out of the four boxes these floors contain micro-encapsulated PCMs. Around the closed synthetic frame a layer of insulation has been installed. In two boxes light-weight insulation was installed, consisting of fourteen thin layers of different reflective and insulating materials with a combined thickness of 20 mm. Before and behind this multi-layered insulation material two cavities of 20 mm are provided. The other two boxes are equipped with heavy-weight insulation, consisting of cellular glass with a thickness of 160 mm. The exterior is formed by a cladding of 15 mm thick water resistant plywood that

[2] Due to the need to come to a proper particle size distribution in the concrete mixes with and without PCMs the total mass of the two types of floors differs 0.5 kg.

Table 1
Building physical constitution of the test boxes in the experimental setup.

Variable	Symbol	Testbox 1	Testbox 2	Testbox 3	Testbox 4
Insulation material		Cellular glass	Cellular glass	Light	Light
Thermal resistance[a]	R	$R_c = 3.8$ (m^2 K)/W	$R_c = 3.8$ (m^2 K)/W	$R_t = 5.6$ (m^2 K)/W	$R_t = 5.6$ (m^2 K)/W
Phase Changing Materials		Present	Absent	Present	Absent
Mass of PCMs in concrete mix	M_{PCM}	5.12 kg	0 kg	5.12 kg	0 kg
Mass of floor	M_{floor}	104.23 kg	104.73 kg	104.23 kg	104.73 kg
Mass percentage of PCMs		4.9%	0%	4.9%	0%
Thermal resistance glazing		High	Standard	High	Standard
Light transmittance	Lt	71%	80%	71%	80%
Solar direct transmittance	Ts	39%	52%	39%	52%
Thermal transmittance	U	0.5 W/(m^2 K)	1.1 W/(m^2 K)	0.5 W/(m^2 K)	1.1 W/(m^2 K)

[a] Values are according specifications of manufacturer.

Table 2
Specifications of the heat storage capacity of the floors.

	Latent heat capacity C_l (at ±23 °C) (kJ/kg)	Specific heat capacity C_p	Bulk density ρ (kg/m^3)
Concrete	0	3.3 kJ/(kg K)	2400
PCMs	110[a]	Negligible	250–350

[a] Value is according specifications of manufacturer.

was painted white to maximise reflection. The roof has an additional layer of white plastic fabric. At the south side of each box an insulated window was installed of 590 mm × 550 mm ($l \times h$). Two windows contain double glazing and two windows contain triple glazing. The configuration and the typical physical characteristics of each box are shown in Table 1.

As Table 1 shows, two concrete floors contain 5% PCMs. In this case a micro-encapsulated mixture of paraffins was used with a melting point of 23 °C. They are provided by BASF under the name of Micronal DS 5008 X. According to the product description, Micronal has a latent heat capacity of 110 J/g (see Table 2). At the start of this research and developing the experimental setup, Micronal was the only product available for research purposes in the Netherlands.

In the framework of this research project the preceding research of Hunger et al. (2009) showed that Micronal can be used in a self-compacting concrete mix with one part Ultrafin 12 and two parts CEM I 32.5 R. However, this research also showed that the polymethyl methacrylate capsules are relatively delicate. To minimise the exposure to mechanical stress, we added the Micronal in the very last phase of the mixing process. Based on differential scanning calorimetry Hunger et al. (2009) obtained an exothermic enthalpy of 99.7 J/g with an onset of 25.20 °C and an endothermic enthalpy of 102.8 J/g with an onset of 22.12 °C. Their Differential Scanning Calometry experiment was conducted using a Perkin Elmer DSC7, therefore we will refer to their temperature values as 22.1 ± 0.1 °C and 25.2 ± 0.1 °C. By making use of the same concrete mixture design as Hunger et al. (2009), it can again be expected that the thermal conductivity of the concrete floor without PCMs is 3.4 W/m K and with PCMs is 2.1 W/m K.

Table 3
Locations of the thermocouples in the test boxes.

#	Description of the location
1	Inside the concrete floor south side close to the window
2	Inside the concrete floor halfway the floor
3	Inside the concrete floor north side close to the backside
4	Outside the box in the top middle of the north side
5	Inside the box in the middle of the east side 31.5 cm above the floor
6	Inside the box south east side 25 cm above the floor close to the window
7	Inside the box south west side 25 cm above the floor close to the window
8	Inside the box in the middle of the west side 31.5 cm above the floor
9	Inside on top of the concrete floor at the south side close to the window
10	Inside on top of the concrete floor halfway the floor
11	Inside on top of the concrete floor at the north side close to the backside
12	Inside the box north east side 31.5 cm above the floor
13	Inside the box north west side 31.5 cm above the floor
14	Inside the box in the middle of the ceiling 60 cm above the floor

2.2. Data acquisition

The test boxes were continuously monitored collecting measurements of individual thermocouples and irradiance sensors every second using a sampling interval of 5 min. These 5 min averages per thermocouple or sensor are presented in Section 3 and were used for further analysis in Section 4. The surface temperature and the internal temperature of the concrete floor were both measured at three different points (see Table 3). Thermocouples were furthermore located in the middle of both sides of the boxes, in the middle of the roof and in the middle of the backside. Temperatures behind the glazing were also measured. In total fourteen thermocouples were used per box. Data acquisition took place by using eight USB TC-08 of Pico for the thermocouples and two USB 6215 of National Instruments for the solar irradiance sensors. Two personal computers

Fig. 2. Meteorological station at the test site.

stored the data by making use of a Labview program that has been developed for this purpose.

All thermocouples are made out of 400 m Teflon insulated TX wire. The accuracy of the thermocouples, their cables and applied data acquisition system is set on plus or minus 0.5 °C, according to specifications of the manufacturer. The amount of solar irradiance was measured by six silicon irradiance sensors type Si-01 TC-T of Mencke and Tegtmeyer placed horizontally in and on top of two test boxes. These sensors have active temperature compensation and were calibrated by the manufacturer in simulated sunlight against a reference cell of the same type. The weather conditions were measured by a weather station (see Fig. 2), being a Vantage Pro 2 of Davis Instruments with a digital thermometer for measurement of T (°C), humidity meter RH (%), cup anemometer for measurement of wind speed V_w (m/s) and a wind vane for the wind direction θ_w (0–360°), and solar sensor for measurement of horizontal global irradiance I (W/m^2). Table 4 gives a comprehensive overview of all sensors applied.

Table 4
Applied sensors in the monitoring system.

Variable	Symbol	Sensor	Unit	Accuracy
Temperature	T	Thermocouples type T	°C	±0.5 °C
		Vantage Pro 2 of Davis Instruments	°C	±0.5 °C
Irradiance	I	Si-01 TC-T of Mencke and Tegtmeyer	W/m^2	±5%
		Vantage Pro 2 of Davis Instruments	W/m^2	±5%
Humidity	RH	Vantage Pro 2 of Davis Instruments	%	±5%
Rain rate	RR	Vantage Pro 2 of Davis Instruments	mm	±1 mm/h
Wind speed	V_w	Vantage Pro 2 of Davis Instruments	m/s	±5%

2.3. Test site

The four boxes needed a location that is not subject to vandalism and that is comparable to the climatic situation most Dutch dwellings are familiar with. A location was found at the campus of the University of Twente, where the windows of the boxes can face the south without much shading of trees, buildings or passing persons to make sure equal circumstances are provided to all four boxes. The boxes were placed at approximately 52.239°N and 6.864°W on top of a 40 foot sea container (see Fig. 3). In the middle at 2.5 m behind the boxes, the weather station is located. The test site is located in the region of Twente, where over the last 10 years daily averages regarding temperature and irradiance were recorded of 0.1 up to 19.6 °C/day and 0.4–6.3 kW h/(m^2 day), respectively (see Figs. 4 and 5). In these years the Royal Netherlands Meteorological Institute (KNMI) indicates that the highest hourly average temperature was 25.2 °C. The annual average temperature was 10.1 °C. Solar irradiance measured an average of 117 W/m^2 and an averaged maximum over 10 years of 769 W/m^2 (KNMI, 2010).

3. Results

The monitoring of the boxes results in a large data collection that provides insights in the influence of the window frame, of the type of insulation and most importantly of the presence of PCMs. In this section the results are shown in the form of climate conditions inside and outside the boxes, before analysis takes place in the next section. Referring to the onset temperatures of Hunger et al. (2009), it is important to distinguish three situations:

1. the PCMs are not thermally charged, because of low levels of irradiance and low ambient temperatures lower than 22.1 °C;
2. most or even all PCMs are thermally charged during daytime, because of significant irradiance and temperatures above 25.2 °C during the day and below 22.1 °C during the evening or night;
3. all PCMs are thermally charged during the day and stays charged during the night, because of high levels of irradiance and temperatures continuously exceeding 22.1 °C.

According to the local data shown in Figs. 4 and 5, the temperature range of 22.1–25.2 °C can be met in June, July and August. In Figs. 6–8 data of the weather station and solar irradiance reference cells give an impression of the temperatures and solar irradiance during June 2010. These data show that especially in the last and first week of June

Fig. 3. View on the four test boxes at the test site.

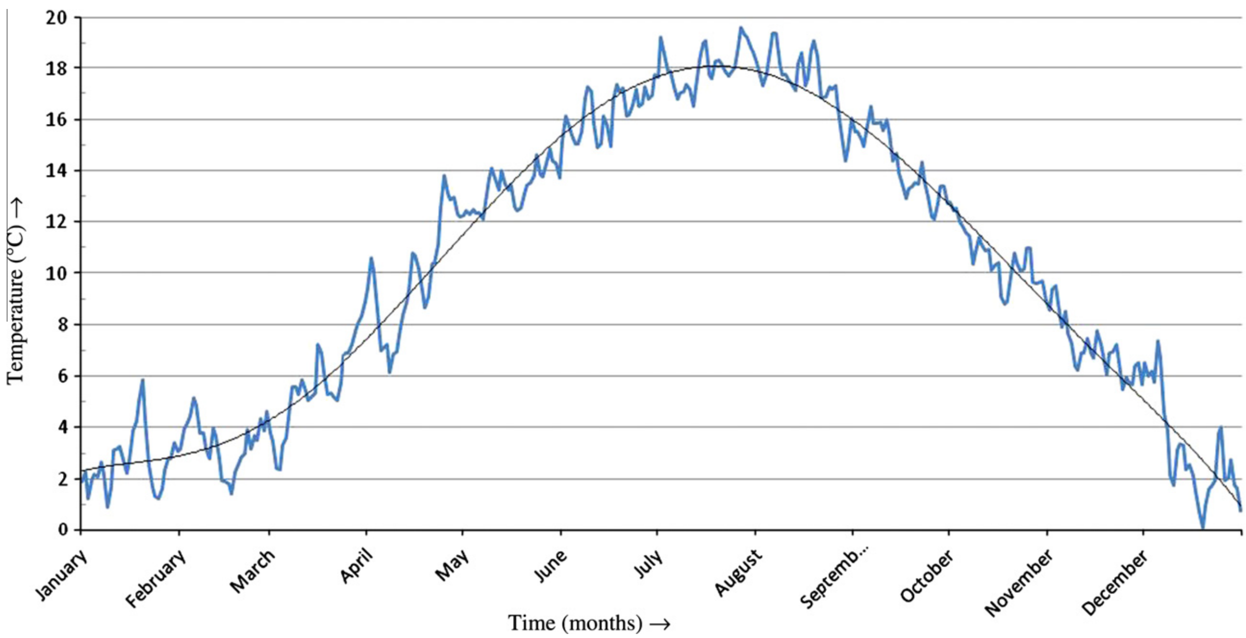

Fig. 4. Ambient temperatures (°C) in the region of Twente in the time period 2001–2010 (KNMI, 2010).

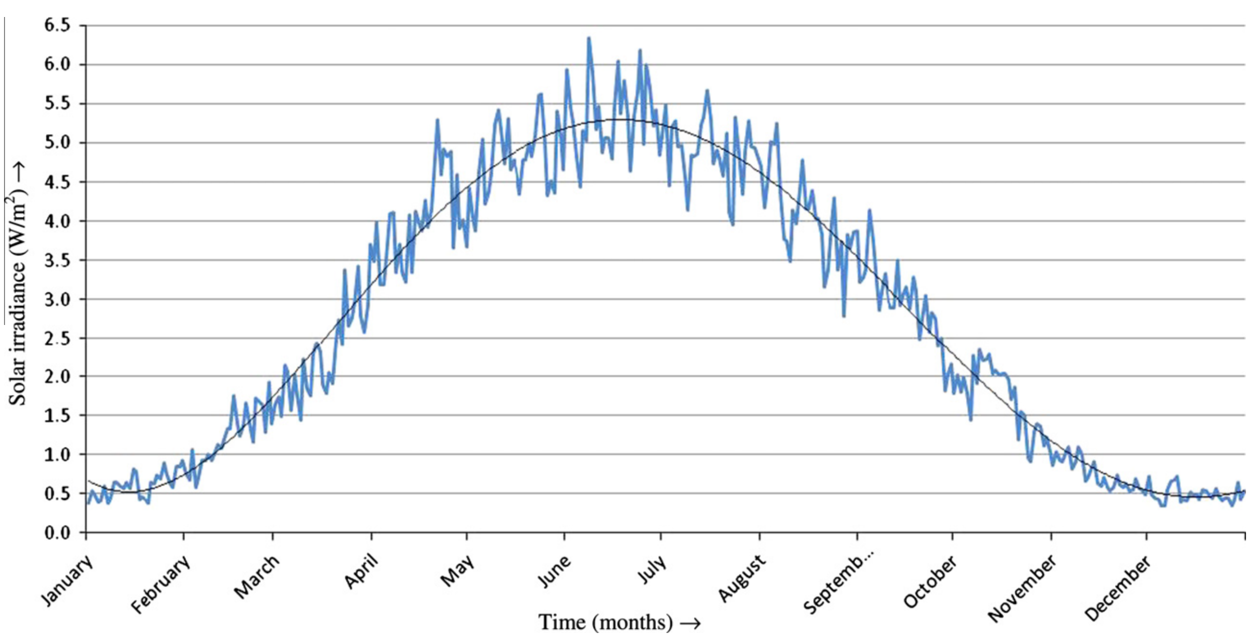

Fig. 5. Solar irradiation (W/m^2) in the region of Twente in the time period 2001–2010 (KNMI, 2010).

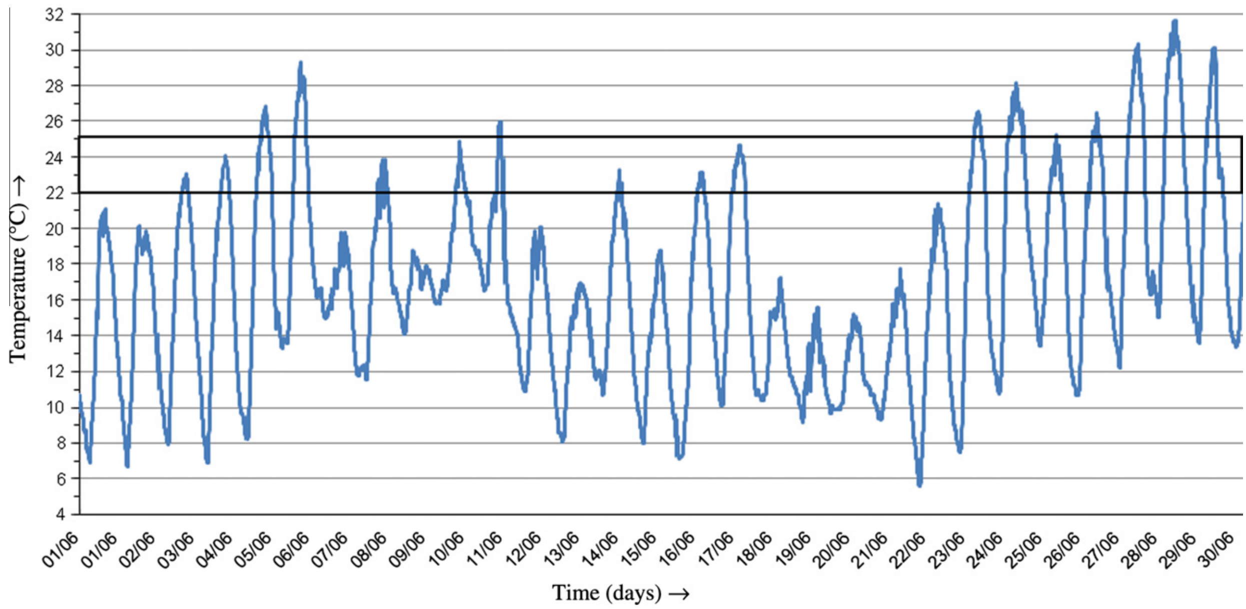

Fig. 6. Ambient temperatures (±0.5 °C) measured by the weather station at the test site in June 2010. The frame indicates the temperature range in which the phase transition takes place.

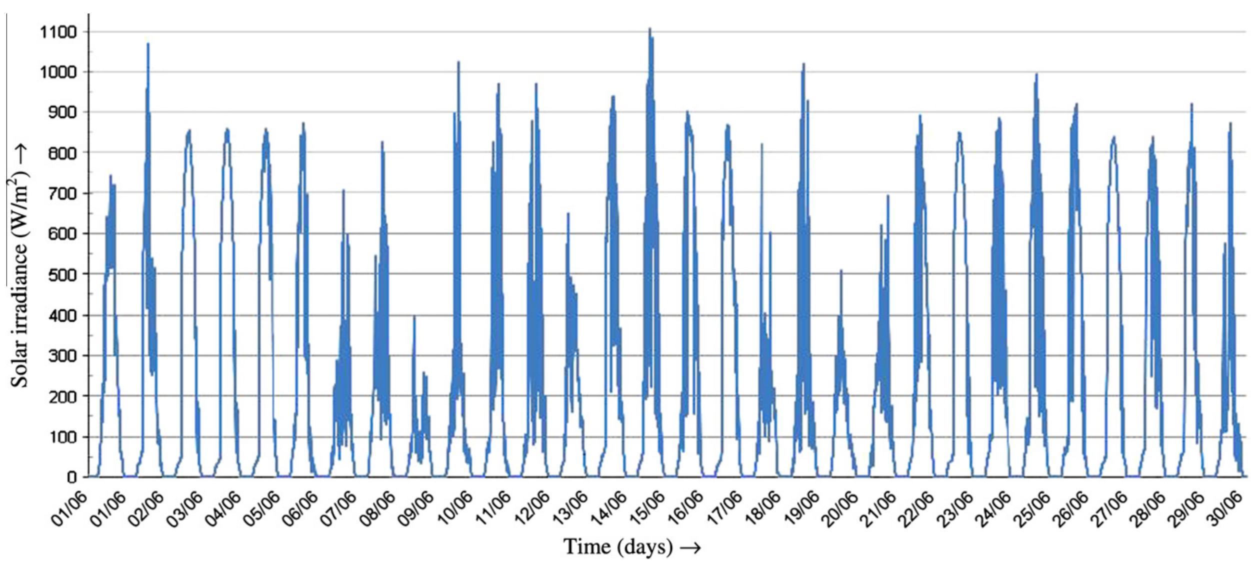

Fig. 7. Solar irradiance (W/m^2 ± 5%)) measured by the weather station at the test site in June 2010.

temperatures rose from below the melting trajectory of the PCMs to above it.

The average daily temperature increased from 14.3 ± 0.5 °C at the 1st of June to 19.3 ± 0.5 °C at the 30th of June. In this period all three distinguished situations seemed to have occurred. In the time period from the 19th to the 23rd relatively low levels of irradiance and low ambient temperatures made it impossible for the PCMs to be charged. In the time period from the 24th to the 26th the PCMs was probably able to be charged and to release the stored heat within 24 h, which can be most interesting for lowering the need for additional heating. In the last time period starting at the 27th up to the 30th of June solar irradiation and ambient temperatures were high, which probably do not enable the PCMs to discharge the stored thermal energy even during the night.

Data of the thermocouples in the front end of the concrete floors are shown in Fig. 9. The room temperatures in the boxes were also monitored. The results of the thermocouples closely located to the ceiling are shown in Fig. 10.

Fig. 9 clearly shows that in the first half of the week after midnight around 24–25 °C (±0.5 °C) the floors with PCMs

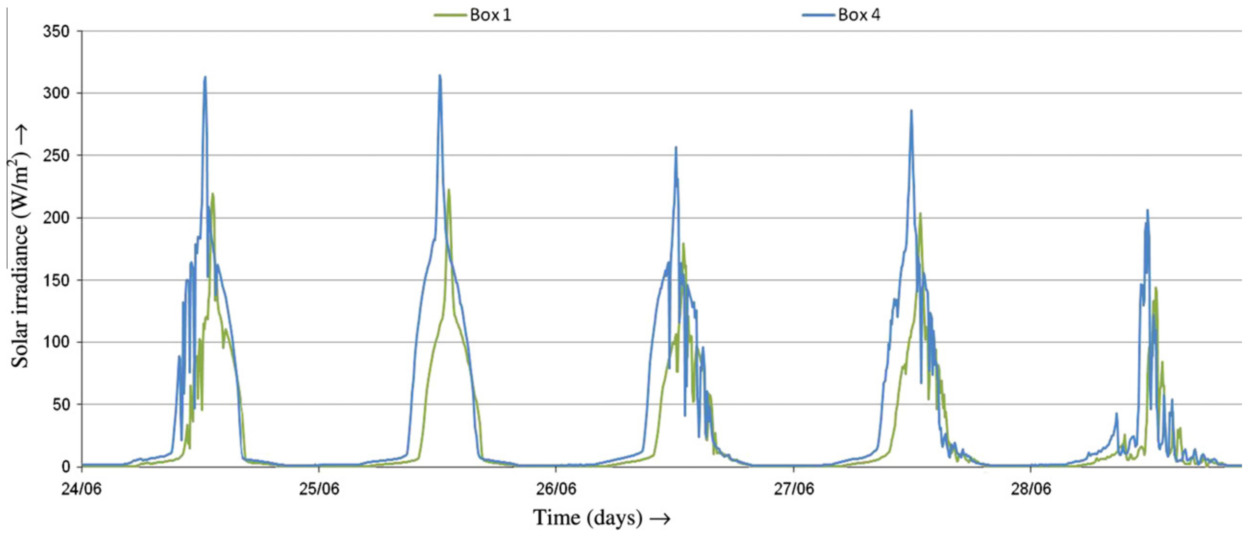

Fig. 8. Solar irradiance ($W/m^2 \pm 5\%$) entering Box 1 and Box 4 measured by ground floor irradiance cells in the boxes by the end of June 2010.

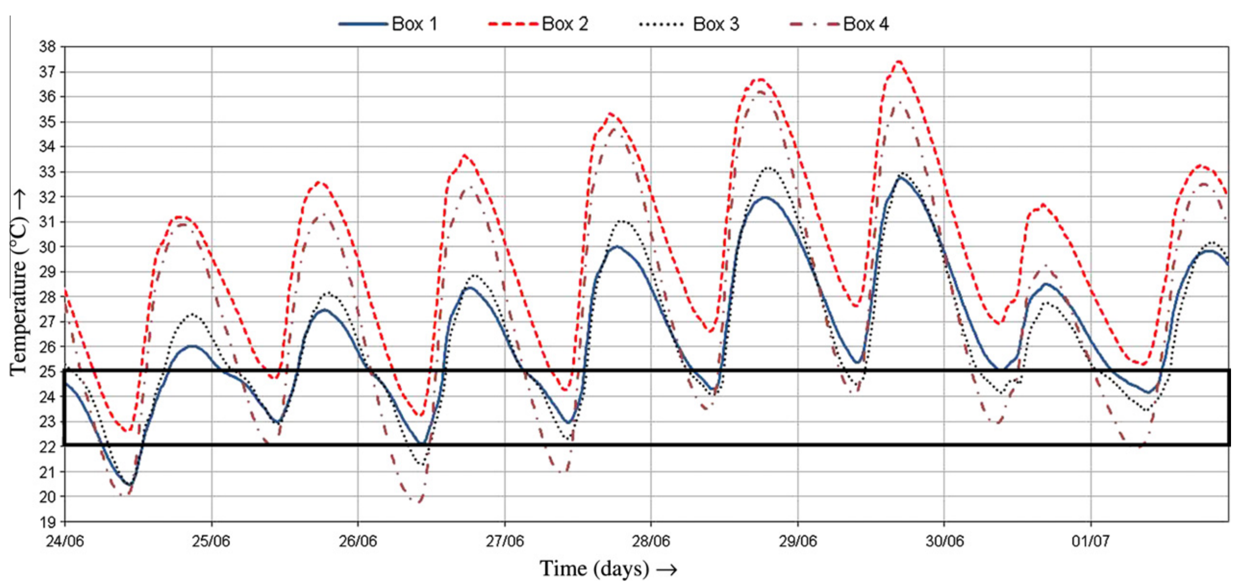

Fig. 9. Temperatures (±0.5 °C) of the floors in the boxes in the last week of June 2010 according to the thermocouples close to the windows. The frame indicates the temperature range in which the phase transition takes place.

(Boxes 1 and 3) are better able to maintain their temperature than the boxes without PCMs (Boxes 2 and 4). The boxes with PCMs are also equipped with an improved glazing system with a high thermal resistance and low solar transmittance, which can explain a lower maximum temperature and a higher minimum temperature. However, these glazing systems cannot be brought into relation with the distinctive smaller slope setting in at around 25 °C during the exothermic process.

The charging of the PCMs, or in other terms endothermic process, is harder to distinguish in these graphs. Nevertheless, small declines in the slopes of Boxes 1 and 3 can be noticed starting in the early afternoon of the 24th, 25th, 26th and 27th of June at approximately 23 °C, which continue up to 25.5 °C. The last 2 days of the week the PCMs in the floors of Box 1 were liquid all the time, because of high ambient temperatures during the night. Therefore, Fig. 9 does not clearly show differences in the slopes of Box 1 during the nightly exothermic process. In Box 3 the PCMs were able to release their heat during solidification, because of the lower thermal admittance and thermal heat resistance of the shell of this box.

4. Cross case analysis

In this section the collected data will be analysed by making four comparisons between the data of the boxes (see Table 1):

1. Box 1 and Box 2 are compared to reflect on the influence of the window system and PCMs, when heavy-weight cellular glass insulation is applied.

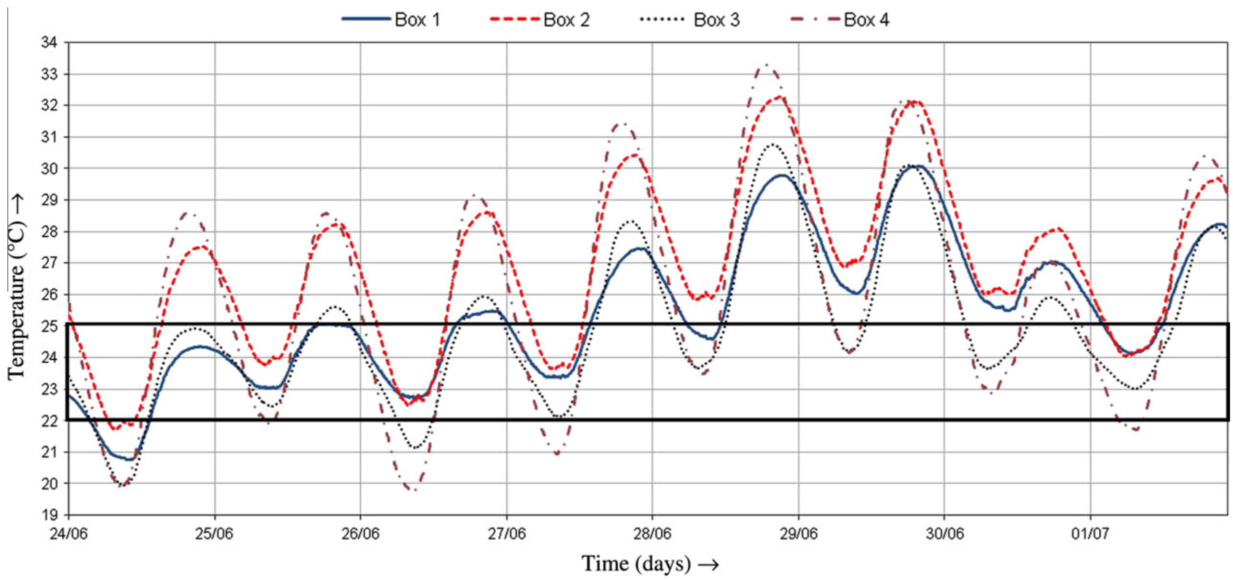

Fig. 10. Temperatures (±0.5 °C) in the boxes in the last week of June 2010 according to thermocouples in the middle of the ceiling. The frame indicates the temperature range in which the phase transition takes place.

Table 5
Minimum and maximum temperatures (±0.5 °C) in the boxes per day.

Date	Testbox 1 Min–Max (°C)	Testbox 2 Min–Max (°C)	Testbox 3 Min–Max (°C)	Testbox 4 Min–Max (°C)
24-6	20.9–24.4	23.0–29.2	19.9–25.2	20.2–28.9
25-6	23.2–25.2	25.1–29.8	22.4–25.7	22.1–28.8
26-6	23.1–25.6	23.8–30.3	21.1–26.2	20.1–29.4
27-6	23.7–27.7	24.8–32.2	22.1–28.6	21.3–31.7
28-6	24.7–30.0	27.0–33.9	23.9–31.0	23.7–33.5
29-6	26.3–30.3	28.3–33.9	24.4–30.6	24.4–32.5
30-6	25.7–30.2	27.3–33.4	24.0–29.2	23.1–30.7
1-7	24.4–28.5	25.4–31.4	23.2–28.5	22.0–30.7

2. Box 1 and Box 3 are compared to reflect on the influence of insulation materials, when an advanced window system and PCMs are applied.
3. Box 3 and Box 4 are compared to reflect on the influence of the window system and PCMs, when light-weight multi-layered insulation is applied.
4. Box 2 and Box 4 are compared to reflect on the influence of insulation materials, when no advanced window system or PCMs are applied.

When comparing the boxes, minimum and maximum temperatures play an important role in order to isolate the effects of PCMs in concrete floors from other design effects. In Table 5 a short overview is given of daily minimum and maximum temperatures.

4.1. Comparison between Boxes 1 and 2

During the time period 24-06 to 01-07 the temperature of the floor is higher in Box 2 than in Box 1 (see Fig. 11). According to the specifications of the window system, provided by the manufacturer, the solar transmittance of the window in Box 1 is 13% less than in Box 2. Values given by the solar irradiance reference cells in the boxes representing the solar irradiance passing through the advanced glazing system seem to support this. The cells in Box 1 mention an average solar irradiance of 17.1 ± 0.9 W/m^2 halfway the ground floor and the cells in Box 4 28.1 ± 1.4 W/m^2. This can explain the basic tendency of lower (minimum and maximum) temperatures in Box 1. However, the solar irradiance entering the boxes does not reach the reference cells under an angle of 90° and the values are less than 50 W/m^2. Therefore, the errors in these data can exceed the mentioned accurateness of ±5% significantly. The light and solar direct transmittance, mentioned in Table 1, remain standing and the missing amount of energy inside the boxes due to differences in daily solar irradiation can explain the temperature difference between Box 1 and Box 2 of 2.3 ± 0.7 °C. The large thermal mass of the insulation package prohibits the floors in Boxes 1 and 2 to quickly change temperature by means of conduction through the shell of the boxes.

The difference between the daily minimum and maximum temperatures for Box 1 (with an average value of 3.7 ± 0.5 °C) is significant smaller than the difference for Box 2 (with an average value of 6.2 ± 0.5 °C). The fact that the thermal transmittance of the window frame is lower for Box 1 than Box 2 can partially explain why these differences are smaller, but the glazing system is less than 8% of the total inner surface. However, the total heat capacity of the PCMs in the concrete floor of Box 1 in the trajectory of 22.1 ± 0.1 °C to 25.2 ± 0.1 °C, given by Hunger et al. (2009), is approximately 563 KJ, which is comparable with a temperature difference of the concrete floor of 1.7 °C. When the presence of PCMs would be the only variation, the maximum temperatures could be at most 1.7 °C lower and the minimum temperatures could be at most 1.7 °C higher. The relatively stable temperatures of Box 1

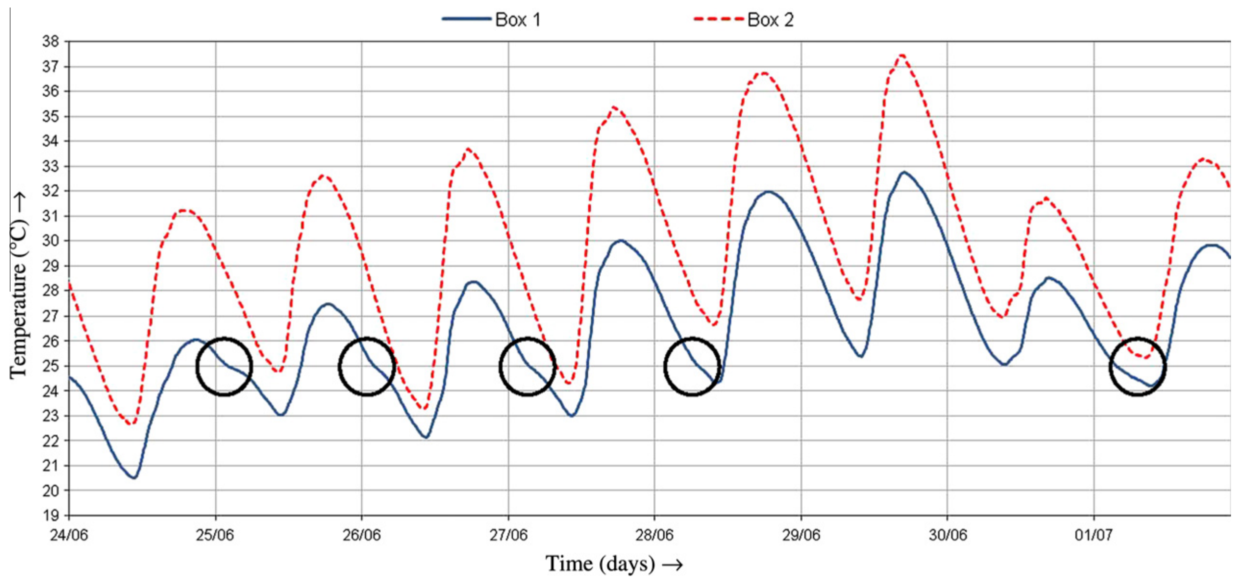

Fig. 11. Temperatures (±0.5 °C) in the floors of Boxes 1 and 2 in the last week of June 2010. The circles indicate the melting trajectory of the PCMs.

compared to Box 2 can therefore for the major part be ascribed to the application of PCMs and not to the application of an advanced window system. When the 5 min data of thermocouples 1, 2, and 3 (see Table 3) in both boxes are compared, it can be seen during the 8 days that temperatures between the concrete slab with and without PCMs on average differ 3.3 ± 0.7 °C, 2.9 ± 0.7 °C, and 3.1 ± 0.7 °C respectively.

4.2. Comparison between Boxes 1 and 3

These two boxes, both having an advanced glazing system and PCMs, show almost comparable temperature figures in the period 24-06 to 01-07 (see Fig. 12). Box 3 has slightly higher maximum temperatures and lower minimum temperatures than Box 1, probably due to the lower thermal admittance and thermal resistance of the insulation material. For the whole 8 day period thermal couples 1, 2, and 3 (see Table 3) show that the temperatures in the concrete slab of Box 1 are on average respectively 0.1 ± 0.7 °C, 0.6 ± 0.7 °C and 0.4 ± 0.7 °C higher compared to the three locations in the concrete slab of Box 3. Reflecting on the accuracy of the thermocouples, these little temperature differences make it hard to draw unambiguous conclusions about the impact of the different thermal insulation applied in the boxes. The use of PCMs seems to make it possible for Box 3 to reduce the decrease of indoor temperatures in the early morning for a considerable time, but in the end temperatures drop below the minimum temperatures of Box 1. The large thermal mass and/or thermal resistance of the insulation in Box 1 can explain the higher floor temperatures at the 30th of June and the 1st of July. In the temperature curves of both boxes the influence of PCMs can be seen in the form of different slope starting at approximately 25 °C when the boxes cool down in the early morning.

4.3. Comparison between Boxes 3 and 4

When data of the boxes with light-weight multi-layered insulation materials is analysed, the PCMs seem to a large extent to contribute to the expected result that maximum temperatures are higher and minimum temperatures are lower (see Fig. 13). The daily differences between minimum and maximum temperatures halfway the floor are on average 5.5 ± 0.7 °C for Box 3 and 8.7 ± 0.7 °C for Box 4. The possibility of the PCMs to significantly increase the minimum temperatures can be noticed at the 26th and 27th of June and the 1st of July, when the minimum temperatures of the floor close to the window are 1.4–1.5 ± 0.7 °C higher in Box 3 than Box 4. In this way solar energy can directly be applied without the use of mechanical systems to heat the inner volume of the box. At the 1st of July the PCMs in Box 3 were able to release heat over a time period of almost 10 h. Similar to the relation between Boxes 1 and 2, Box 3 has also an advanced glazing system of which the surface is relatively small compared to the total thermal transmission surface. Again, the amount of solar irradiance entering Box 3 is also smaller than in Box 4.

4.4. Comparison between Boxes 2 and 4

In the former comparisons maximum temperatures of the individual boxes were showing large differences. When Box 2 and Box 4 are compared, it can be noticed (see Fig. 14) that the minimum temperatures differ (on average in this time period 3.5 ± 0.7 °C per day) more than the maximum temperatures (only 1.0 ± 0.7 °C per day). During the night the thermal losses of Box 4 are larger than the losses of Box 2. During the day the light-weight insulation seems to be able to offer resistance to incoming heat in the form of solar radiation, but

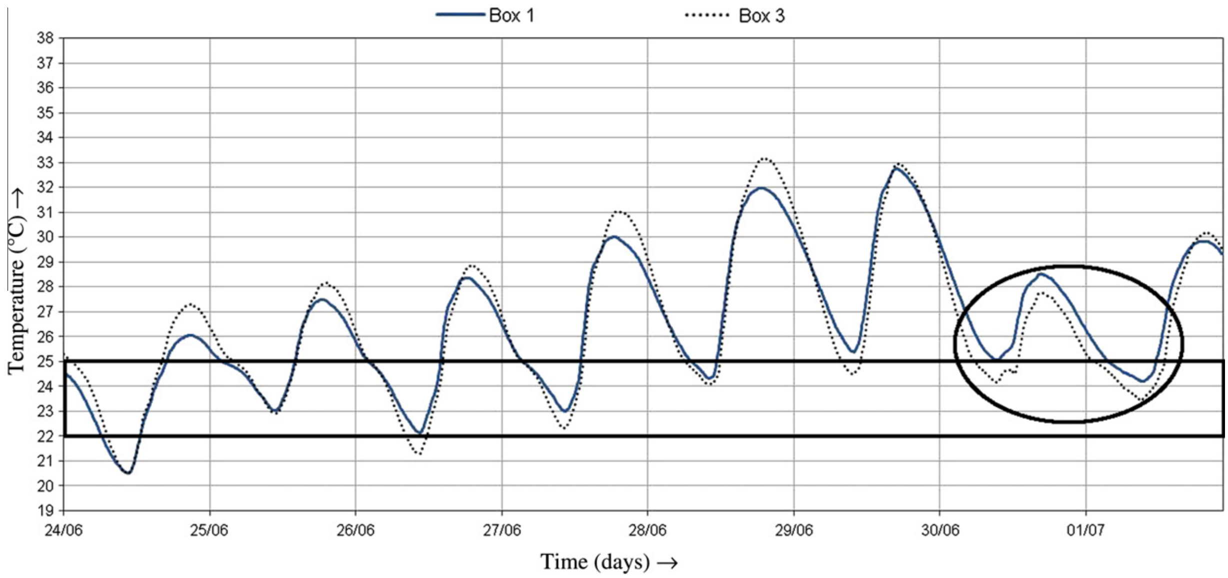

Fig. 12. Temperatures (±0.5 °C) in the floors of Boxes 1 and 3 in the last week of June 2010. The oval indicates the time period in which the large sensible heat capacity of the insulation in Box 1 enables higher floor temperatures than in Box 3.

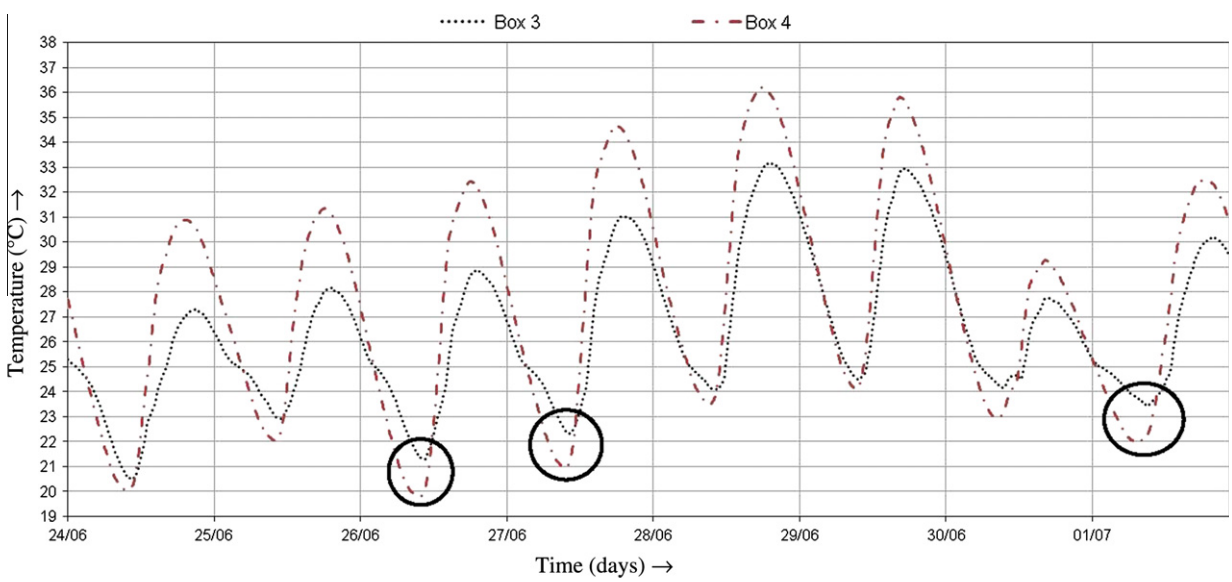

Fig. 13. Temperatures (±0.5 °C) in the floors of Boxes 3 and 4 in the last week of June 2010. The circles indicate the possibilities to increase minimum temperature significantly by using PCMs.

offers less thermal admittance and thermal resistance in the form of conduction to outgoing thermal energy flows compared to the heavy weigh insulation. When comparing data of the thermocouples 1, 2 and 3 at their specific locations in the concrete slabs (see Table 3), it can be seen that the temperature differences between Box 2 and Box 4 are smaller at the front close by the glazing of the box than at the back, where no solar irradiation directly heats the concrete floor. On average the temperature differences for the whole 8 day period are 2.2 ± 0.7 °C at location 1, 2.3 ± 0.7 °C at location 2 and 2.6 ± 0.7 °C at location 3.

5. Results and discussions

The experimental setup was developed to offer the opportunity to gain more insights on how PCMs can be used in concrete floors in buildings to heat living rooms during the early evening or even night in order to avoid auxiliary heating.

The first research question focused on the effects of PCMs in concrete floors on indoor temperatures compared floors without micro-encapsulated PCMs. The data shows that the storage of thermal energy in combination with an advanced (although relatively small) glazing system can

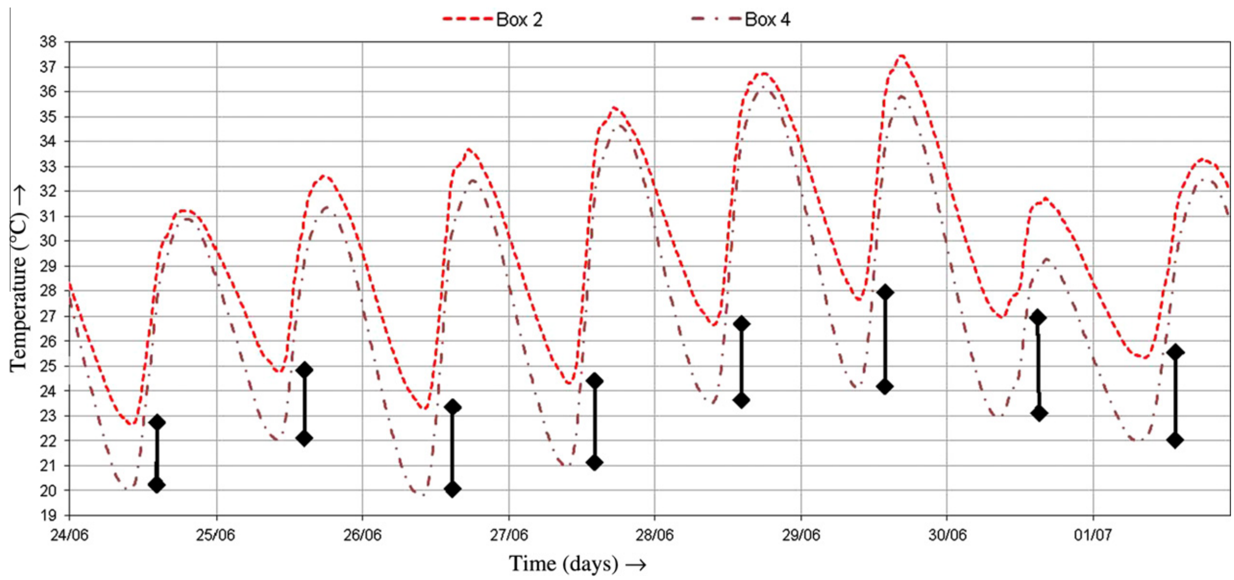

Fig. 14. Temperatures (±0.5 °C) in Boxes 2 and 4 in the last week of June 2010. The differences between the minimum temperatures are highlighted.

lead to 11 ± 2% (in case of Boxes 3 and 4) or 16 ± 2% (in case of Boxes 1 and 2) lower maximum temperatures and 7 ± 3% (in case of Boxes 3 and 4) higher minimum temperatures in comparison to concrete floors without PCMs and average glazing systems.

Data provided by thermocouples in the boxes showed that the PCMs influenced the inner climate at all locations in the boxes. However, a living room with a height of 2600 mm instead of 690 mm might be expected to be too large to be effectively heated by PCMs in the floors. Furthermore, the test boxes only had a large thermal capacity in form of the floor. Closely around the plastic framework insulation was applied. In a real life situation the inner walls within the thermal shell of a house provide a much larger sensible heat capacity. Therefore the applied latent/sensible heat capacity ratio of 1:19 in this experiment is hard to achieve in a real dwelling.

This ratio also applies in comparing the light and heavy insulations applied in the boxes. The reduced availability of thermal energy to be stored by the micro-encapsulated PCMs was noticed, when heavy-weight insulation is installed instead of light-weight insulation. The high thermal capacity and high resistance against thermal conductivity of the heavy-weight insulation seems to temper the effects of PCMs, which brings us to the second research question. The second research question was namely related to the type of insulation applied. We were able to reduce the temperature difference in using light or heavy-weight insulation from 3.5 ± 0.7 °C without PCMs to 0.8 ± 0.7 °C with PCMs and advanced glazing system. This especially shows the advantage of using PCMs in light-weight constructions to increase their admittance values, at least within a certain temperature range.

The third research question considers a proper melting point. The former experiments of Hunger et al. (2009) and the experimental data show that it is better to speak of melting trajectory. When the research started the availability of PCMs on the Dutch market was limited. The used PCMs with an expected transition temperature of 23 °C were the only product available for the Dutch market at that time. The data show that this transition temperature is too high to offer additional comfort and to reduce heating during heating season, but the used PCMs did show that in June maximum temperatures can be reduced and minimum temperatures can be increased. Average temperatures over the past 10 years show that July and August offered 174 h, where the average temperature per hour was above 22 °C. On approximately 50 days per year (an average over the last 30 years) the maximum temperature will exceed 22 °C.

When it is possible to have a transition temperature around 20.5 °C with an accompanying transition trajectory of 19–22 °C, the number of hours with an average temperature above 19 °C will increase by a factor 5.6. In that case PCMs can store thermal heat in the months April to September. In the Netherlands, April and September are the traditional months in which the heating season normally ends and starts. On approximately 100 days per year (again an average over the last 30 years) the maximum temperature will be above 19 °C. Although the number of hours with average temperatures above the transition trajectory or in other words above 21 °C increases, the thermal comfort experienced in living rooms with this 20.5 °C PCMs is not expected to be different from living rooms without PCMs on these warm days, because the sensible heat capacity of brick work and concrete components will have the upper hand.

6. Conclusions and recommendations

The main objective of this study was to gain insights in how PCMs embedded in concrete floors can help in heating living rooms during the evening and early night in a moderate climate by only making use of solar irradiation as a source for thermal energy. Our experimental research on the application of PCMs in concrete floors shows that PCMs can effectively store thermal energy in a constructional context without applying mechanical systems. The use of boxes seems to be a useful method to study the effects of PCMs.

Nevertheless, some possibilities seem to exist to improve the constitution of the box, besides the already mentioned latent/sensible heat capacity ratio. During the last week of June high ambient temperatures and much solar irradiation were namely available, but our expectation is that during April and September lower ambient temperatures and shorter time periods of solar irradiation call for shorter charging times in the form of a thinner floors. Relatively thick floors, like the floors of approximately 50 mm used in this research, have a large latent heat capacity, but also need a long time period to be charged. Based on the data of thermocouples in the concrete floor close to the windows, halfway the boxes and in the back of the boxes, the PCMs can be most efficiently used when they can be applied in a concrete mix that functions as a thin top layer on the floor of the living room, that is directly exposed to incoming solar radiation. In this regard the advanced glazing system can also have a negative impact, because less solar irradiation will reach the floor and less thermal energy can be stored.

Future research on the application of PCMs in construction elements can focus on using PCMs with a higher latent heat capacity and with a lower transition temperature than the PCMs used in our experimental research. The use of PCMs to heat living space during the evening and early night by the end and start of the heating season can probably be achieved by using a melting temperature of approximately 20.5 °C, which is expected to be close to the optimum. Averaged over the last 10 years there were 14 times more hours that the ambient temperature exceeded 20.5 °C than 23.7 °C (as an average of 22.1 °C and 25.2 °C). This means that during more days PCMs can be charged and during evenings they can be discharged, reducing the need for additional heating in houses in the first and last weeks of the heating seasons in moderate climates.

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