

# Temperature reduction due to the application of phase change materials

Conrad Voelker <sup>a</sup>, Oliver Kornadt <sup>a</sup>, Milan Ostry <sup>b</sup>

<sup>a</sup> Department of Building Physics, Bauhaus-University Weimar, Coudraystrasse 11a, 99423 Weimar, Germany

<sup>b</sup> Faculty of Civil Engineering, Brno University of Technology, Department of Building Structures, Veveri 95, 602 00 Brno, Czech Republic

(Received 7 May 2007; received in revised form 25 July 2007; accepted 28 July 2007)

---

## Copyright Notice

Copyright 2008 Elsevier. This article may be downloaded for personal use only. Any other use requires prior permission of the authors and Elsevier.

The following article appeared in the journal Energy and Buildings 40 (5) 2008, 937-944 and may be found at <https://doi.org/10.1016/j.enbuild.2007.07.008>.

---

## Abstract

Overheating is a major problem in many modern buildings due to the utilization of lightweight constructions with low heat storing capacity. A possible answer to this problem is the emplacement of phase change materials (PCM), thereby increasing the thermal mass of a building. These materials change their state of aggregation within a defined temperature range. Useful PCM for buildings show a phase transition from solid to liquid and vice versa. The thermal mass of the materials is increased by the latent heat. A modified gypsum plaster and a salt mixture were chosen as two materials for the study of their impact on room temperature reduction. For realistic investigations, test rooms were erected where measurements were carried out under different conditions such as temporary air change, alternate internal heat gains or clouding. The experimental data was finally reproduced by dint of a mathematical model.

*Keywords:* Summer overheating in buildings; Phase change materials; PCM; Paraffin; Salt hydrate; Numerical simulation; Mathematical model; Heat storage

---

## 1. Introduction

In buildings with massive masonry or concrete walls, comfortable summer temperatures dominate due to the high heat capacity of components and assemblies. In contrast, buildings with modern lightweight constructions have little comparable heat storage, resulting in summer overheating as a major problem. The highly glazed surfaces in modern office buildings have an additionally significant influence here, with a high potential of solar gains.

Before resorting to the utilization of additional air conditioning, a possible solution may be the emplacement of so-called phase change materials (PCM) that provide for an increase in heat capacity. These materials change their state of aggregation within a defined temperature range. Common PCM for the application in buildings show a phase transition from solid to liquid phase and vice versa. It follows then that surface and indoor air temperatures can be reduced by using PCM during hot periods. Therefore, the deficient lagging thermal protection of lightweight buildings in summer can be improved for thermal comfort.

The idea of improving the thermal buffer through the application of phase change materials has been common knowledge for many years. The first kind in use was natural ice. In the past, different innovative systems were developed that go back to the application of other PCM. Relevant PCM for the usage in rooms are paraffin, fatty acids, salt hydrates and their eutectic mixtures [1],[2]. The most common method for obtaining paraffin is to extract it during the refining process of crude oil. It is noteworthy for its chemical stability and a high specific heat capacity. Phase instability and supercooling effects, with a solidification temperature below melting point, are quite unusual. Flammability and low-heat conductivity cause a reduction in paraffin's effectiveness.

Further examples of previously researched PCM are salt hydrates, for example made up of calcium chloride hexahydrate ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ) or sodium sulphate ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ). These materials possess a very high storage capacity due to a comparatively high density. Crucial disadvantages that have been identified are supercooling effects and phase instability [2].

In contrast to pure phase change materials that melt at a discrete melting point, PCM that can be applied in the building industry are mixed materials, melting at a particular temperature range that is dependant on their chemical composition. During the 1980s, the first research was conducted where phase change materials, especially paraffin, were integrated into building materials to solve the problems of thermal protection in summer [3]. Due to important investigations in the field of materials research and microencapsulation techniques in recent years, a reasonable integration of PCM in building materials became possible [4]-[6]. The utilization of microencapsulated paraffin in plaster represents a recommendable application [7]-[9].

### Nomenclature

$A$	surface area ( $\text{m}^2$ )
$c$	heat capacity ( $\text{J/kg K}$ )
$d$	layer thickness (m)
$h$	heat transfer coefficient ( $\text{W/m}^2 \text{K}$ )
$I$	solar radiation ( $\text{W/m}^2$ )
$l$	latent heat ( $\text{kJ/kg}$ )
$m$	mass (kg)
$n$	air change rate ( $\text{h}^{-1}$ )
$Q$	heat (kJ)
$r$	solar energy reducing factor
$t$	time (s)
$U$	heat transmission coefficient ( $\text{W/m}^2 \text{K}$ )
$V$	volume ( $\text{m}^3$ )

### Greek letters

$\theta$	temperature ( $^\circ\text{C}$ )
$\lambda$	heat conductivity ( $\text{W/mK}$ )
$\rho$	density ( $\text{kg/m}^3$ )
$\Phi$	heat flow (W)

### Indices

a	air
e	exterior
g	glazing
i	indoor
l	liquid
m	melt
r	room
s	solid
T	transmission
v	ventilation
w	wall

For realistic investigations, four identical test rooms were erected where modified gypsum plaster and a salt mixture were chosen as PCM agents. All the test rooms were built as lightweight constructions and possess a highly glazed facade ratio [10],[11]. The findings to these experiments will be compared with the results of a mathematical model [12] and finally discussed.

## 2. Character of the used PCM

### 2.1. Plaster with microencapsulated paraffin

The applied PCM-plaster is a special gypsum plaster, which consists of PCM, gypsum, mineral aggregates as well as admixtures to improve the working properties. The integrated PCM is microencapsulated paraffin with a diameter of approximately  $5 \mu\text{m}$  and has a melting range of between  $25$  and  $28 \text{ }^\circ\text{C}$ . The influence of the PCM capsules on vapour diffusion is expected to be negligible and therefore comparable with conventional gypsum plaster [13].

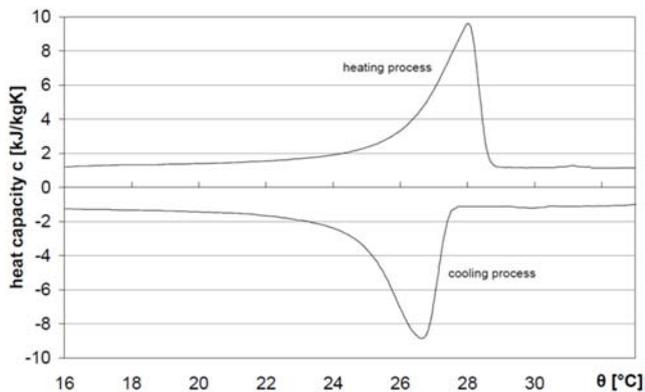


Fig. 1. DSC-measurement of the PCM-modified plaster.

Through the Differential-Scanning-Calorimetry (DSC), the sensible and the latent heat of the PCM-modified plaster were measured with a constant heat and cooling rate of 2 K/min. It was shown that the peak temperature in the cooling mode is at 28.0 °C. There is no significant supercooling effect because the solidification process starts nearly at the same temperature as melting process stops<sup>[14]</sup>. The characteristic of the phase change process is not discrete, but rather, it is situated in a temperature range (Fig. 1). Beyond the phase change the heat capacity of the PCM-modified gypsum plaster reaches an amount of  $c_{\text{sensible}} = 1.15 \text{ kJ/kgK}$ , which is equal to the heat capacity of pure gypsum plaster. Henceforth, the heat energy that can be stored in the temperature range of the phase change can be determined by the following equation:

$$Q = m \cdot c \cdot \Delta\theta \quad c = c_{\text{latent}} + c_{\text{sensible}} \quad (1)$$

The heat conductivity of the phase change materials can only be measured indirectly through the experimental determination of the thermal diffusivity. Therefore, a test series with the laser flash instrument NETZSCH-LFA 427 was conducted. With a sample of PCM-modified plaster the conductivity of temperature was determined for different temperatures. The thermal diffusivity of a material is the significant parameter of the transient heat transmission following the Fourier equation. In the phase change range the thermal diffusivity is a function of the temperature as a result of the latent heat storage. The heat conductivity is assumed as constant in the solid respectively in the liquid phase.

Table 1:  
Thermophysical properties of paraffin

Material	Paraffin
$\theta_m$ (°C)	28.0
$Q_{\text{latent}}$ (kJ/kg)	244.0
$\rho$ (kg/m <sup>3</sup> )	987.0
$\lambda_{\text{liquid}}$ (W/mK)	0.20
$\lambda_{\text{solid}}$ (W/mK)	0.28

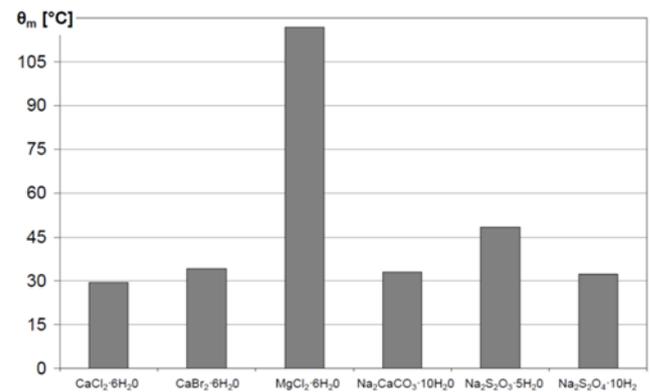


Fig. 2. Graph of the melting temperatures of the salt hydrates.

The density of the measured material is assumed to be independent of the temperature and the state of aggregation and was determined experimentally. Table 1 shows the parameter which were used for the numerical calculation.

## 2.2. Modified $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$

Available salt hydrates have melting points between 7 and 117 °C (Fig. 2). All salt hydrates show, depending on the water content, a different water vapour pressure<sup>[15],[16]</sup>. Both water content and vapour pressure are temperature-dependent. For this reason, salt hydrates have to be used in hermetically sealed containers or encapsulated to guarantee a low water vapour transmission. Salt hydrates show comparatively high densities, but undergo a volume change during the freezing process, some more than others. Supercooling is a major problem for salt hydrate PCM and therefore most of the commercial products include nucleating additives.

All products being marketed have a good margin of safety with respect to toxicity. Some of the additives proposed as nucleators are toxic, but are used at concentrations which are low enough to be safe. Furthermore, salt hydrates are not combustible. The salts used for commercial salt hydrate PCM are all produced in large-scale production by the chemical industry. It is possible to divide salt hydrates into the following groups depending on their melting characteristics: Congruent, quasi-congruent and semi-congruent melting PCM, congruent isomorphous PCM and eutectic as well as incongruent melting PCM<sup>[17]</sup>.

Table 2:  
Thermophysical properties of the modified  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ <sup>[17]</sup>

Material	$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$
$\theta_m$ (°C)	29.6
$Q_{\text{latent}}$ (kJ/kg)	190.8
$\rho_{\text{liquid}}$ (kg/m <sup>3</sup> )	1562
$\rho_{\text{solid}}$ (kg/m <sup>3</sup> )	1802
Salt (%)	50.66
Water (%)	49.34

**Table 3:**  
Composition of the modified  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$

Chemical material	Weight ratio (%)
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	96.5
NaCl	0.5
KCl	2.0
$\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$	1.04

The applied material calcium chloride hexahydrate is inexpensive and abundant. It is obtained by a separation process from brine, which in turn, is extracted from subterranean deposits.  $\text{CaCl}_2$  is also produced as a by-product of several industrial chemical processes.  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  shows a supercooling of up to 10 K, therefore an added nucleator is needed to produce an applicable PCM. As nucleator it is possible to use for example BaO,  $\text{Ba}(\text{OH})_2$ ,  $\text{BaCO}_3$ ,  $\text{BaSO}_4$  or  $\text{Sr}(\text{OH})_2$  [17]. Although these are toxic, the amounts used for nucleation are small enough that they present just little practical hazard. Usually, nucleators are used in levels of 1 to 2 %. Calcium chloride hexahydrate is relatively non-toxic and is also not combustible. Its thermal properties can be seen in Table 2.

The melting point of the pure calcium chloride hexahydrate is too high to decrease temperatures of the indoor air in summer time especially in light weight constructions. For practical use, salt hydrates with a melting point between 23 and 27 °C are needed. Therefore, a salt mixture based on calcium chloride hexahydrate was developed.

To decrease the melting point of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , the additives NaCl and KCl were added. Furthermore,  $\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}$  acts as a nucleator (Table 3). The melting point of the modified  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  lies between 25.5 and 27.0 °C, which means it is suitable for the practical use in buildings.

**Table 4:**  
Composition of the experimental objects envelopes [15]

Material	$d$ (m)	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\lambda$ (W/mK)	$c$ (J/kgK)
Gypsum plaster board	0.0125	900	0.25	1000
Mineral wool	0.20	30	0.04	1030
Gypsum plaster board	0.025	900	0.25	1000

### 3. Instrumentation and measurements

#### 3.1. PCM-modified plaster

To analyse the possibilities of PCM in detail, two identical test rooms were built near Weimar, Germany. They are thermally separated in order to offer similar conditions (Fig. 3). Test measurements showed that both rooms behaved thermally equal. For the construction, only lightweight building materials such as gypsum plasterboards or mineral fibrous insulating material were used. The thermal mass is considered to be low (Table 4).

Subsequently both rooms were plastered. While in one room a paraffin-modified plaster was applied on the surrounding walls (Table 5), the second room was provided with a conventional gypsum plaster. The thickness of the plaster coating was 1 cm in the beginning and later increased to about 3 cm. The plastered surface area per room counts 52 m<sup>2</sup>. During a third series of measurements additional tubes filled with a modified  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  were introduced to improve the thermal effect in the PCM-conditioned room. Several thermocouples were fixed on the surface of the plaster, which enabled the measurement and comparison of the temperatures at different locations in the room. Additional thermocouples in the plaster enable the investigation of the temperature profile. Data was recorded in intervals of 15 min

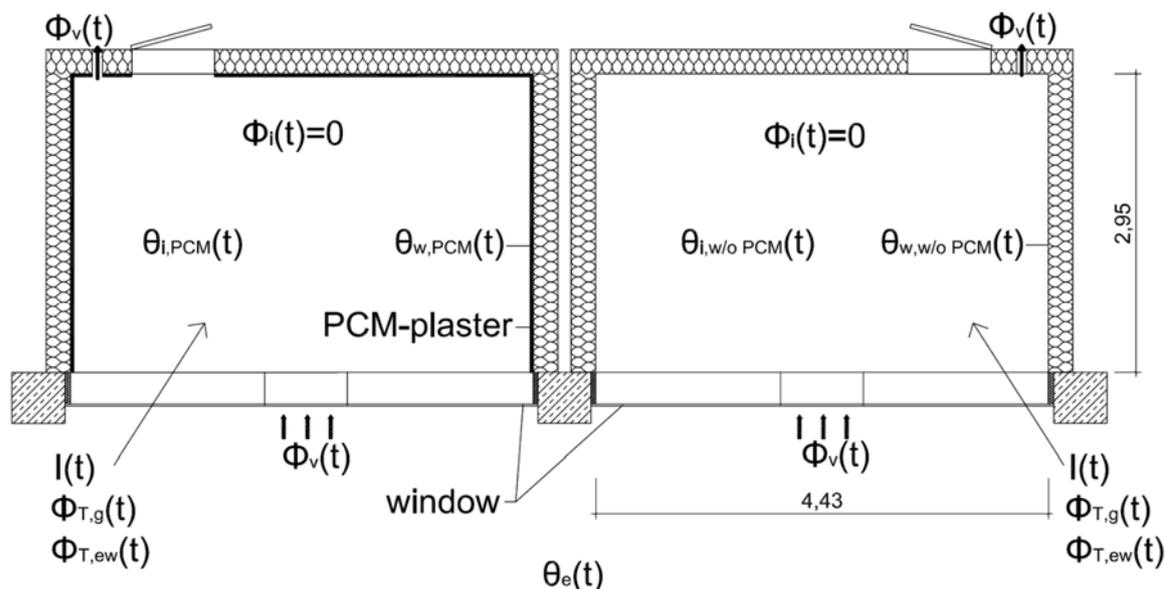


Fig. 3. Test rooms (on the left with PCM plaster).

Table 5:  
Used PCM in the experimental object

PCM		Paraffin plaster
$m$	(kg)	193.8
$l$	(kJ/kg)	244.0
$Q$	(kJ)	47287.2
$Q/V_r$	(kJ/m <sup>3</sup> )	1125.1

with the data acquisition system Ahlborn Almemo 5990-0. The test series was carried out under controlled variable conditions with parameters like temporary air change, internal heat gains or clouding.

Over the course of 2005, different readings of the temperature sequence in the test rooms with and without PCM were carried out. The parameters of the air change rate, as well as the strength of coating of the plaster, were varied. A typical run of the ambient and the indoor temperature and the solar radiation is shown in Fig. 4. The rooms were ventilated with an airflow of approximately 80 m<sup>3</sup>/h, which is equivalent to an air change rate of  $n = 2 \text{ h}^{-1}$ . Managed by a clock timer the fans operated 7 p.m. to 7 a.m. to help the required discharge of the PCM. During the day a base ventilation of  $n = 0.5 \text{ h}^{-1}$  is assumed. In Fig. 5 the daily maximum temperatures of a week can be compared. The regulating influence of a PCM layer of 3 cm on the indoor temperature becomes thereby obvious. During warm days a reduction of the peak temperature of about 3 K in comparison to the room without PCM can be achieved.

In Fig. 6 the effect of the microencapsulated paraffin is demonstrated in detail. The point of the phase change, which occurs in the temperature range between 25 and 28 °C, can be seen in a sharp bend in the curve during the heating due to the melting process. This takes place during the cooling phase too, due to the solidification process in development. In both rooms the air temperature rises intensely due to the impact of the solar radiation, while the ambient temperature at noon achieves approximate 20 °C. A high temperature spread between day and night has to be ascribed to the low thermal

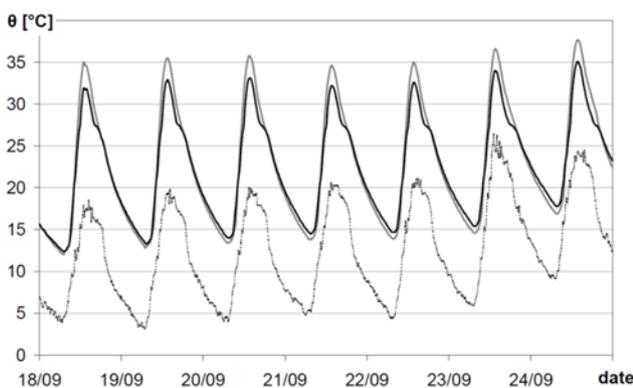


Fig. 4. Air temperature (grey without PCM, black with PCM), ambient temperature (dotted); strength of coating of the plaster 3 cm.

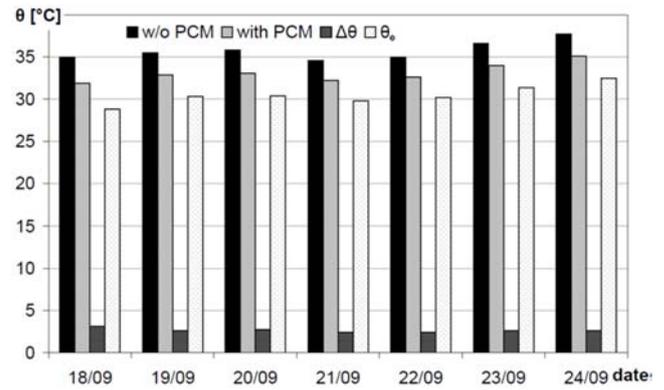


Fig. 5. Comparison of the daily peak temperatures.

mass of the test rooms. Until the room temperature attains 25 °C, the beginning of the melting process of the PCM, the temperature curves of both rooms stay convergent. Above 25 °C, the PCM-conditioned room heats up slower, caused by the high melting enthalpy of the PCM. This results in a temperature difference of up to 3 K. The heat storing effect can also be observed during the night. If the melting temperature of the PCM is achieved, the room cools down slower because of the stored latent heat. Consequently, by using PCM the room temperature gets damped by day as well as at night.

In case of insufficient nocturnal solidification of the PCM as a result of high indoor temperatures, e.g. due to high solar radiation during the day, the functionality of the PCM can be limited. In Fig. 7 such a limit of the usage of PCM due to insufficient discharge during a heat wave is pointed out. This series of measurements from May 2005 was carried out similarly with nocturnal ventilation and without the impact of internal heat gains. The strength of coating of the plaster was 1 cm. Additionally 200 kg of the salt hydrate CaCl<sub>2</sub>·6H<sub>2</sub>O were placed in the PCM-conditioned room. The reduction of the peak temperature is therefore with 4 K even higher than in the previous case.

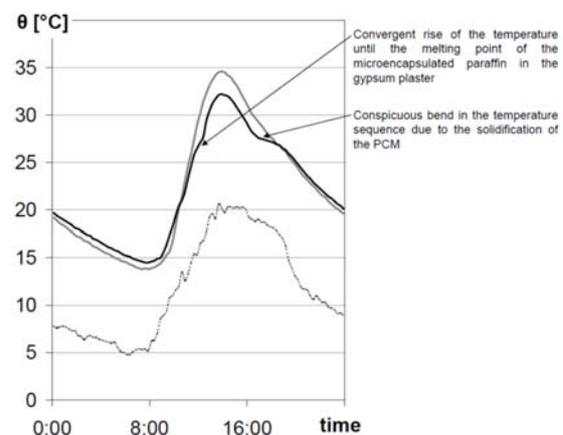


Fig. 6. Air temperature (grey without PCM, black with PCM), ambient temperature (dotted).

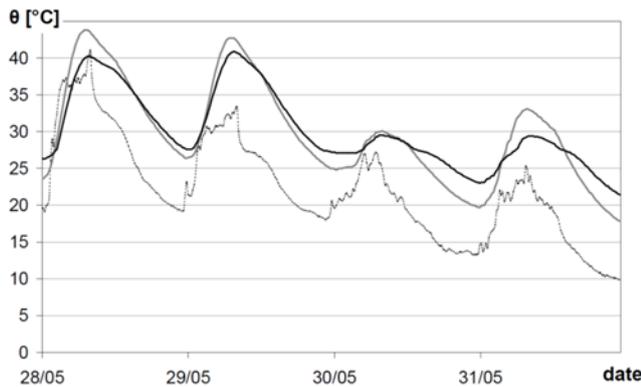


Fig. 7. Limits of the functional capability during a heat wave in summer 2005: air temperature (grey without PCM, black with PCM), ambient temperature (dotted).

The diagram indicates that the room without PCM was heated up until 44 °C and the room with PCM up to 40 °C. Such high temperatures result from the high intensity of the solar radiation as well as the large window area of the test rooms. In the following night the PCM-conditioned room merely cools down until the solidification temperature of the phase change materials (28 °C), which therefore can be discharged only insufficiently. These properties cause an attenuated effect already at the following day. In the night of May 31st the PCM is able to solidify due to the fall below the melting temperature; the functionality of the system is reconstituted. However, in case of expected high solar radiation resulting in high indoor temperatures it is necessary to adjust the melting point of the PCM to the estimated daily/ nocturnal indoor temperatures [14].

3.2. Salt mixture

To verify the properties of the modified CaCl<sub>2</sub>·6H<sub>2</sub>O two identical experimental objects were erected in Vrtežir near Brno, Czech Republic, one object with and another one without PCM to measure the indoor climate simultaneously under the same external conditions [18]. Both objects are lightweight constructions with a single glazed window; details are listed in Table 6.

As a phase change material, the previously developed modified CaCl<sub>2</sub>·6H<sub>2</sub>O was applied (Table 7). This salt mixture was filled in six PVC tubes with a diameter of 63 mm and a length of 1.0 m underneath the ceiling. A PVC plug sealed each end of the tubes. Between the tubes and the ceiling, there was space for the necessary airflow.

Table 6: Composition of the experimental objects envelopes

Material	d (m)	ρ (kg/m <sup>3</sup> )	λ (W/mK)	c (J/kgK)
Chipboard	0.022	850	0.11	1500
Glass wool	0.120	250	0.04	840
Chipboard	0.020	600	0.08	2000
PE foil	0.0001	1470	0.35	1470

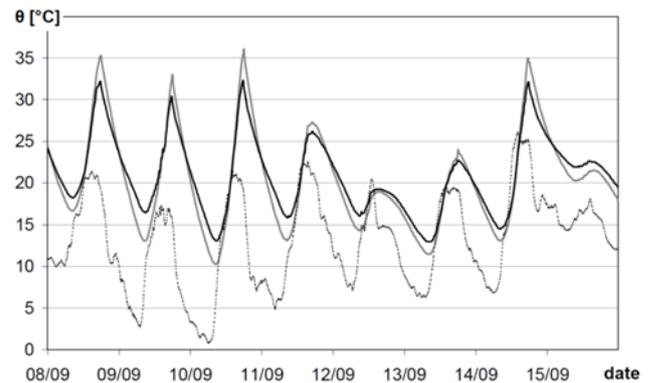


Fig. 8. Indoor temperature (grey without PCM, black with PCM), ambient temperature (dotted).

In comparison to the investigations done with the PCM- modified plaster objects, different measurements were carried out. A typical run of the ambient and indoor temperatures can be seen in Fig. 8. Using thermocouples (NiCr–Ni) that were placed on different locations, readings were made in order to get interior and ambient temperatures, the surface temperature and finally the temperature of the salt. The data was recorded in an interval of 15 min with the data acquisition system Ahlborn Almemo 2290-8. The experiment proved the effect that phase change materials have on thermal performance. For example, on 10/09 the maximum daily temperature in the test cell without PCM (room 1) was 36.1 °C and in the object with PCM (room 2) 32.3 °C, which means a difference of 3.8 K (Fig. 9). On the other hand, temperatures during the night in room 2 were higher than in room 1, which is the result of the solidification process of the salt hydrate.

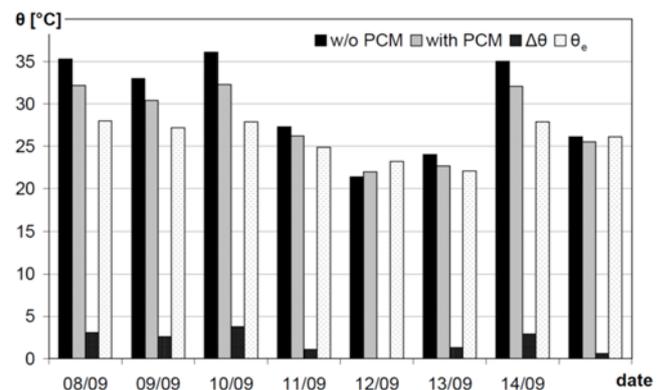


Fig. 9. Comparison of the peak temperatures.

Table 7: Used PCM in the experimental object

PCM	Modified CaCl <sub>2</sub> ·6H <sub>2</sub> O
m	(kg) 14.5
l	(kJ/kg) 192.0
Q	(kJ) 2784.0
Q/V <sub>r</sub>	(kJ/m <sup>3</sup> ) 1344.9

## 4. Numerical calculation and modelling

### 4.1. Numerical model

A simplified model, based on an energy balance, was developed to characterize the mathematical process and to estimate the temperature trend in a PCM-equipped room<sup>[12]</sup>. It was not the aim to consider all effects, but rather to describe the essential processes with a comparatively small number of parameters. Nevertheless, the impact of the fundamental parameter should always be shown by the model. It is assumed that no heat transmission through the inner walls occurs due to an adiabatic boundary in the boundary layer plaster – gypsum plaster board.

It is worth mentioning that the room temperature is mainly determined by the impact of the ambient temperature  $\theta_e(t)$ , the solar radiation  $I(t)$ , internal heat gains  $\phi_i(t)$  and the air change rate  $n(t)$ . Beside these forces, the room temperature  $\theta_i(t)$  and temperature of the inner partitioning  $\theta_w(t)$  are affected by the heat storage capacity of the surrounding walls as well as by the ingoing and outgoing heat flow  $\phi$ . Both temperatures  $\theta_i(t)$  and  $\theta_w(t)$  can be calculated by the following coupled energy balance equation:

$$\dot{\theta}_i(t) = -(a_1 + a_4)\theta_i(t) + a_4\theta_w(t) + \Omega(t) \quad (2)$$

with  $\Omega(t) = a_1\theta_e(t) + a_2I(t) + a_3\Phi_i(t)$

and  $\dot{\theta}_w(t) = b_1b_2[\theta_i(t) - \theta_w(t)] \quad (3)$

The coefficients  $a_1$  till  $a_4$  as well as the factor  $b_1$  are presumed to be constant and result as follows:

$$a_1 = \frac{U_{ew}A_{ew} + U_gA_g + \rho_a c_a n V_a}{\rho_a c_a V_a} \quad a_2 = \frac{rA_g}{\rho_a c_a V_a}$$

$$a_3 = \frac{1}{\rho_a c_a V_a} \quad a_4 = \frac{h_i A_{PCM}}{\rho_a c_a V_a} \quad b_1 = \frac{h_i A_{PCM}}{\rho_{PCM} c_{PCM,s} V_{PCM}} \quad (4)$$

The index *PCM* comprises the entire layer of plaster. The solar energy reducing factor  $r$  takes the solar gains into account, attenuated by the position of the sun, the clouding, the overall heat gain coefficient of the windows and the orientation of the room. The factor  $b_2$  is dependent on the temperature  $\theta_w$  of the PCM-containing interior walls

$$b_2(\theta_w) = \begin{cases} 1 & \theta_w < \left(\theta_m - \frac{\Delta\theta}{2}\right) \\ \frac{c_{PCM,s}}{c_{PCM}} & \left(\theta_m - \frac{\Delta\theta}{2}\right) \leq \theta_w \leq \left(\theta_m + \frac{\Delta\theta}{2}\right) \\ \frac{c_{PCM,s}}{c_{PCM,l}} & \theta_w > \left(\theta_m + \frac{\Delta\theta}{2}\right) \end{cases} \quad (5)$$

whereby the heat capacity  $c$  of the PCM in solid and liquid states, as well as during the transition period, plays an important role.  $\theta_m$  is the average melting point and  $\Delta\theta$  the temperature range of the melting process.

### 4.2. Boundary conditions

In the following section, the indoor temperatures are calculated with the simplified model basing on the measured climate conditions. Differences between the measured and the calculated data are to be expected, because the mathematical model considers only the essential processes with a small number of parameters.

The process variables  $\theta_i(t)$  und  $\theta_w(t)$  of the mathematical model comprise the ambient temperature  $\theta_e(t)$ , the solar radiation  $I(t)$ , internal heat gains  $\phi_i(t)$  and the air change rate  $n(t)$  as periodical functions. Hence, for the solution of (3) and (4), it is helpful to describe these functions in a closed form. The series of measurements of  $\theta_e(t)$  and  $n(t)$  were approximated with a Fourier series. The least squares method provided the basis for the curve fitting. For the approximation of the solar radiation  $I(t)$  it is useful to split up the curve in daily segments.

With the help of the least squares method it is consequently possible to fit the series of measurements piecewise with polynomials.

The following details, concerning the characteristic of the rooms, are necessary for the calculation:

- the effective heat transfer coefficient  $h_{i,eff}$  is calculated according to [12] with  $1/h_{i,eff} = 1/h_i + d_w/2\lambda_w$  ( $h_i = 7.7 \text{ W/m}^2\text{K}$ )
- solar energy reducing factor  $r = 0.5$
- with/without PCM covered surrounding areas  $A_{w,PCM} = 52.12 \text{ m}^2$
- volume of the layer with/without PCM  $V_w = 1.07 \text{ m}^3$ ,  $V_r = 42.03 \text{ m}^3$
- glazed area  $A_g = 15 \text{ m}^2$

### 4.3. Results

To solve the differential equation system (2) and (3) the computer algebra system Maple was used. External as well as internal forces were described with periodical functions, the coefficients resulting from (4) and (5) were adapted to the real boundary conditions of the test rooms, which makes the results of the calculations comparable with the real temperature curves (Fig. 4 and Fig. 10). The calculations of the room air temperature make it possible for the essential processes to be described. During the day, the temperature sequence is up to 2 K realistically represented and just slightly delayed. This applies to both rooms: with as well as without PCM. The usual bends are clearly distinguishable during the phase change and always occur if PCM is employed. The bend, due to the melting process, is only obvious at the end of the reference week because only in these days of the week does the PCM in the plaster melt completely. The process of solidification is slightly delayed and deformed. Greater differences arise out of the calculation of the nocturnal cooling of the rooms. The calculated room air temperature is situated in the top 6 K below the measured data in both rooms with and without PCM.

The calculated temperature sequence of the walls, the basis of the progression of the air temperature caused by phase change, matches additionally the character of the measured temperatures. It became visible once again that the calculation of the nocturnal cooling can only be characterized as limited realistically speaking, even though the calculation of the temperatures by day was successful.

The insufficient nocturnal calculation is caused by different impacts. In the mathematical model neither vertical nor horizontal temperature fields are taken into account, which redounds in an inaccurate description of the phase change. This is intensified by disregarding the temperature gradient in the surrounding wall, or rather, in the plaster due to the used simple energy balance. It is furthermore worth stating that, with the formulation of the model, more simplifications concerning the constants have been carried out, for example the solar gains.

A further reason is the lack of mathematical description of the substantial thermal mass of the surrounding construction. However, the resulting difference between the simulated and the real sequences can be assessed as marginal, since the rooms have been erected with a low thermal mass.

Finally, the temperature sequence can be reproduced characteristically by calculations with the mathematical model: both with and without the impact of phase change materials. And this, especially for daytime temperatures, is of particular importance for the estimation of functional capability of PCM.

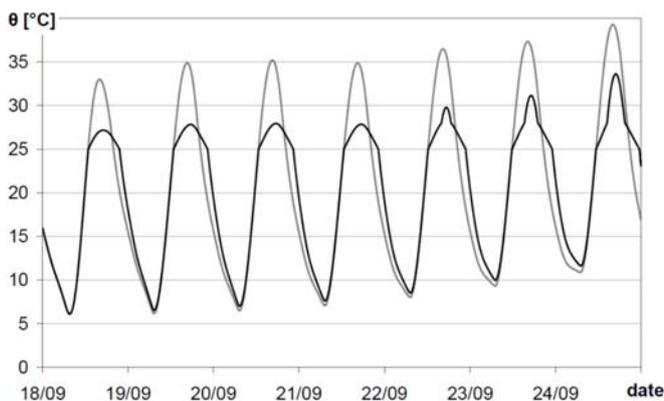


Fig. 10. Calculated air temperatures (grey without PCM, black with PCM).

## 5. Conclusion

The utilization of phase change materials (PCM) in buildings increases the thermal mass and contributes consequently to an improvement of the thermal protection in summer. This was shown by means of measurements using paraffin as well as a salt mixture. A reduction of the peak temperature of up to 4 K could be ascertained. Furthermore,

it could be proven that the PCM forfeit their characteristic heat storage capacity after a few consecutive hot days, if they cannot be discharged over night. Efficient night ventilation can counteract such effects. The influence on the measurement of different parameters like the air change rate was varied to simulate the daily routine of an office.

A mathematical model, based on an energy balance equation, was developed to estimate the temperatures in a PCM-conditioned room. The measurements were used for the validation of the model. As regards the calculations it was helpful to approximate the boundary conditions in closed forms. On this account the ambient temperature as well as the air change rate were described using Fourier series. The solar radiation was divided in daily segments and approximated with polynomials. Finally, with the aid of this mathematical model, the effects of the PCM could be reproduced numerically.

## 6. References

- [1] G.A. Lane, Encapsulation of heat of fusion storage materials, in: Proceedings of the Second South Eastern Conference on Application of Solar Energy, Baton Rouge, Louisiana, USA, (1976), pp. 442–450.
- [2] B. Lenzen, Entwicklung und Untersuchung eines latentwärmespeichernden Baumaterials zum Einsatz in transparent gedämmten Außenwänden, VDI-Verlag, 2002.
- [3] D.W. Hawes, D. Banu, D. Feldmann, Latent heat storage in concrete, Solar Energy Materials 19 (3–5) (1989) 335–348.
- [4] E. Jahns, Microencapsulated phase change material, in: Proceedings of the International Energy Agency, Energy conversion through energy storage programme (ECES), Annex 10: 4th Workshop, Benediktbeuern, Germany, 1999.
- [5] D. Elberfeld, Verkapselung von Latentwärmespeichern in einer Siloxanhülle, Ph.D. Thesis, Universität Oldenburg, 2001.
- [6] P. Schossig, H.-M. Henning, S. Gschwander, T. Haussmann, Micro-encapsulated phase-change materials integrated into construction materials, Solar Energy Materials and Solar Cells 89 (2–3) (2005) 297–306.
- [7] S. Hoffmann, O. Kornadt, Phasenübergangsmaterialien (PCM) als Latentwärmespeicher in Revitalisierungsobjekten, in: Schriften der Bauhaus- Universität Weimar, Revitalisierung von Bauwerken, 2006, 129–134.
- [8] S. Hoffmann, O. Kornadt, Phase change materials against indoor over-heating, in: Proceedings of the 4th CIB W 108, Meeting on Climate Change and the Built Environment, Paris, France, 2005.
- [9] S. Hoffmann, O. Kornadt, D. Chow, G. Levermore, An investigation on phase change materials under climate change conditions, Building and Environment, in press.
- [10] B. Waldhelm, O. Kornadt, Einfluss von Phasenübergangsmaterialien zur Verbesserung des Raumklimas, wksb 50 (54) (2005) 28–31.
- [11] C. Voelker, O. Kornadt, Experimentelle und numerische Untersuchung zur Reduktion sommerlicher Überhitzung durch Phasenübergangsmaterialien, wksb 51 (56) (2006) 3–9.

- [12] O. Kornadt, R. Rudolph, K. Guerlebeck, Absenkung von Raumlufttemperaturen in Hitzeperioden, *wksb* 47 (49) (2002) 7–12.
- [13] A. Zoeller, Personal Communication, Maxit Deutschland GmbH, 2007.
- [14] S. Hoffmann, Numerische und experimentelle Untersuchung von Phasenübergangs-materialien zur Reduktion hoher sommerlicher Raumtemperaturen, Ph.D. Thesis, Bauhaus-Universität Weimar, 2007.
- [15] DIN EN 12524, Building materials and products – hygrothermal properties – tabulated design values, German version EN 12524, 2000.
- [16] G.A. Lane, *Solar Heat Storage: Latent Heat Materials*, vol. I: Background and Scientific Principles, CRC Press, Boca Raton, Florida, 1983.
- [17] G.A. Lane, *Solar Heat Storage: Latent Heat Materials*, vol. II: Technology, CRC Press, Boca Raton, Florida, 1983.
- [18] M. Ostry, Effect of the Thermal Storage Properties of the Phase Change Materials on the Indoor Environment, Ph.D. Thesis, Brno University of Technology, 2005.