

Research Framework for an Experimental Study on Phase Change Materials in Scaled Models of Dutch Dwellings

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Abstract

In modern Dutch dwellings, about 10% of the annual use of primary energy is used for cooling, whereas about 50% of the primary energy is used for heating. With the technology of Phase Change Materials (PCMs) energy savings can be made in both areas. PCMs are materials with a high latent heat capacity which are, by melting and solidifying at a certain temperature, capable of storing and releasing a certain amount of energy. Unlike sensible storage materials, PCMs absorb and release heat at a nearly constant temperature. At hot days the PCMs can store (part of) the excessive heat to form a (temporarily) buffer. The heat is released again when the temperature drops below the melting temperature of the PCM. As a result, people inside a building incorporating PCMs can experience more comfort than in conventional buildings.

To measure the possible energy savings, an experimental research facility was set up. In this field set-up, modern Dutch dwellings are simulated by using scaled models with and without PCM in the concrete floors. These models are provided with sensors measuring the inside temperature and the incoming solar irradiation. As a reference, a weather station collects data on the outside temperature, humidity, solar irradiation and wind speed. By comparing these data, the influence of the PCM's becomes apparent.

In this proposition paper, a research framework to analyse the influence of PCM will be presented. To provide models, software packages will be assessed. The software package, which must be able to calculate the thermodynamic differential equations dynamically, will visualize the incoming and outgoing energy flows. The results, regarding the effectiveness of PCM, will also be implemented in the computation methodology of the Energy Performance Coefficient (EPC).

Keywords:

Phase Change Materials, Built Environment, Solar energy, Energy Savings, Experimental Research

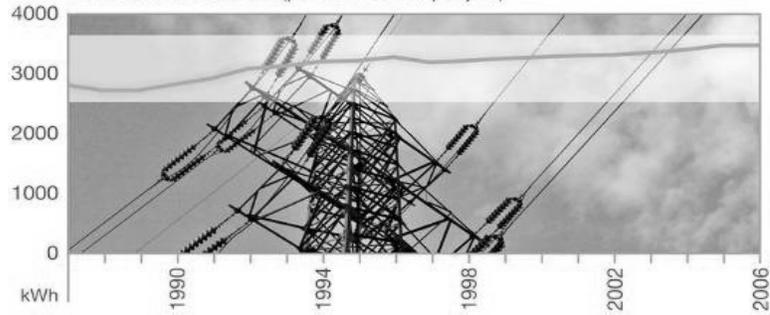


Figure 1 : Increase of annual electricity consumption in Dutch households, per household [1]

1 INTRODUCTION

Nomenclature

A_{gs}	Total ground surface [m^2]
A_{fs}	Total thermal transmission surface [m^2]
C	EPC Correction factor
E	Energy [J]
J	Joule (MJ = MegaJoule)
K	Kelvin
k	Thermal conductivity coefficient [$W/(m \cdot K)$]
L	Thickness of wall [m]
m	meters
U_{total}	Annual primary energy use of a house [MJ]
q	Heat density [W/m^3]
\dot{q}	Heat flux [W/m^2]
S	Surface of integration
s	seconds
T	Temperature [K]
t	Time variable [s]
u	Internal heat per volume [J/m^3]
W	Watts
x, y, z	Spatial variables for direction [m]
in	Subscript for inside
out	Subscript for outside

Because fossil fuels will probably not available forever, the world nowadays deals with energy saving. With still increasing demands, one is, as a result, becoming more interested in being energy efficient. Man can see this trend for example in the electronics branch, like with computers, laptops and mobile phones.

Although better technologies, smarter designs and a growing awareness and interest in energy results in better energy efficiency, an average Dutch household still uses more and more electric energy, which can be seen in Figure 1.

There are several reasons for this increase. The most important one is an increasing number of household

appliances. Especially the amount of dryers, dishwashers, small electronic devices and the usage of computers increased during the last decade [1].

Another reason is the decrease of habitants per dwelling. This will result in higher electricity consumption per household, because a single person household uses about one-third more electricity than a household with two persons uses. Also, on average, a household with either one of a double-income couple will use more electricity (because they tend to have more timesaving appliances) compared to households with persons who are often at home [1].

A third reason is that many household appliances stay in stand-by mode more often these days. This seems to be underestimated, because most people apparently think they do not use that much more electric energy. Also some electric devices consume electric energy even when the power button is turned off.

A last reason is the increasing demand for cooling during summer times to increase human well-being. A Phase Change Material (PCM) can contribute to human well-being.

PCMs form a relatively new and promising technology that may both decrease the electricity consumption during summer times ("space cooling", see Figure 2) and the energy needed for heating the building. These materials are capable of storing heat temporarily and therefore save on cooling demand.

This paper will present a research framework [3] to analyse the influence of a PCM in a concrete floor in a Dutch climate. After this introduction, section 2 starts with a theoretical background of PCM. The physical principle, the possibilities and the applications of PCM will be explained here and an overview of different types of PCM will be given.

In section 3 the problem definition and some research objectives will be formulated. It also gives an indication of where PCMs can have a positive effect on the image of the building industry nowadays. The impact of this research will be further clarified in sections 4 (societal and scientific relevance).

Section 5 shows the experimental set-up which will give an answer on the research question. This set-up consists of four test boxes, with different glazing insulation and absence or presence of PCM in the concrete floor. It explains how this set-up is built and where it is located.

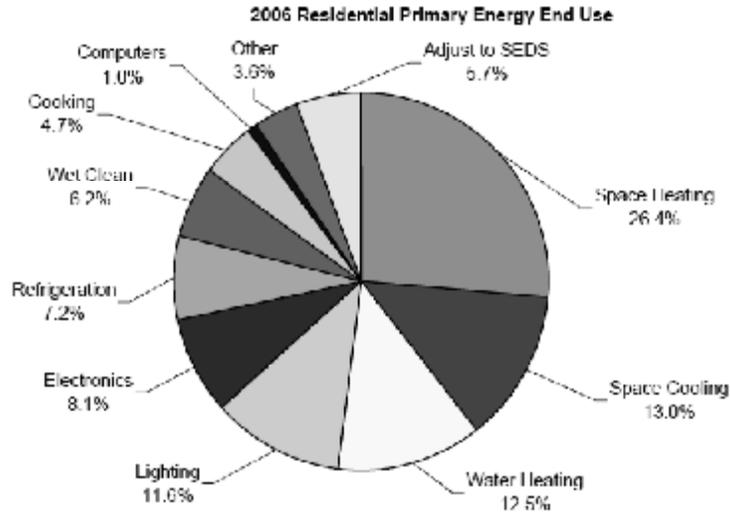


Figure 2 : Primary energy use of U.S. households [2]

The research methodology will be explained in section 6. This section will give a stepwise route to answer the research question. Also some interesting software packages will be discussed here.

In section 7 a summary of the research so far will be given as well as some points of interest for further research. Briefly some preliminary results will be given.

2 Theoretical background

2.1 What is a PCM?

When a solid material is getting heated, its temperature is raising. If the amount of heat is large enough, the solid will start melting. At that point, during the melting process, the temperature will stay constant and the thermal energy is absorbed by the material.

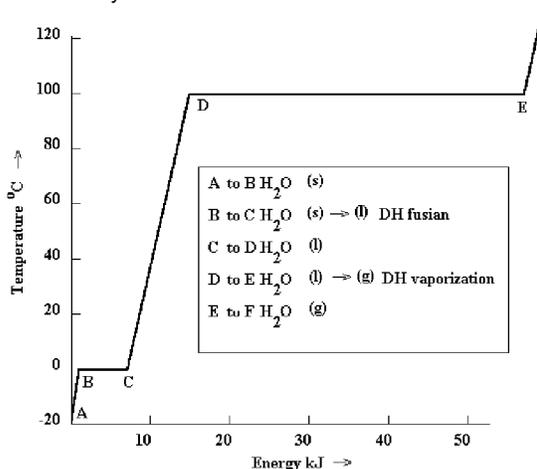


Figure 3 : Latent heat, from B to C and from D to E of water

In Figure 3 this is trajectory B-C. By absorbing this so-called latent heat, a temporarily buffer of energy is

¹ This is true if the solid material consists of only one type of molecules.

formed. The temperature will increase again if the material is totally molten and does so until it reaches its boiling point. Then the same process happens again: temperature during the phase change stays constant. When the material is cooled down, the process will take place in opposite direction.

A PCM behave like this physical principle, but unlike conventional (sensible) storage materials, PCMs absorb and release heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [4]. Thus PCM is a material that is capable of storing latent heat and therefore might improve the total heat capacity of the internal constructions. As a result, people inside a building incorporating PCMs can experience more comfort than in buildings without PCMs.

2.2 PCM: Classification, Properties & Applications

Several materials can be suitable as a PCM that is capable of saving energy in the built environment. There are both organic and inorganic substances as well as a mixture of organic and/or inorganic substances with different melting points; the eutectics. The organic PCMs can be separated into paraffins and non-paraffins, whereas the inorganic PCMs can be separated into salt hydrates and metallics. Figure 4 gives an overview of the different sorts of PCMs [5].

The organic PCMs have some physical advantages over the inorganic and eutectics PCMs. They have a broad temperature range and because of this, selection of the right organic PCM is easier. Organic PCMs are highly compatible with conventional materials of construction; they are chemically stable, safe and non-reactive. The downside of organic PCMs is their higher costs.

If investment is the criterion, one should opt for an inorganic PCM, which is also easier available [5]. The downsides of an inorganic PCM are that the change of volume due to temperature differences is very high and that they suffer from decomposition and supercooling, which can affect their phase change properties.

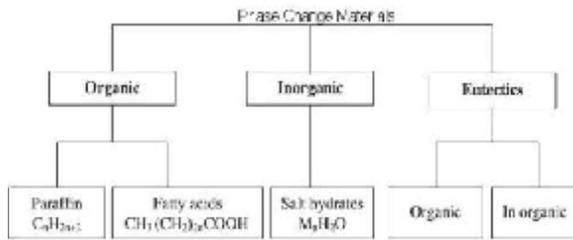


Figure 4 : Classification of PCMs [5]

Most of the PCMs that were used in the built environment for thermal storage in conjunction with both passive storage and active solar storage for heating and cooling in buildings, have melting temperatures between 20-32°C [6].

There are two purposes for using PCMs in buildings. Natural heat (that is solar energy) can be used for heating or night cold for cooling. Or manmade heat or low temperature sources can be the reason for installing PCMs. In any case, storage of thermal energy is necessary to match availability and demand with respect to time and also with respect to heating and cooling capacity. Basically three different ways to use PCMs for heating and cooling of buildings are [6]:

1. PCMs in building walls;
2. PCMs in other building components other than walls; and
3. PCMs in heat and cold storage units.

The first two are passive systems, where the heat or cold stored is automatically released when indoor or outdoor temperature rises or falls beyond the melting point. The third one is active system, where the stored heat or cold is in containment thermally separated from the building by insulation. Therefore, the heat or cold is used only on demand and not automatically [6].

2.3 Heat Transfer & Energy Balance

On a clear day, solar irradiation heats up the building shell. By means of conduction this heat is transferred through the walls and by means of mainly convection it finally heats up the room inside. If steady state can be assumed and the supplied heat is constant through a constant cross-cut, the temperature of the room inside is calculated with:

$$T_{in} = T_{out} - \sum_{i=1}^n \frac{Q_i}{k_i} \quad (\text{Eq. 1})$$

In this formula the sum interprets the different surface layers with different thicknesses and different thermal conductivities. But this only holds for steady state

situations. In real world this is never the case, for example because irradiation is never constant and therefore the produced heat from the sun is not constant over time. Another example is the influence of the wind blowing over a surface. Both its speed and direction is never constant, making calculations and predictions very difficult.

Prediction of the 3D temperature profile in this room then is based on the standard heat equation. Suppose a PCM will be used as a passive system in this room. When it comes to internal heat generation, due to melting or solidifying of the PCM, the (extended) heat equation becomes:

$$\frac{\partial Q}{\partial t} = \nabla \cdot \left(\frac{\partial Q}{\partial x} + \frac{\partial Q}{\partial y} + \frac{\partial Q}{\partial z} \right) + \dot{Q} \quad (\text{Eq. 2})$$

In which the added ' \dot{Q} ' represents the internal heat density [W/m³] of PCM.

The energy balance for such a system can then be formulated as:

$$\frac{\partial Q}{\partial t} - \frac{\partial Q_{out}}{\partial t} = \int_V \dot{Q} - \dot{Q}_{out} \quad (\text{Eq. 3})$$

In this formula, the integral represents the time rate of change of the total amount of accumulated energy. The formula holds for passive PCM systems only, because a passive PCM system can only exchange energy with its surroundings through heat transfer.

3 Problem definition & research objective

The Dutch building industry is a rather conventional industry. Although there are high demands and there is a trend of being innovative, the overall image of the Dutch building industry is not very good [7]. A good example of this image is the traditional concrete and brickwork style of Dutch dwellings. Basically, on the building and construction aspect of dwellings, there are not very much changes in the last decades compared to Germany, in which houses with different building shells are more common. The downside is that one has to find other techniques to reach the energy-efficiency goal. With the niche of PCM the Dutch concrete and brickwork style can be maintained, whereas the energy-efficiency of these materials can be increased in a simple way.

The planned research is aimed to give insight in the energy saving possibilities of PCMs in the Dutch building sector as well as presenting a simulation model that visualize the energy flows within such a dwelling. In this way the planned research can be divided into a main research question and a sub research target.

The main research question can be stated in the following way:

Table 1 : Building physical constitution of the test boxes in the experimental setup [10].

	Test box A	Test box B	Test box C	Test box D
Insulation material (thermal resistance)	Cellular glass 3.8 (m ² ·K)/W	Cellular glass 3.8 (m ² ·K)/W	Light multilayered 5.6 (m ² ·K)/W	Light multilayered 5.6 (m ² ·K)/W
Phase Change Materials in concrete floor (weight percentage)	Present ± 5%	Absent 0%	Present ± 5%	Absent 0%
Thermal resistance glazing (thermal transmittance)	High 1.1 W/(m ² ·K)	Low 0.5 W/(m ² ·K)	High 1.1 W/(m ² ·K)	Low 0.5 W/(m ² ·K)

“What is the influence of using PCM in the Dutch built environment and what is the influence of PCM on the Energy Performance Coefficient (EPC) of a standardized Dutch dwelling?”

To answer the research question a research facility at the University of Twente is set up. This facility will give a practical answer, based on measurements. This will be further described in section 6.

The sub target is aimed at modelling. Modelling is necessary for monitoring purposes and to visualize the energy flows within the model. To calculate a theoretical lowering of EPC, the simulation model can be used and the results can be compared with the found experimental data. In a later stadium the temperature boundary conditions can be coupled with climatologic data, to predict energy savings at any place.

Because making a simulation model of real test objects involves combining differential equations from heat transfer and turbulent media, a software package that can handle this should be found. The sub target can be summarized in the following way:

Visualize energy flows within the simulation model by using a software package that is able to calculate with differential equations from heat and mass balances, using the finite element method.

The results of the model are verified with the experimental data.

4 societal & scientific relevance

In March 2007 the European Union (E.U.) leaders agreed on the renewable energy target. All the 27 E.U. member-states will each decide how they contribute to meeting a 20% boost overall in renewable fuel use by 2020. Also the member-states will cut their carbon dioxide emissions by 20% from 1990 levels by 2020 [8]. The EU plan involves:

- A 10% minimum target on the use of bio-fuels in transport by 2020;
- A commitment to increase use of solar, wind and hydroelectric power;
- A possible ban on incandescent bulbs, with filaments, in offices, street lights and private homes by the end of the decade [8].

The plan does not mention energy saving, which can greatly reduce energy consumption and therefore make those targets less difficult to reach. For example, the Netherlands have 2.31% (2005 figure) of their primary

energy consumption from renewable energy sources. Their target is 14% in 2020 [9]. This requires a major step of improvement regarding less energy consumption, better energy efficiency and a big step forward into sustainable energy sources. Actually, it seems quite impossible to reach this target without saving on fossil fuel consumption.

Starting from 2006 the Dutch Building Code requires dwellings to be made with an EPC of 0.8 or less.

The EPC is introduced for new residential buildings starting from the end of 1995. The EPC is a result of an integral energetic assessment of a building and its installations made during the design phase. It is a index that can give an indication of the energy efficiency of a new building. The EPC for new residential objects is calculated as follows [10]:

$$EPC = \frac{Q_{total}}{350 \cdot A_{G} + 65 \cdot A_{W}} = \frac{1}{C}$$

(Eq. 4)

The EPC takes only energy used to heat and cool the building (and water) and energy consumed by lamps into account. For heating up the building a reference climate model is used.

Energy consumed by household appliances is not taken into account. Therefore the energy consumed in reality is higher and the EPC cannot be used to 'predict' the energy bill.

Because of the international energy agreements, the Dutch will further reduce the EPC level to 0.4 in 2015. This means that 50% of the primary energy used for buildings energy should be saved. PCM can provide in less energy consumption and can be a good way to lower the EPC. Lowering the EPC means it is an attractive way to reach the required EPC goal, provided that it is economically feasible. Implementing PCM in the traditional Dutch building industry is a good way to reduce on fuel consumption.

5 experimental field set-up

At the Campus of the University of Twente four models are made, called test boxes, that differ in kind of insulation and presence of a PCM in the concrete floor. In this experimental field set-up a mixture of paraffins in powder form encapsulated in polymethyl methacrylate microcapsules is used. It has a melting point of 23°C [11] and the PCM is used as a filler in concrete. Therefore one will not see any differences compared to normal concrete. In Figure 5 one can see an impression of these test

boxes and in table 1 one can see the different types of insulation that are processed [12].



Figure 5 : The four test boxes on top of a sea container, after the third one a weather station is visible

The size of the test boxes is scaled to about 1.35 m by 1.10 m (l × w). The scaled dimensions result in a 115 times smaller air volume and a floor surface that is thirty times smaller compared to a standardized Dutch dwelling. It is expected that the influence of this down scaling is relatively small, because the mass of air and heat capacity per kilogram are low compared to the mass and heat capacity of the floor [12].

As can be seen in figure 5 the test boxes all have at one side a window consisting of 0.36 m² glass. Nowadays it is normal to use double glazing with an U-value of 1.1 W/(m²·K). This is used in two of the four test boxes. The other two consists of triple glazing, having an U-value of 0.5 W/(m²·K).

Another difference is the insulation and materials used in the sides of the test boxes. Because of practical advantages cellular glass with a thermal resistance of

3.81 (m²·K)/W, is used in two test boxes. The other two test boxes have a light form of insulation, having a thermal resistance of 5.6 (m²·K)/W, when taking a cavity of 20 mm into account.

The last difference between the test boxes is the presence of PCM in the concrete floor. Two of them have PCM present.

The test boxes are installed on the Campus terrain of the University of Twente located in Enschede, The Netherlands. They are placed outdoor on the roof of a sea container (2.55 m height) to avoid disturbances and to prevent unwanted shading. The test boxes are packed with temperature sensors and two test boxes can measure the solar irradiation. A separate weather station collects weather data every five minutes, containing outside temperature, solar irradiation, humidity, wind speed and wind direction.

6 research methodology

Now with the research question in mind, how to find an answer on it? The research methodology will be separated into some major steps.

Because this is an experimental research, the first step is finalizing the research facility and getting insight of the computation methodology of the EPC. At the point of writing, saving weather data, for example, is still troublesome. This is a preparation step that still has to be done. After finishing this step, it should be possible to generate and save weather data automatically.

The next step is finding a useful software package for the modelling. There are three different candidates: COMSOL[®], ANSYS[®] and TRNSYS[®]. Key points will be pricing, model accuracy and hardware requirements. All the three packages have their own advantages and

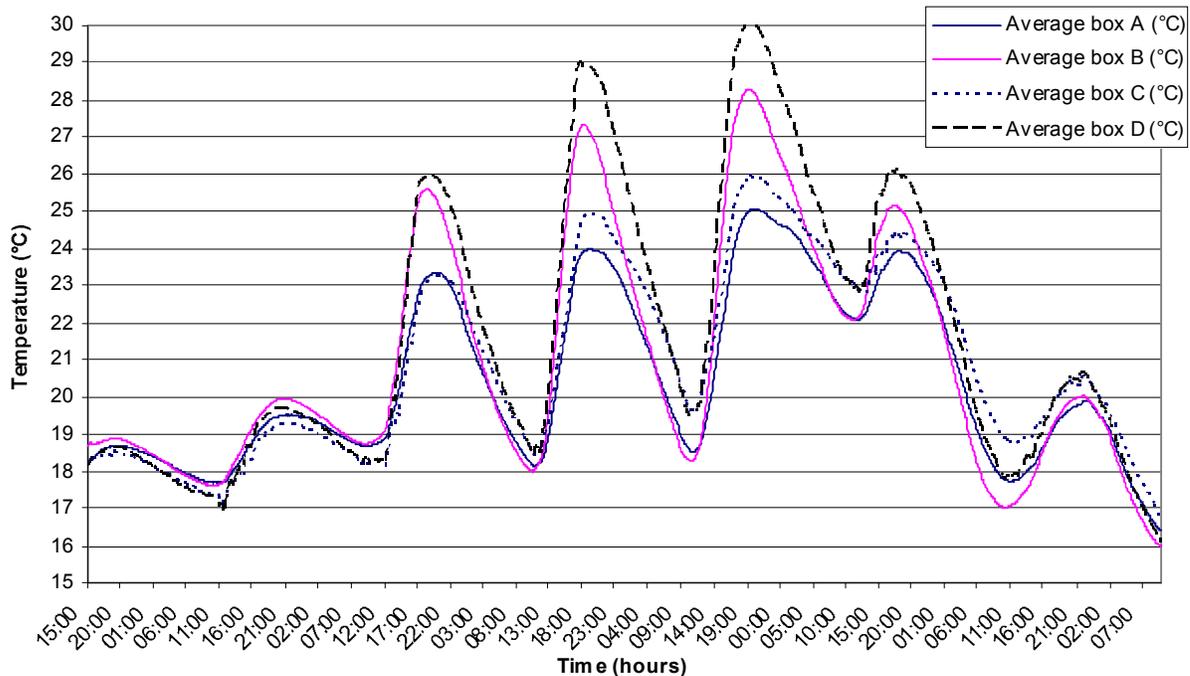


Figure 6 : Temperatures of the four concrete floors from 8-27-2008 15:00 till 9-3-2008 09:45 [12]

disadvantages. At the point of writing the COMSOL® package seems to have an advantage, because it can handle partial differential equations from both the energy field as well as the aerodynamics field together. This will enhance accuracy and speed up the calculations.

Also, synchronously, weather data will be collected and comparison between the different test boxes will take place. This will give a qualitative insight in the energy saving possibilities of the different test boxes.

After finding the right software package, the third step is to find an answer on the question: "What information (variables, constants/properties and formulas) do I have and what of this information is of importance?" So a clear picture of all the relevant physical effects have to be made. What phenomena are relevant to be modelled? What assumptions will be made? And what side effects can be neglected? Because of the complexity and importance of this step, a lot of attention will be paid on the requirements and specific configuration.

The fourth step is the drawing of the test box. If the geometry of the test box is too complex for the found software package, a 3D CAD software package will do the job. Nowadays all commercial CAD packages are able to export shapes to other software. After importing this shape into the found software package, boundary conditions can be set. This will be done with the assumptions made in the third step. Now the program is ready to solve the heat problem and give data about energy, temperatures and pressures.

The fifth step is comparing the temperatures from the simulation model with the real experimental temperatures from the test boxes and the weather station. Where are the differences? How can they be explained? And how can the boundary conditions be changed to give a fairer (compared to the real world) solution.

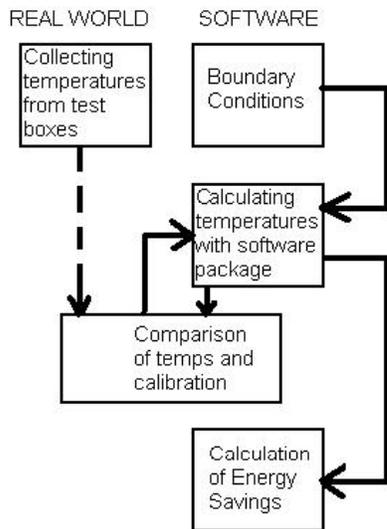


Figure 7 : Visualisation of step 5

In this step also an answer should be given on the question: *How much* energy can be saved on a yearly basis with PCM in concrete in the Netherlands? If the

boundary conditions are changed in such a way that the calculated temperatures are quite close to the real temperatures, the found software package is able to calculate the energy savings due to the presence of PCM. An overview of this step can be seen in Figure 7.

The last step is making an official document that describes the lowering of the EPC by using PCM in Dutch dwellings. Here information from step one will be used.

7 DISCUSSION & further research

This research proposal is focused to give a practical, but quantitative, answer on the energy saving possibility of PCM in concrete in a Dutch climate. The PCM in the experimental set-up is chosen in such a way that its saving potential is as high as possible for a Dutch situation. An important thing to realise is that PCMs store heat only temporarily and the question arises for how long it can store its heat. If the temperature is above the melting temperature of the PCM for such a long time that the PCM is able to melt completely, the net energy saving due to the PCM itself is zero. In southern Europe for example, it is expected that the energy saving potential is *relatively* lower, because of this effect. As a result a different PCM will be chosen there, with a higher melting point.

Some preliminary effects of PCMs can already be given, because the weather station and the twelve temperature sensors inside the test boxes have already been collecting data. The sensors are equally distributed among the four concrete floors.

Figure 6 shows the average temperatures of the floors per test box from 8-27 15:00 till 9-3 9:45. As can be seen, test box A and C, each containing PCM in the floors, have lower peak temperatures than test box B and D, which do not contain any PCMs [12].

There are only big differences when the maximum temperature is raising above 23°C, so the PCM can absorb the surrounding heat by melting, temporarily avoid further increasing temperatures. The figure also suggests that the presence of PCM is of more importance for saving energy than the type of insulation. Whether this is really true cannot be concluded from data of only seven days.

Further research will show how much energy can be saved practically and what kind of energy can be saved. It is expected that most energy that can be saved is electricity, because lower peak temperatures means lower cooling demands.

8 acknowledgments

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