

MASTER

Application of PCM in concrete

improvement of the indoor comfort and reducing energy demand

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Preface

Since the beginning of my master study I was driven by the idea of a sustainable building. Here I tried to think about smart solutions to reduce energy use and the ability to reuse materials. This is why I did some extra subjects to get more insight in the possibilities of renewable energy for example.

This project you find in this study is about the possibility to enhance the building materials so they are able to offer a more comfortable indoor area. The Phase Change Materials which are applied in concrete are one of the latest materials which are introduced to the buildings for a more energy efficient building.

SGS INTRON has supported me in studying the application of PCM in concrete and for this opportunity I want to thank the whole company.

Secondly it is with great pleasure I introduce to you several persons which have helped me throughout the whole project with great interest in the outcome. Ir. L.A. van Schaijk and ir. R. Leppers who supervised me throughout the whole project, and P.H. Cappon who helpt me with building the setup and executing the thermal tests.

At last I want to thank my graduation committee.

- Prof. dr. ir. H.J.H. Brouwers
- Ir. L.A. van Schaijk
- Dr. ir. A.J.J. van der Zanden
- Ir. R. Leppers

Mart van Haaren

Summary

Energy consumption is more and more topic of a variety of research. Especially in the built environment a lot of energy is used and thus a lot of potential energy reduction is possible. Unfortunately the reduction of energy demand often decreases the indoor climate comfort of a building.

With the introduction of Phase Change Materials (PCM) into the concrete, both factors can be influenced. PCMs increase the heat absorption of a wall what results in more heat capacity in a room which can be used during periods where a shortage of supply is present. In this way the energy consumption is lowered for the HVAC installation.

Secondly the PCM can be introduced to compensate for bigger or brighter windows. A larger amount of sunlight can be accepted in a room because the PCM captures the heat to release it during the night instead of an extra HVAC installation to keep the room in a comfortable range.

The introduction of PCMs into the concrete is done in two ways. First the sand from a standard mixture is replaced by the PCM particles. Secondly the PCM is impregnated into lightweight aggregate particles and a mix is made with this impregnated and not impregnated lightweight particles.

During this study, research is done to the consequences of introducing PCM into the Concrete mixture. Since the PCM is added to the structural concrete the newly found mixtures are investigated for their structural and thermal properties. Exception is the mixture made with lightweight aggregates. Here only the air is replaced with PCM and therefore the theorem is adopted the strength does not change with the addition of PCM.

The mixtures in which the sand is replaced by PCM are tested for their resulting strength. This is done first by building mortar prisms of the different PCMs and tested for their compressive and flexure strength, secondly there are some cubes made with the PCM and tested for their compressive strength.

The result of the mortar prism test was a general drop in strength when sand is replaced by PCM. When adding more than 5 Vol.% the compressive strength drops with over 50%. Besides the strength problem, also the workability with more than 10 Vol.% was bad. The mixture became very dry or very wet depending on which PCM was used.

With the knowledge gathered from the first test and with the results from several articles which say the best place for PCM's is in the top layer of the concrete, a new test is done with concrete cubes.

These cubes exist of a layer of PCM-concrete and a layer of normal concrete. After building this dual layer cubes, they are tested for their compressive strength by executing this test on the side where both layers are visible. This shows the main strength for this dual layer concrete wall is just one class below the expected strength when no PCM is used.

Here can be concluded that for the strength it is important to place the PCM concrete on a strategic place in the room to keep the strength of the structure as high as possible.

With the strength measurements done the thermal qualities are tested. This is done by making PCM concrete samples with several thermocouples in it to measure the temperature distribution through the concrete.

These samples are then placed in a semi-adiabatic surrounding and heated from one side. This heating is done in two ways. First three heating cycles between different temperature ranges are applied to the samples to find the thermal diffusivity for the three areas, and a 24 hour temperature cycle is applied to get a simple simulation of a day.

The results of the diffusivity measurements show the thermal diffusivity is much lower around the melting range than before the melting range, what was just like expected. Interesting is the fact that the thermal diffusivity stays lower during the higher temperatures above the melting range.

To explain this phenomenon, several possibilities were investigated. The outcome was that most likely the moisture in the sample made some shortcuts in the lower temperature ranges. Another important reason was the heterogeneous mixture what made the heat flow through the material without first completely melting the PCM during its way through the sample.

The results from the temperature measurements of the day cycle shows the BASF versions give a clear melting point around 26 degrees. The Salca versions do not show a clear melting point. But also results in lower peaks and the samples with PCM all show a slower raise in temperature. The filled lightweight versions showed a similar effect as the samples with PCM from BASF in it.

After the performed tests, several conclusions can be drawn. First the strength of the mixtures drops rapidly by the replacement of the sand by PCM. But by combining layers of PCM-concrete with layers of concrete without PCM, the strength decrease can be kept to a minimum. In this way it is possible to implement PCMs into the building environment with the use of prefabricated concrete parts.

The thermal properties of PCM-concrete are the most interesting of the properties. Here the specific heat is increased by the addition of PCM and this is shown by the lowered thermal diffusivity of the samples. Also the peak temperatures are lowered, and the difference over the samples show there is more heat needed to heat up the sample.

Although there was an improvement on the thermal consequences of PCM-concrete, there can be concluded the chosen melting point was too high. Afterwards the PCMs were not completely melted during the measurements. This shows the speed of the reaction of PCMs is very slow and should therefore be activated long before the maximum allowed temperature is reached in a room.

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1. Introduction

Since the 1940's so called Phase Change Materials (PCM) are studied because of their great latent energy storage capacity. A wide range of applications is studied. Especially the energy problems of today are a big activator in the search for more energy efficient buildings. Figure 1 shows the energy consumption by the build environment which is about 39%. This gives a lot of potential to save energy for example by the use of PCMs.

In different studies the PCMs are studied while used in an active system as well as passively applied in a building.

In an active system the PCMs are used in a controlled storage container where the storage temperature is optimized for the melting temperature of the PCM.

Passive use means the PCMs are placed in a room and are not controlled which means the natural energy flow is responsible for the efficiency. For example a lowered ceiling made of PCM-plates only stores and releases the energy latently when the room temperature is in the range of the PCM.

Although PCMs are often studied, the application of the PCMs has still not been a success in the built environment. This is mainly because of the high costs of the PCM and the hard to predict benefits.

In this study is focused on the passive application of PCMs. The advantage of passively used PCM, no controlling system is present which could break down during the lifetime of a building. The absence of a controlling system makes the application a lot cheaper. Not only because of the maintenance cost but also the energy needed to make the control system work.

A disadvantage of passive use is the inability of users to influence the behavior of the PCM. This means if the PCM does not meet its energy saving properties there is no other way than add extra energy using systems to a building to reach the desired indoor climate.

In this study the PCMs are applied in concrete so the PCMs are available the whole lifetime of a building, because the concrete is mostly used structural. Again this could be financially interesting because the PCMs only have to be applied once in a building during its lifetime.

Besides the energy saving possibilities of the application of PC-concrete in a building, the PCM-Concrete can also offer another advantage. By the application of PCM-concrete in the room more heat can enter the room without a change in the indoor climate. This results in more freedom for in the building design to apply bigger, more or brighter windows.

The goal of this study is to optimize the use of PCM-concrete in a room. The PCM-concrete is studied for its structural and thermal benefits and drawbacks to determine its behavior.

From this knowledge can be determined if and how well the application of PCM-concrete can be used to give extra freedom to the architect.

Share of energy consumed by major sectors of the economy (2007)

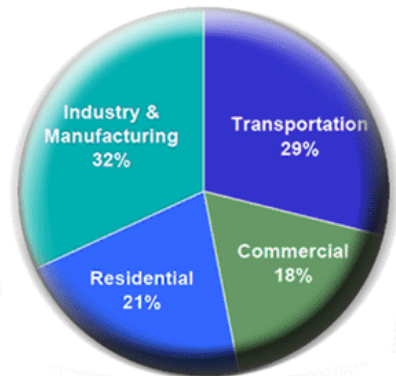


Figure 1: Energy demand per sector (<http://www.clearpathsus.com/articles/buildgreen.html>)

2. Vision

In today's building environment the optimization among comfort, health and energy-consumption becomes more and more important. Rising energy-prices, increased comfort demands by the users of the building and better regulations are all incentives to improve these factors.

Especially the energy saving possibilities was reason to introduce Phase Change Materials (PCM) into the building environment. PCMs make it possible to store energy for a short period of time. The PCM stores energy by its phase change, the phase change requires heat; so-called latent heat. This heat is absorbed by the material and does not result into a temperature rise of the material itself as long as the material has not fully changed its phase.

Using PCMs, heat is absorbed by the building environment. This means more heat can enter the room without a temperature change. Since it is absorbed; the heat is used later in time when more heat is needed to keep the room within a desired temperature range.

If more heat is allowed into the room more architectural options are possible to improve the health and comfort of a room. For example increasing the window size or get rid of the sun blocking coatings without increasing the temperature of the room. The larger windows and brighter natural light into the room improves the view increasing the comfort and well-being of the persons inside the room. The extra light can also lower the demand of artificial light decreasing the energy demand of a building. Mayhoub and Carter (2011) describe the advantage on the efficiency of employees having a good view and a lot of sunlight in a room.

With the introduction of PCM it is possible to passively improve a building on all three mentioned factors; energy consumption, light and temperature. But to maximize the advantages it is important to know how to use this PCMs and what the limitations are. This research aims at getting knowledge about the efficient use of the PCMs.

3. Problem definition

Past research shows the costs of PCMs are too high to be economical viable for use in the building environment. Furthermore the quantitative effect of PCMs on the energy efficiency of a building is hard to predict, this makes an investment an uncertain enterprise.

In this study the PCMs are placed inside architectural loadbearing concrete. The goal of this research is to make the volumetric blend of concrete and PCMs as efficient as possible. Therefore an enquiry of the parameters that are influencing the architectural efficiency is needed. These parameters are:

- The type of PCM: efficiency depends on chemical and physical properties of the different types of PCMs.
- The amount of PCMs in the concrete: more PCMs mean that more energy can be stored in the PCM-concrete mixture.
- The distribution of the PCM in the walls: the absolute amount of PCMs per square meter of concrete wall.
- The measured changes in heat capacity of the PCM-concrete mixture: the amount of energy a PCM-concrete mixture, with a certain density, absorbs compared to a standard concrete.
- The changes in temperature penetration: heat needs time to penetrate the wall to activate the PCMs. There is a maximum amount of energy that can be transported. This limits the efficiency of the mixture.

By knowing all these parameters it is possible to predict the behavior of the PCM-concrete mixture. Using a simulation-tool it can be determined what possible thermal improvements can be made to the PCM-concrete mixture, and how the placement in a room can influence the efficiency of the mixture.

The study is limited to a passive implementation of PCMs, so the effect relies only on natural effects.

The focus during this study is on the following questions:

- What is the best performing PCM-concrete mixture?
 - What is the effect on its strength?
 - What is the thermal diffusivity of the mixture?

By the use of multiple practical tests these questions are studied.

4. Literature study

To apply Phase Change Materials, knowledge has to be gathered about the way heat is stored and which materials can be used, considering their advantages and disadvantages. Sharma et al. (2009) published articles about this subject and their papers are used for this research. In the next chapters a discussion will be given about the different theoretical parts of this research. First an overview will be given about latent heat storage. Second information is given about concrete and the PCMs available. From there the criteria for the use of PCMs in concrete are set.

4.1. Theory of latent heat

In a normal situation heat is absorbed by a material and thereby rising the temperature of the heated subject to a certain extend. Supplied heat that affects the temperature of the material is called sensible heat. Another option for a material to absorb heat is by latent heat. Here the energy is absorbed by a phase change of the material for example; melting. The heat can be released by changing the material back into its previous stage; a crystal. Possible phase changes are displayed in Figure 2. Not only the transition from solid to liquid is displayed but also the transition from liquid to gas and from solid to gas. In every phase change, the same phenomena take place but at different temperatures and with different amounts of necessary energy.

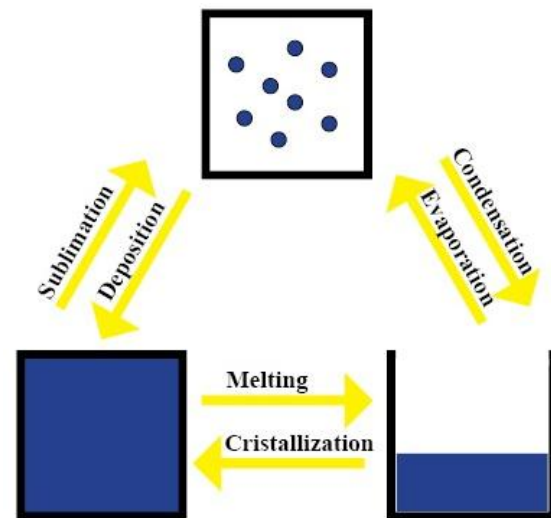


Figure 2 Phase transitions a material makes when heated or cooled

A clear example for these phase change phenomena is water. Figure 3 shows the absorbed energy or enthalpy graph of water. From A to B water is in a solid, ice, state. When energy is added the temperature rises, hence sensible heat is supplied. At point B the ice starts to melt and the temperature does not increase anymore. At that moment the energy is absorbed without temperature change and the heat is absorbed as latent heat. Once the ice is fully melted the temperature starts rising again if any energy is added, this means the heat is stored as sensible heat again. The energy needed to change from the solid phase to the liquid phase is called the heat of fusion. It is expressed in Joule/kg. If water reaches its boiling temperature (at point D), a similar process takes place. But this time water changes from the liquid-phase to the gas-phase.

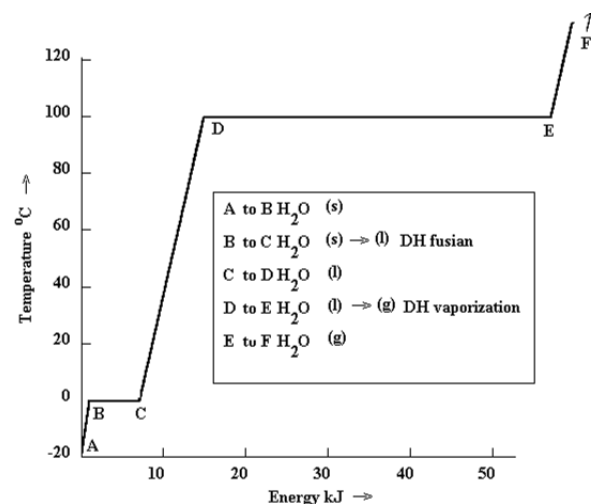


Figure 3 Energy needed for water to increase in temperature

The explanation for the phenomenon of latent heat lies in the change of the position of the molecules. Figure 4 shows the three phases and corresponding positions of the atoms of a material. At a low temperature (bottom of Figure 4) the material is solid, and here the molecules are bound to an organized crystalline structure. For the second stage, the liquid phase, the bounds between the molecules are broken. This process costs a lot of energy supplied by the latent heat. The third stage

is the gas-phase; again the bounds that now exist, Van der Waals forces, have to be overcome. This means the molecules get even more freedom to move, and therefore also the molecular volume changes.

For an explanation it is necessary to know which forces are present. First there is the repellent force between the positively and negatively charged parts of the atoms. The second force is the attraction force between the negatively and positively charged atoms. In the solid state the attraction energy between the atoms is larger than the repellent energy; therefore the atoms are positioned in a crystalline structure. When the temperature rises, the repellent energy becomes larger than the attraction force; hence they are no longer trapped in a fixed structure, resulting in a free movement of the molecules. The energy needed to eliminate

the crystalline structure between the molecules is the latent heat.

In the built environment this theory of sensible and latent heat also applies. The different components of a building absorb energy given their specific heat (C_p) of the several materials and their masses (volume x density). If there is more material-mass or volume available in a room, more material needs to be heated; therefore the room will heat up more slowly. In a normal building all construction materials are solid and will not change phase during regular working conditions, therefore the heat is always stored as sensible heat. The melting point of PCMs is within the temperature range of a normal building. Therefore the use of PCMs will increase possible energy storage without increasing the temperature, since a PCM is more likely to absorb the supplied heat as latent heat.

Using PCM in architectural materials means an improvement of the heat absorbing capacity of the used materials in a room. With the added PCM the heat absorption becomes higher around a specific temperature, hence the melting point of the PCM.

4.2. Concrete

In this research the focus is on implementation of PCM-concrete in the building environment. This means the design of a building does not have to change, but only the material it is made of. Therefore knowledge has to be gathered about the properties of concrete.

Concrete is a material commonly made of four components: cement, water, aggregates and additives. Cement is the bounding element that is activated by water. This bounding element keeps the aggregates together. Figure 5 shows the aggregates, stones, bounded by the cement.

Aggregates can be of different origin. In today's Dutch concrete, this ingredient is made from sand and gravel. But this is different for other countries. Also more and more concrete is made use of elements with a lower density like expanded clay.

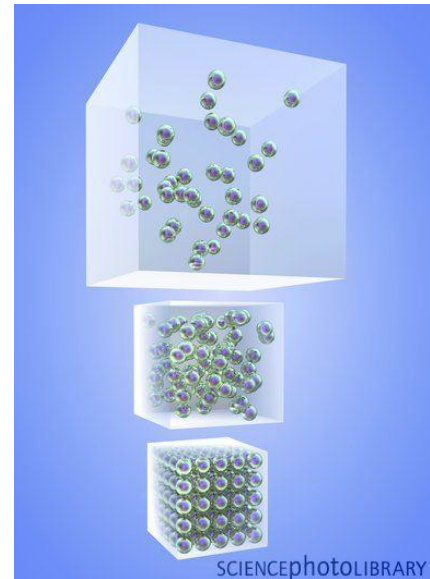


Figure 4: molecular states of gas, fluids and solids.



Figure 5: Concrete structure

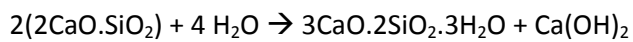
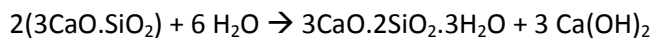
Cement is the binding agent of the concrete and can be made of pure Portland cement, blast furnace cement or fly ash cement. Table 1 shows the basic molecular elements of Portland cement.

Table 1: Cement ingredients

Minerals of portland		
tricalciumsilicaat	3CaO.SiO ₂	C ₃ S
dicalciumsilicaat	2CaO.SiO ₂	C ₂ S
tricalciumaluminaat	3CaO.Al ₂ O ₃	C ₃ A
tetracalciumaluminaatferriet	4CaO.Al ₂ O ₃ .Fe ₂ O ₃	C ₄ AF

The last component of concrete is the additives. This group mostly exists of plasticizers or colors. With the addition of materials from this group the standard hydration process is influenced. This way it is possible to make special concretes or to keep the fresh concrete longer process able

when the different elements are mixed, water and cement start to react. This is called the hydration process. The different elements of cement forms Ca(OH)₂ by the following reactions:



These are the so called C-S-H or Calcium-silicate-hydrates.

If this reaction is interrupted by other elements the characteristics of the fresh concrete can be negatively influenced. For example if some of the elements react with elements that do not belong to the reaction, this reacting element does not react with the concrete elements anymore. This Results in less structural elements in the concrete.

4.3. Phase Change Materials

Every material shows a phase transformation from solid to liquid at its melting point or during its melting range. In fact every material can be denoted as a phase change material. The suitability of certain materials largely depends on their thermal properties like their melting point (T_m) or melting range and the amount of latent heat necessary to achieve a full phase change. PCM that can be used to store heat in the building environment, hence have their melting point in the temperature operating range of a building, can be divided into three groups. These three groups are shown in Figure 6 these groups are further divided into several subgroups.

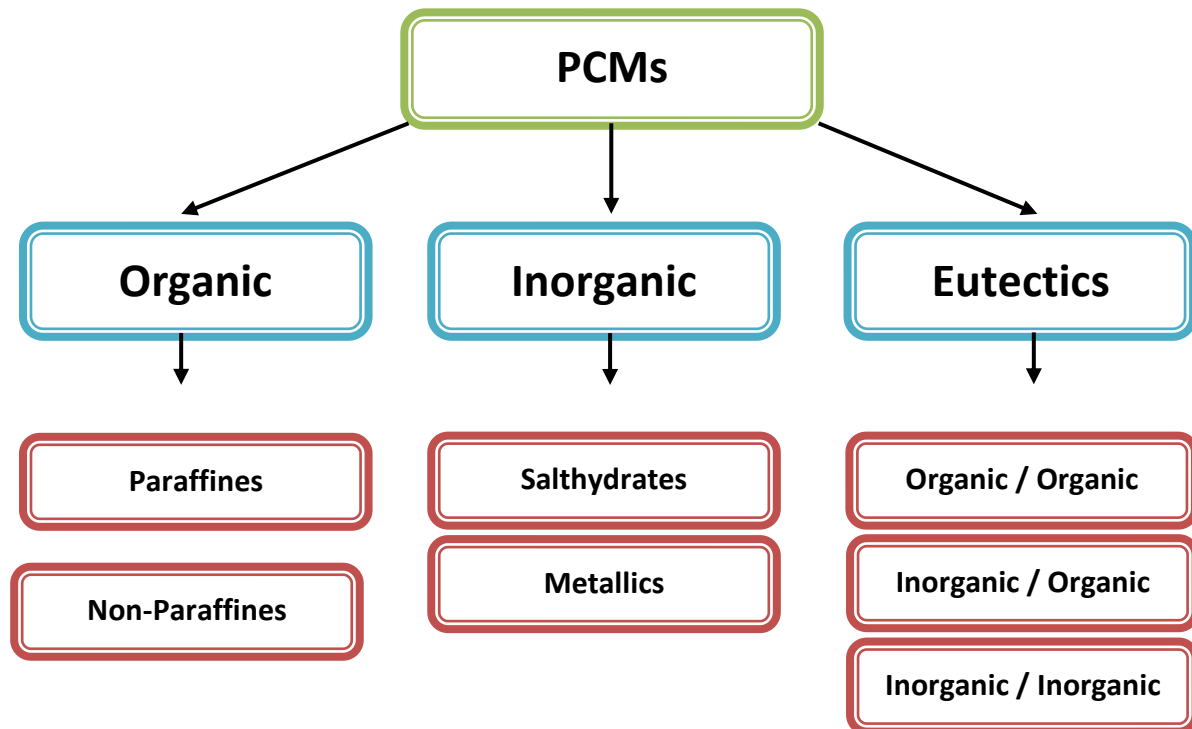


Figure 6 Categories of Phase Change Materials (Sharma et al., 2009)

As can be seen in Figure 6, PCM can be divided into three main groups: organics, inorganics and eutectics. The organic materials are a subcategory of the chemical alkane family and are also known as paraffins. Paraffins have a general molecular formula of the type $\text{CH}_3(\text{CH}_2)_n\text{CH}_3$ in which n is an integer and denotes the paraffin chain length. Its melting point depends on the chain length (n). Non-paraffins typically have functional groups attached to their base paraffin molecular chain. Inorganics consist of compositions of salt hydrates or metallics. Typically the salt hydrates are formed by hydrating a blend of metallic and non-metallic (salt ion) components. The third category; eutectics are formed by a mix of organic and/or inorganic materials creating the possibility to combine the optimal organic or inorganic properties. The study and use of eutectics is relatively new and shows promising results for the future. In the following paragraphs the three groups of PCM are explained in more detail.

4.3.1. Organics

Organic materials are separated in paraffin and non-paraffins and are based on carbon molecules. From here they are discussed separately.

Paraffins

Paraffins have a general molecular formula: $\text{CH}_3 (\text{CH}_2)_n \text{CH}_3$ with n the integer to denote the chain length. Most paraffin PCMs are made of technical grade paraffins. A technical grade paraffin is a paraffin with a little contamination in it, but has about the same properties as its pure version but is much cheaper.

Paraffins are available in a large range of melting temperatures. The melting temperature and the size of the heat of fusion depend on the chain-length making it easy to build the right paraffin.

Furthermore the paraffins have a very congruent melting and freezing process which means they freeze and melt rapidly without phase segregation. They are also self-nucleating, meaning they form the new crystalline structure quickly so no super-cooling of liquid phase material is present. Final note regarding paraffins is that they are inert to reaction with other material and have a low electric conductivity. On the downside, paraffins are flammable justifying its use in candles.

Non-paraffins

Non-paraffins have a similar molecular base as paraffins but parts of the H-molecules are replaced by another group of molecules, for example fatty esters, alcohols and glycols. They also have a high heat of fusion and a low conductivity. Furthermore they also do not suffer from segregation.

Besides its toxicity another negative characteristic of non-paraffins is their high flammability. Also this material is less economical viable since it is about two to two and a half times more expensive as technical grade paraffins.

4.3.2. Inorganics

Inorganic material consists of two sub groups: salts and metallics.

Salts

Salt consists of a blend of metal and non-metal atoms, creating a lot of possible molecular combinations and therefore a lot of different types of salt. These salts all have different characteristics creating a lot of different PCMs with different melting points. Usually these PCMs have a high heat of fusion and a large heat conduction, almost twice as large as organic materials. Furthermore they are not flammable. A big difference with the organic materials is that the salt does not actually melt; it hydrates and de-hydrates. In order to have a congruent process there need to be enough water molecules available in the surroundings.

Another property of salt is its poor nucleation, therefore super-cooling arises. This can be solving by the use of nucleating agents, they can help to minimize this effect.

From an economic point of view salts have a great advantage. Salt is a very cheap material and is largely available. Therefore this material is investigated extensively.

Metallics

This type of material has not been researched extensively for use as a PCM even though it has its advantages. These advantages are its high thermal conductivity and the low necessary fusion heat. On the other hand, this material has a high density resulting in unnecessary weight increases. Furthermore it is expensive compared to the other possible materials that can be used as a PCM.

4.3.3. Eutectics

Eutectics are formed by a mix of organic and/or inorganic materials. Using eutectics the advantages of organics and inorganics can be combined. One of the advantages of this combination is a well-defined melting point instead of a melting trajectory. Unfortunately eutectics are relatively new; a lot is unknown about the possibilities of the material, creating a disadvantage.

4.4. Criteria for the PCM to use in concrete

When PCMs are introduced into the concrete, there are several requirements that have to be taken into account.

First the introduced PCM should not interact with the hydration process of the drying concrete. This could negatively influence the strength of the mixture.

Second, the PCM should have a melting point within the temperature operating range of the built environment. This temperature range is between 19 and 30 degrees Celsius. If the melting point lays outside this range heat is stored as latent heat when the room is already uncomfortably hot or cold. A last requirement regarding the melting behavior of the PCM is that it should melt congruently and without super cooling.

A third criterion is the total heat of fusion this is the total latent heat that can be stored in the material when it transforms from solid to liquid. The more heat can be stored the larger the time delay becomes between the start of the heat supply and an unwanted temperature increase.

The last major criterion is the speed of adaption of the PCM; especially for a passive system this is important. Heat has to enter the PCM as quickly as possible, meaning the thermal conductivity has to be high. If the PCM would suffer from a low thermal conductivity this would create a barrier for the heat to enter the PCM. In that case a large amount of heat will be stored as sensible heat in the concrete instead of latent heat storage in the PCM, which is not beneficial.

The last notable factors are: chemical stability, non-flammability and degradation characteristics. Due to fire safety the flammability should be kept to a minimum. A chemical stabile material means it would not react with its surroundings; therefore the PCM should be inert to the materials it contacts.

Table 2 shows the resulting advantages and disadvantages for every type of PCM-material.

Table 2 Selection criteria for Phase Change Materials

Selection criteria for latent heat storage materials	Organic	Inorganic	Eutectic
- Melting temperature in the desired operating temperature range	+	+	+
- High latent heat of fusion per unit volume	-	+	0
- High specific heat, high density and high thermal conductivity	-	+	0
- No super cooling	+	-	+
- Chemical stability	+	-	0
- Not-flammable	-	+	0
- No degradation	+	-	0

4.4.1. Encapsulation

To tackle some disadvantages of PCMs and to widen the range of possible PCMs for the built environment, encapsulation is used. Using encapsulation the PCM can be separated from the environment and kept together when it is liquid. But also, if the encapsulated materials are mixed with another material, the PCM will not influence the material it is mixed with. Furthermore salt hydrates will not turn to a lower grade hydrate since the water is captured in



Figure 7 Macro encapsulation

the encapsulation. This means salt hydrates also become interesting for the implementation into concrete.

Generally speaking there are two groups of encapsulated materials. The macro encapsulated group and the micro encapsulated. Macro encapsulated materials are captured in containers like the examples in Figure 7.

Micro encapsulation is the encapsulation of just a few molecules in a polymer container. This gives a powder that can easily be implemented in construction materials like concrete. Figure 8 shows a powder that is made of encapsulated PCMs. This is nowadays used in a gypsum board to enhance its heat storage capabilities.



Figure 8: Micro encapsulation

With the encapsulation a new review of the PCM-groups is needed and given in Table 3.

Table 3: Selection criteria for latent heat storage materials

Selection criteria for latent heat storage materials	Organic	Inorganic	Eutectic
- Melting temperature in the desired operating temperature range	+	+	+
- High latent heat of fusion per unit volume	-	+	0
- High specific heat, high density and high thermal conductivity	-	+	0
- No super cooling	+	0	+
- Chemical stability	+	+	0
- Not-flammable	-	+	0
- No degradation	+	+	0

With the encapsulation the salt hydrates become an interesting option. They can handle the heat quicker and store more energy. Besides these two advantages this material is environmental friendly.

Combining the information of the several PCM possibilities and the set requirements for application in the built environment the choices for PCMs were made. For this research an encapsulated salt hydrate and encapsulated paraffin.

4.5. Earlier research

In the literature a lot of research is done to the use of PCMs. A brief summary is given first; from there the focus is on passive use of PCMs installed in concrete.

The first article is written by Telkes (1940) around 1940, they investigated the use of sodium sulfate decahydrate to store solar energy. This paper started the focus on implementing PCMs in the built environment.

The last twenty years more and more studies have been done because of the demand for energy savings in the built environment. Four groups can be distinguished: PCMs in combination with free cooling, PCMs for peak load shifting, PCMs in active and passive building systems.

When PCMs are used in combination with free-cooling, the low night temperatures are utilized to cool down the PCMs which are placed in the ventilation system. During the day the hot air passes the PCMs and its heat is absorbed by the PCMs. Medved and Arkar (2008) studied the cooling potential of this utilization of PCMs. The efficiency depends on the amplitude of the ambient air

temperature over time. A large fluctuation in ambient temperature means there is a high energy flow that can be stored and released by the PCMs, hence a high utilization and therefore efficiency. The researchers also found out that the melting temperature of PCM has to be around the average room temperature for an optimal result.

A different way of using PCMs is the so-called peak load shifting. During the day a building has to be cooled by the air-conditioning system, therefore the demand for electricity varies significantly over day and night. By using PCMs the peak energy demand can be delayed to a more off-peak moment since it stores the heat that would be eliminated immediately by the cooling system in a normal situation. The heat storage in the PCMs still means the air-conditioning has to eliminate the heat but the cooling process can be shifted to a later moment in time. Thereby profit can be made by the lower prices for electricity in for example the evening. Big financial reductions are possible as proven by Kondo and Ibamoto (2006).

Another way of using PCMs is in an active system. Here the PCM is mostly used as a storage unit. An example of this way of usage is shown by Kaygusuz (2009) who built a heat storage from $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$. This gives a large energy storage capacity in a small space. A lot of other variations and combinations were mentioned by Zhu and Zhenjun (2009).

The last and most important group of studies for this thesis is the application of PCMs in a passive building system. Here the latent heat storage capability of a PCM is used to reduce the energy consumption of a building. By various simulations and experimental studies the advantage of the PCMs in the built environment were proven, every study with a different result. This shows the complexity of predicting the behavior of PCMs in the built environment.

Several possibilities were used to implement PCMs in the built environment. Some of the examples are plates of PCMs and also gypsum boards with PCM in it. Also there are plasters on the market with PCM in it and another option is the implementation of PCMs in a concrete structure.

Because the focus of this study is on the implementation of PCMs in concrete, only the relevant articles are discussed here.

Three ways of implementation are used. The first is impregnating the concrete. This is done by Hawes (1992). In this case the Concrete blocks are emerged into the PCM and because of the porosity of the



Figure 9: PCM-concrete buildings in Spain.

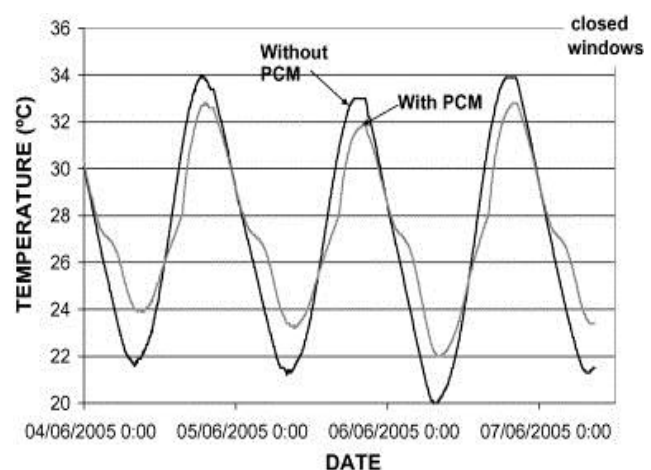


Figure 10: Temperature measurements in a PCM-concrete building

material, it is filled with PCM. Advantage of this way of impregnating is the strength is not influenced. Disadvantage is the possibility to leak and the limited amount of PCM that can be impregnated.

The second way is using microencapsulated PCMs that are implemented in the concrete mixture. This is done for example by Cabeza and Leppers (2007). In this case it is possible to implement more PCM into the concrete and leakage can be prevented. The strength however is negatively influenced. Figure 9 shows the concrete structure in which several walls are made from PCM-concrete. Figure 10 shows the temperature curve of the inner temperature of the room with and without PCMs. There is a clear difference in peak temperature and also the time it takes to reach the peak temperature is different.

Entrop and Hunger (2009) investigated Concrete with the same microencapsulated PCMs as Leppers. They not only looked at the mechanical and thermal properties, but have also investigated the behavior of the PCMs in the concrete. One of the problems with PCMs in concrete was encountered during the mixing of the concrete. The capsule in which the PCM was encapsulated was not resistant against the mixing procedure and the alkaline environment of the fresh concrete.

The last option is impregnation of lightweight aggregates. This option is used by Zhang (2004).

Here the aggregates are impregnated under vacuum, and the filled aggregates are used in the concrete mixture as a replacement for a part of the normal aggregates. This means the strength stays the same as the standard lightweight concrete, and the thermal properties are improved. Another advantage of this way of implementing is the absorption of heat already takes place during the curing process. This has a positive influence on the strength the concrete reaches. Figure 11 shows some lightweight aggregates that are filled with PCM. The result of the built concrete is enhanced energy absorption of the concrete

In this research the last two implementation methods are investigated. Because the strength of concrete is a very important factor, the versions with the implementation by the replacement of sand are also investigated on their strength, and their influence on the hydration process.

4.6. Simulations from literature

Over the last years not only practical tests are done. Since the computer becomes more and more advanced, simulations become a more important factor in research. With the use of simulations it is easier to look at the behavior of PCM in the built environment.



Figure 11: Unfilled(left) and filled(right) lightweight aggregates

Nowadays there is a wide range of program's that can be used for simulations, for example ESP-r, Comsol and TRNSYS. It is important when PCMs are integrated in a simulation, the transient option is chosen. Only that type of simulation is capable of implementing the heat absorption, what is the main factor for PCMs.

Because of the wide range of articles about simulations of PCM, in this chapter, only simulations with PCMs applied in building parts are discussed.

Heim (2004) has simulated a room with walls covered with a PCM-gypsum layer. He showed a significant effect on the indoor temperature and the influence of the melting temperature. Figure 12 shows the utilization of the PCM with a certain melting temperature.

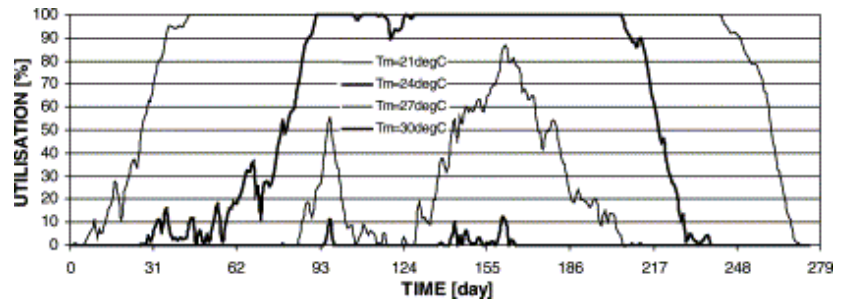


Figure 12: Utilization of the PCM during the summer period for different melting temperatures.

Schossig (2005) shows the application of PCMs in existing construction materials. Here a lightweight construction is simulated where plates with integrated PCMs are used. This is done by encapsulated PCMs which are introduced in the building process of the plates. Figure 13 shows the indoor air temperature of a room with and without PCM. As can be seen the temperatures above the PCM melting temperature of 26 degrees are significantly lowered.

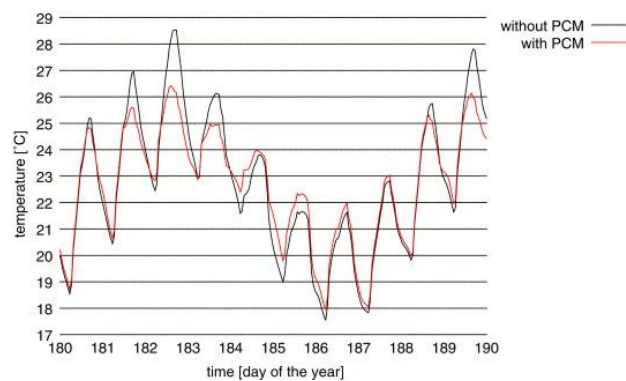


Figure 13: Indoor air temperature with and without PCM.

Huang et al. (2006) placed PCM plates in the cavity of a wall. Here also improvements are measured in the simulation. Especially the summer time showed a lower temperature in the room. Also he showed it is important to look at the placement of the plates. Even in the cavity it is important to place the plate on the inner wall instead of the outer wall.

Kuznik (2008) focused on the influencing factors for the efficiency and the optimizing of the thickness of plates with PCM which are placed inside a room. The factors that were taken into account were the melting temperature of the PCM, the indoor and outdoor temperature and the thickness of the isolation in the wall. Figure 14 shows the impact of the indoor temperature swing. A lot more energy is captured in the PCMs when the swing is bigger. So this shows it is important to have a certain temperature swing to have advantage of the PCM. Another interesting fact is there is an optimal thickness of the PCM plates. It is useless to make an

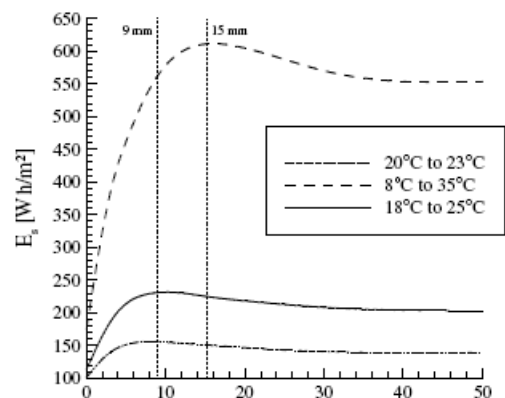


Figure 14: Energy absorption with different temperature cycles inside a room.

infinite thick PCM layer, because not more energy is absorbed in the time the PCM is active.

Where Kuznik focused on the thickness and the outdoor influences, Zhou et al. (2009) focused on the properties of the plates and where they are placed. This means the thermal conductivity the internal convection of the room and again the melting temperature. Conclusions are the melting temperature has to be close to the range the inner temperature has to be in. Also placing on the wall should be the most efficient place but in this case the floor is covered with a wooden floor that makes the PCM less efficient so it is not a very solid conclusion. Figure 15 shows the schematic view of the room which is used for the simulation. The influence of the indoor convection is of big influence because the energy is well distributed with a higher air speed.

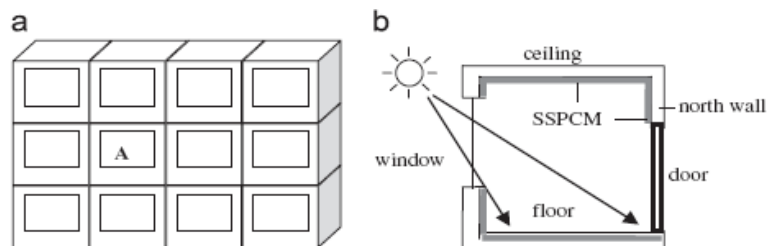


Figure 15: Schematic building used for simulations.

The articles discussed show a clear indication that Phase Change Materials are able to improve the indoor environment, but also shows there are a lot of influencing factors on the efficient use of the PCM.

When a prediction is made by the use of simulation a wide range of factors should be taken into account to find the influence of the PCM to the room or building. This makes a simulation a very delicate exercise to perform.

5. The structural performance of PCM-concrete

With the introduction of PCMs in concrete a new kind of mixture is developed with unknown properties and because concrete is mostly used in a constructive way, it is important to know the constructive strength of the material. In the Netherlands, strength tests are prescribed in the NEN standards. Because of the comparability of the tests with other mixtures, the standard tests from NEN are used in this research. Earlier research done by Entrop (2009), shows a decrease in strength when the PCM is introduced into the mixture. One of the reasons for this decrease is the replacement of sand. Sand is made from very strong silica which is replaced by a partly hollow shell which is not made from a similar strong material.

In this research two different PCMs are introduced into the concrete by replacing the smallest particles of the sand with PCM. The strength is then tested by two kinds of tests. First the test as described in NEN-EN 196, which is a prism test, and second a test as described in NEN 206-1 and NEN 8005.

5.1. Strength test with prism samples

The first mixtures are produced and tested with respect to NEN-EN 196. This test exists of small mortar prisms and is completely standardized. Four percentages of PCM are chosen to implement in the mortar prisms. Earlier research (2007) showed that more than 20 Vol.% of PCM means there have to be taken additional measures for a workable mixture, this amount is chosen as the maximum amount of PCM into the mortar. Table 4 shows the different mortar mixtures, as also a reference mixture without PCM for comparison. Every mortar mixture is produced three times to guarantee a representative experiment.

The samples are built as described in NEN 196, and are 160 x 40 x 40 mm. The used materials are Portland cement, sieved sand in fractions between 0.063 mm and 2 mm, water and PCM from Salca and BASF. Annex 1 shows the details about the used materials. Figure 16 shows the different ingredients before mixing, and Figure 17 shows the mold which is used. As can be seen from every mixture 3 prisms are made in one mold.



Figure 17: Ingredients prism's



Figure 16: Prism mold

Table 4: mixtures for the different PCMs

Mixtures		M1	M2a Vol. 3% BASF	M2b 5% BASF	M2c 10% BASF	M2d 20% BASF	M3a 3% Salca	M3b 5% Salca	M3c 10% Salca	M3d 20% Salca
Cement	(gr)	450	450	450	450	450	450	450	450	450
Water	(gr)	225	225	225	225	225	225	225	225	225
Sand (gr)	1 - 2 mm	458	458	458	458	458	458	458	458	458
	0,5 - 1 mm	448	448	448	448	448	448	448	448	448
	0,25 - 0,5 mm	147	147	147	147	36	147	147	147	36
	0,125 - 0,250 mm	236	235	194	93	0	235	194	93	0
	0,063 - 0,125 mm	60	0	0	0	0	0	0	0	0
PCM	(gr)	0	20	33	66	132	35	58	115	230

Casting the prisms was done in a room which had a constant temperature of 20 °C and was kept at 65% relative humidity all the time. This room was located at the laboratory of SGS INTRON, and is specially designed to perform these castings under very stable conditions. The materials were placed in the room already days before casting to ensure the same conditions for every prism.

After one day of curing, the prisms were placed in a container full of water which was located in the same room. This procedure is performed to exclude any external factors that could influence the comparison.



Figure 18: Pressure strength measurement device

After 7 days of curing, the prisms were tested for their compressive and flexural strength by the use of the press which is seen in Figure 18. The same test was done again with the other two prisms from the same mixture after 28 days.

5.2. Results of the prism tests

Figures 19 and 20 show the results of the pressure tests. The solid line in both Figures represents the result after 7 days and the dotted line is the result after 28 days. As expected the pressure strength, as well as the tensile strength, drops with the addition of PCM in the prism. In the first percentages the strength rapidly decreases. From 10 to 20 percent the strength curve is less steep. Results are given in MPa. This makes it possible to compare with other prism tests.

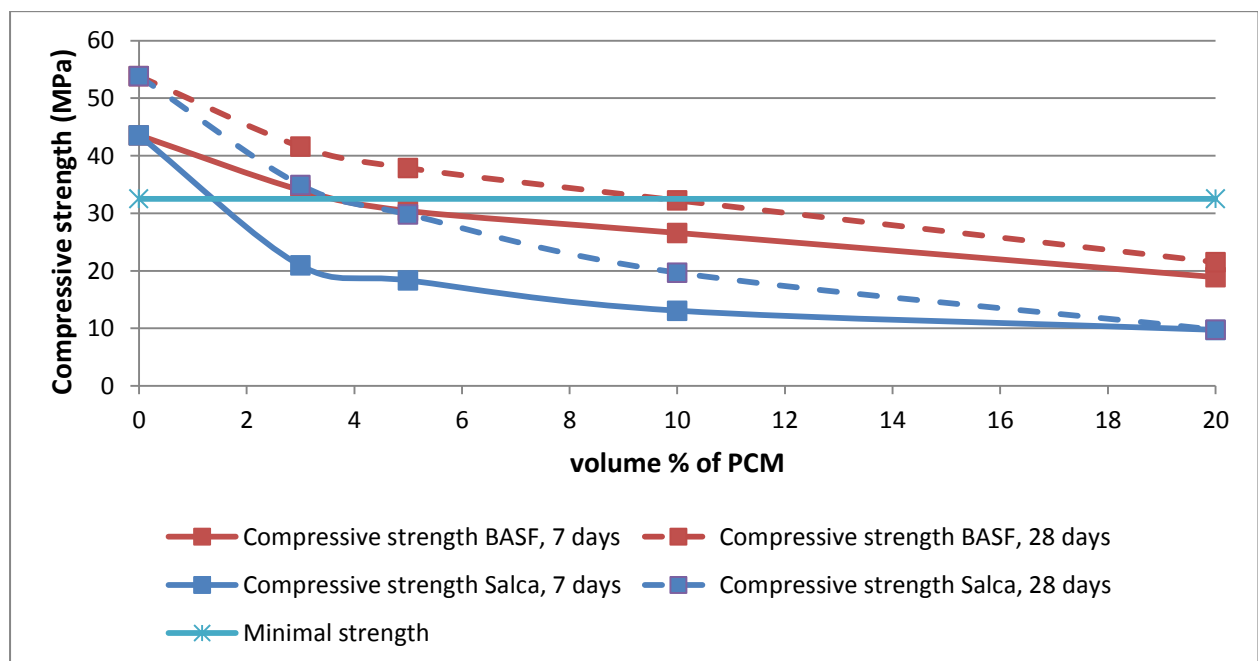


Figure 19: Resulting compressive strength of the different samples after 7 and 28 days.

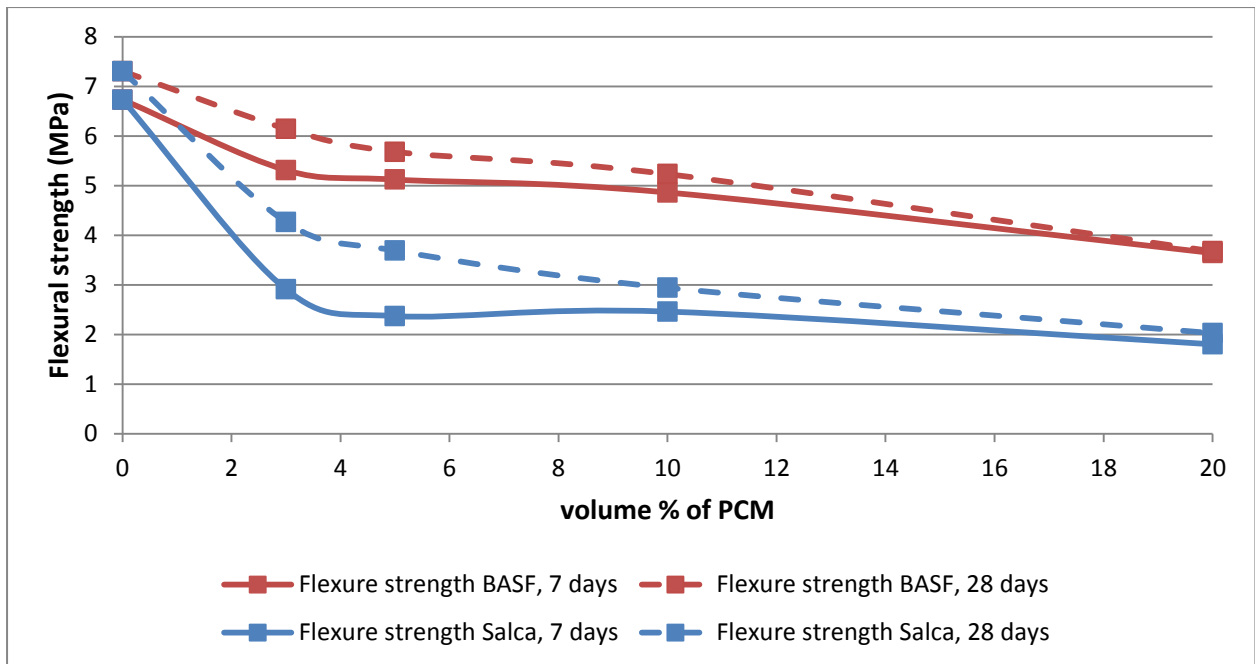


Figure 20: Resulting tensile strength of the different samples after 7 and 28 days.

5.3. Analysis

Already during the building of the prisms the first influence of the PCM is noticed. The workability of fresh concrete is influenced by the addition of PCM. Due to the influence of the particle size of PCMs, the fresh concrete becomes more fluid with the addition of Salca PCM, which particles have a bigger size than the sand particles which are replaced by the PCM. The mixtures with BASF PCM become dryer. BASF has particles which are smaller than 0.125 mm and therefore smaller than the sand particles which are replaced. With the changes in particle size, also the surface area of the particles changes what means the water film over all the particles differs in size which needs another amount of water to mix a workable concrete. Although the workability is influenced, no additional plasticizer was added to get a good comparison of the consequences of adding PCMs.

The results of the compressive and flexure tests show a reduction in strength of the prisms when sand is replaced by PCM particles. With the addition of 5 to 10 Vol.% of PCM the biggest decrease is noticeable. The PCM from BASF shows in this test the most promising results. With 10 Vol.% of sand replaced by PCM from BASF the strength become 50% of the original strength. With replacement of 10 Vol.% of the mixture by Salca PCM, the strength drops even more to just under 30% of the original strength.

With the decreasing strength of the concrete mixtures, its constructive quality is lowered drastically. Without PCM, this cement performs as expected by its properties. After 28 days the strength lays between 42.5 MPa and 62.5 MPa. After adding 5 vol% of Salca PCM into the mixture the strength drops under the minimum requirement for strength to qualify the cement type. In Figure 19 this bottom line is shown, and as can be seen the PCM-concrete mixture does not perform well with over 5 Vol.% of PCM in the mixture.

The first reason of the decreasing strength is because of the replacement of sand by much weaker PCM material. The shell of the PCM is not as strong as sand what decreases the strength of the total mixture.

Another problem with specifically the PCM from Salca is that it is made of salt hydrate. If the shell breaks the salt is released harming the hydration process. This is caused by a reaction between the salt and the cement which has a negative influence on the hydration process and decreases the amount of bondages made by the cement between the aggregates.

The first clue to this diagnosis was given by the look of the prisms as can be seen in Figure 21, where the prisms are covered by white particles. Also the prism's with BASF felt greasy what is a clue the paraffin has also left its shells. In this case the BASF PCM has the advantage because paraffin does not interact with the hydration process and therefore the strength is less influenced by the paraffin.

Earlier research showed different results for the quality of the PCMs from BASF but by the look of the prisms some broken shells are present. Since there is no earlier research done for the shells of the PCM from Salca and the salt could be harmful for the hydration process, the quality of the shells is investigated in more detail.



Figure 21: Prism's with white particles over it

5.3.1. Salca PCM shell test

To investigate if the strength could be influenced by any broken shells, a sample of the prisms is impregnated with resin. When this prism is filled with resin, the broken shells are filled inside the concrete. After impregnating the prism it is cut in half and placed under a microscope to see if there are broken shells visible.

With the microscope figure 22 and Figure 23 were made and show some PCM particles in the concrete. Where the resin entered the shell it is colored green. This shows one of the two particles visible on the picture was broken during the curing process what released the salt into the concrete. With the use of the microscope, more broken shells were found, what means the salt was able to influence the hydration process with as result, a weaker concrete mixture.



Figure 23: Two PCM particles from whitch one is broken.

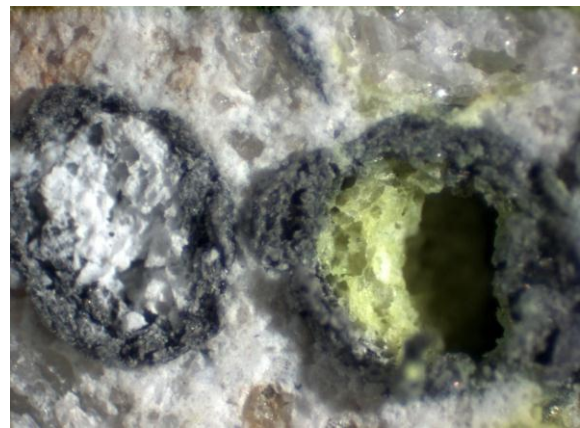


Figure 22: Close up of the two particles

5.4. Combination cubes

With the prism tests a first indication of the consequences of PCM as a replacement of sand into the concrete is given. Furthermore there are several articles available about PCMs implemented in concrete. Studies about sand replacement all show a decrease in constructive strength of the concrete.

Some of the studies had some simulations done, and they show the heat is mostly captured in the first few centimeters of the concrete structure. This means the wall does not have to be made out of PCM-concrete completely to obtain maximal result. Only the first centimeters with PCM are effective. Therefore is chosen to look at the possibility to make a dual layer wall since prefab is much more used these days. In this case it is interesting if the PCM stays in the first few centimeters. Advantage of this option could be the lower costs because of the smaller amount of PCM used, and the increasing strength because most of the concrete is made of conventional concrete.

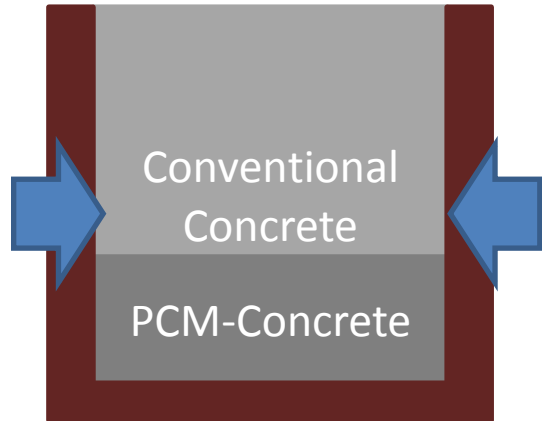


Figure 24: different layers in the mold for the cubes.

With this knowledge, compressive tests with the concrete cubes are performed with respect to NEN 206-1. Two types of concrete are mixed. One mixture is made without PCM and on with PCM. The mold is than filled with the mixture with PCM and on tops the mixture without PCM is placed as can be seen in figure 24. Here is also visible on which side the cube is tested for its compressive strength.

Table 5 shows the different recipes used. On top of every PCM-concrete mix, the concrete without PCM is placed. This concrete is made with the ratio similar to mixture B1.

Table 5: Mixtures of the different concrete blocks

Concrete		B1	B2a 5 Vol.%	B2b 10 Vol.%	B3a 5 Vol.%	B3b 10 Vol.%
Cement	(kg)	311	311	311	311	311
Water	(kg)	165	165	165	165	165
Gravel	16 tot 32 mm	409	409	409	409	409
Gravel	8 tot 16 mm	409	409	409	409	409
Gravel	4 tot 8 mm	410	410	410	410	410
Sand	0 tot 4 mm	722	589	456	589	456
PCM	(kg)	0	44	88	75	150
Water-cement ratio		0,53	0,53		0,53	

As can be seen in Table 5, only 5 Vol.% and 10 Vol.% is made for testing. This is done because the workability is influenced too much when more PCM is added. Since the intention is not to use any other extra plasticizers the biggest amount is 10 Vol.% of PCM in the first 5 cm.

Because the PCMs appear to be damaged during the mixing of the ingredients, extra care is taken to get the PCM into the mixture. First the cement is mixed with the different aggregates and water, than at the last moment the PCM is added and the mixing is than done by hand. In this way is tried to prevent broken shells of the PCM by the mixing procedure.

After casting the different mixtures, they are placed in a room which is constant 20 degrees and has a moisture level of 65%. After one day of curing the blocks were taken from their molds and placed in a water bath for 27 days to complete the curing process.

After 28 days of curing, the blocks were tested for their pressure strength. Besides the pressure strength, a visual inspection is done to see if the PCM-concrete stayed in place during the curing process. Figure 26 shows the concrete blocks after 28 days of curing, and Figure 25 shows the PCM-concrete layer is still present on the bottom of the block. This means this way of casting could be an easy way to implement PCM into a prefab concrete slab.

Annex 3 shows the results of the pressure tests. With these results the graph in Figure 27 is made to compare the two Concrete-PCM mixtures.

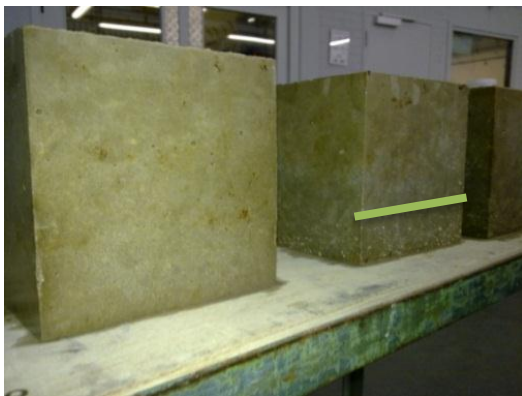


Figure 25: PCM visible only under the line



Figure 26: Resulting concrete blocks

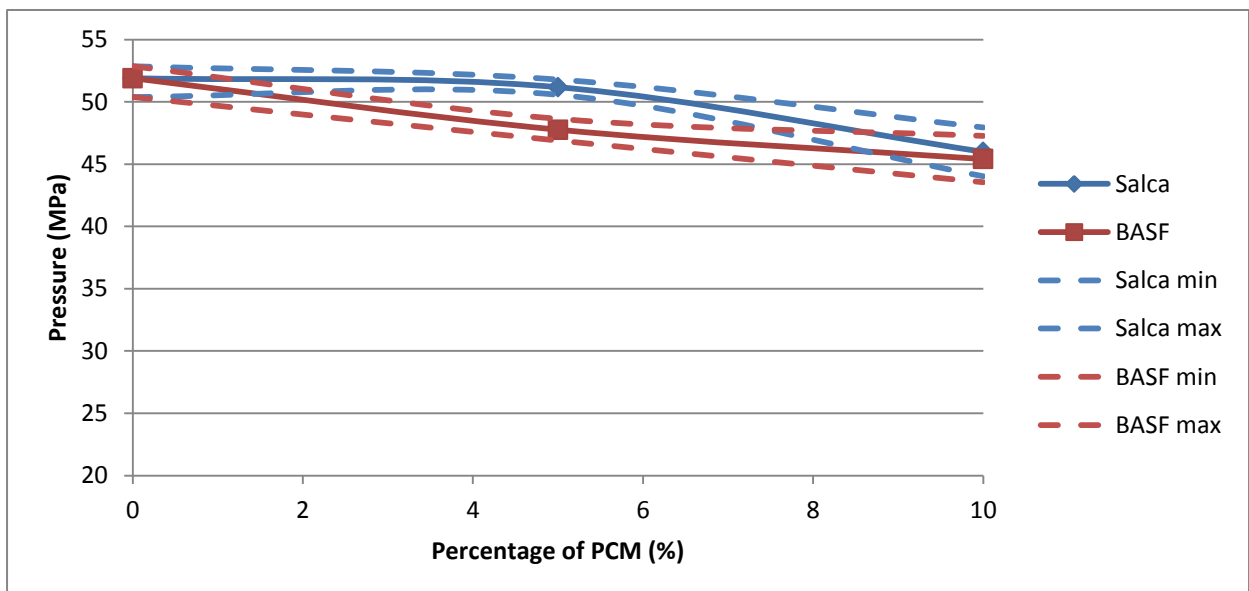


Figure 27: Resulting pressure strength with the different PCMs and volumes of PCM.

The results show the cubes made with PCMs from Salca appear to be slightly stronger than BASF, although the earlier prism test showed the opposite result. This could indicate the mixing procedure is of importance when PCM-concrete is produced. The Hobart mixer as showed in Figure 28 is in that case not suited for the mixing of PCM-concrete.



Figure 28: Hobart mixer

With the gained numbers about the strength of the concrete blocks they can be compared with the strength classes as known in the Netherlands. Table 6 shows the most common classes in the Netherlands. There are higher classes but these are only useful in high strength concrete.

Not only the block strength is shown but also the cylindrical strength. In the future both shapes have to be

made but in this case only the block strength is measured, since there was just a small amount of PCM available.

The blocks without PCM reach C40/50. The blocks from Salca as well as from BASF reach with the addition of 10 Vol.% of PCM still a strength class of C35/45. This means the addition of the PCM only reduces the strength with one class.

This means it is interesting to further investigate this dual layer concrete. Strength is reduced but just a little and with the advantage of the lower costs for the PCMs and the similar performance in a room.

Since there was just a limited amount of material no further research is done to this promising option but this is certain the way to go in the future.

Table 6: Concrete strength classes

Strength class	Cylindrical compressive strength (MPa)	Cubical compressive strength (MPa)
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C28/35	28	35
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C53/63	53	63

6. Thermal properties

With the goal of this research to find the benefits for the energy demand of a room when introducing Phase Change Materials into structural concrete, the thermal consequences of the mixtures are discussed and compared with conventional structural concrete.

The absorption of heat into the structural concrete depends on two important factors. First is the amount of heat that can be stored in a certain amount of PCM-concrete. Second factor is the speed with which this is done. The quicker the room adapts to the influencing factors the better the room keeps its comfortable temperature range.

Earlier research showed the use of PCM-concrete walls resulted in a lower room temperature as shown by Cabeza and Leppers (2007). This gives several advantages, first there is the improved comfort for the persons in the room, and secondly less energy is needed to keep the room within a preferred temperature range.

Besides the measurements done in the past, some simulation based studies were performed. The materials were described by the use of a temperature depended specific heat capacity (C_p). Around the melting temperature the C_p is increased with the heat of fusion and after this temperature the C_p is as big as it was before the melting temperature. The temperature depended specific heat is mathematically described as $C_p(T)$.

Because the materials in the earlier performed simulations were not heterogeneous and now there is made a heterogeneous material, the expectation is that the material will not react in a similar way as in the simulations. Therefore the thermal diffusivity (α) is introduced for multiple temperature ranges. Thermal diffusivity is the speed with which the heat flows through the concrete. The measured thermal diffusivity could be used as a tool to predict the effect of the PCM-concrete mixture in a room.

6.1. Theory

To understand how PCM influences the energy demand starts at looking at the heat flows in a room. Figure 29 shows a simple room in which a certain heat flow (Q) to the wall. This heat is influenced by the heat transmission coefficient (h) and the temperature difference between the air temperature in the room and the surface temperature of the wall.

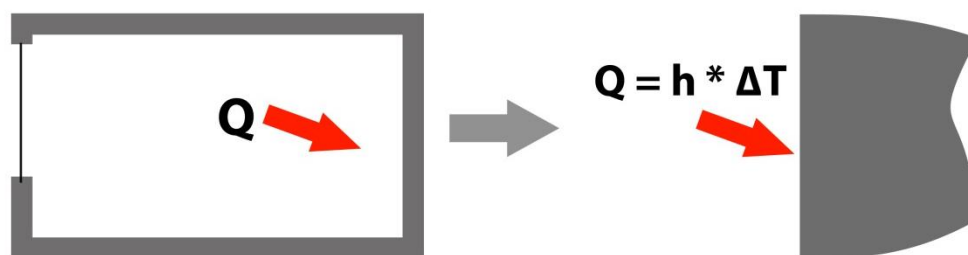


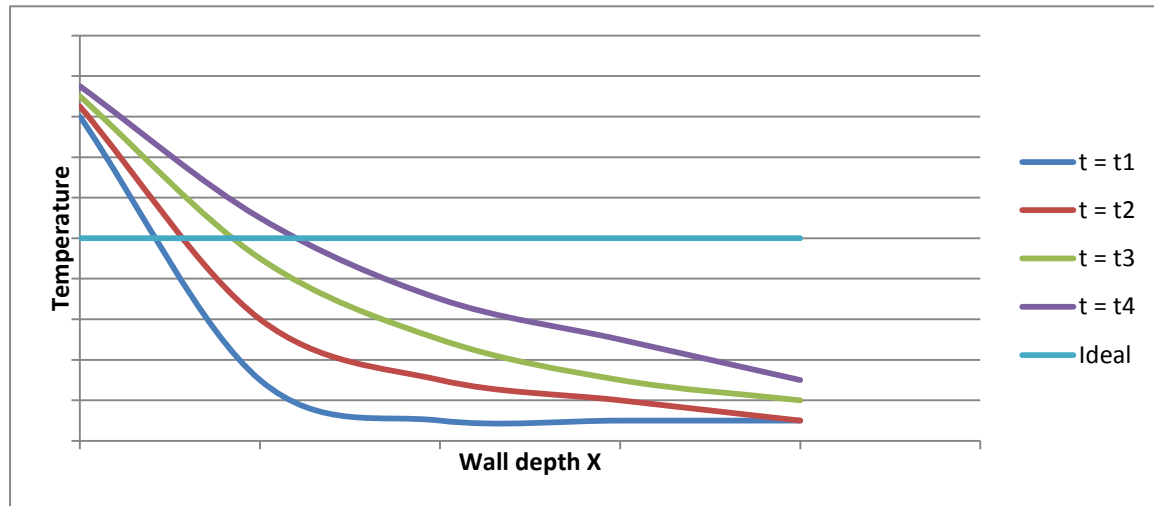
Figure 29: Simple representation of the heat which is delivered to the wall

Equation (1) shows the equation which describes the heat flow into the concrete. Here Q is the heat flow in W/m^2 , h the convective heat transfer coefficient in $W/m^2.K$, T_∞ The temperature of the air inside the room and T_s the surface temperature.

$$Q = h * (T_\infty - T_s) \quad \text{Eq. 1}$$

Equation (1) shows the surface temperature has to be as low as possible to have a large heat flow from the room to the wall. When a certain heat flow is present towards the wall another phenomenon becomes present which is the heat distribution through the wall.

As can be learned from the book introduction to thermodynamics and heat transfer (1997), an ideal situation is where the heat is immediately distributed evenly over the wall. Here we call that the lump system. In reality however it takes time to distribute the heat evenly over a certain amount of



material.

Figure 30 shows this typical temperature distribution through the wall at different times and equation (2) forms the mathematical description of these lines.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad \text{Eq. 2}$$

This shows the temperature in the wall reacts with a time delay to the temperature changes over the wall. This delay depends on the thermal diffusivity coefficient (α). When the diffusivity coefficient is very low, the temperature, and thus the heat, is distributed very slowly over the concrete and the heat stays in the first few layers of the concrete. This results in a higher surface temperature.

Figure 30: Heat distribution into a wall for different times and an ideal situation.

All this result in the conclusion the thermal diffusivity has to be high to keep the surface temperature low and the heat flow towards and from the surface of the wall as high as possible.

To be able to influence the thermal diffusivity, this is studied in more detail. Equation (3) shows the influencing factors of the thermal diffusivity.

$$\alpha = \frac{k}{\rho * C_p} \quad \text{Eq. 3}$$

Here the k is the thermal conductivity in W/m².K, ρ is the density in kg/m³ and C_p the specific heat in J/kg.

With the addition of the PCM to the concrete a new specific heat is created which is different for different temperatures. For a representation of this new specific heat is made use of earlier research. Because the PCMs melt around a certain temperature the specific heat depends on the temperature of the PCM-concrete mixture. Therefore the C_p is in this case temperature dependent around room temperature and is written as $C_p(T)$. The result is a thermal diffusivity depending on temperature as shown in equation (4).

$$\alpha(T) = \frac{k}{\rho * C_p(T)} \quad \text{Eq. 4}$$

By this formula the diffusivity can be divided in three parts which are the thermal diffusivity before, during and after the melting temperature. The first and third part will be similar but the second part during the melting will be significantly lower. Because in this research is worked with a heterogeneous material the thermal diffusivity is measured to find the influence of the latent heat in this mixture.

To simplify the thermal diffusivity it is described as three parts which are as said the thermal diffusivity before, during and after the melting point. Taken into account the different PCMs which are used in this study this result in the following thermal diffusivity equation.

$$\alpha(T) = \begin{cases} \alpha_1, & T < 20 \\ \alpha_2, & 35 < T < 20 \\ \alpha_3, & T > 35 \end{cases} \quad \text{Eq. 5}$$

By measurements within the different temperature ranges the diffusivity for that specific temperature range is determined. As said earlier the expectation is a similar thermal diffusivity before and after the melting point and during the melting point a very low diffusivity in comparison to the other two. This expectation is based on equation (4) because during the melting temperature a lot of energy can be latently absorbed by the PCM what means the temperature rises more slowly.

Besides the latent heat factor, also the thermal conductivity will change when the PCM is melted. In case of paraffin material this factor will decrease. For salt the thermal conductivity will be slightly higher. This result in a slightly higher or lower thermal diffusivity after the PCM is melted compared with the solid PCM, but the influence is small in comparison with the melting PCM.

6.1.1. Theoretical analyze of the energy distribution and latent heat absorption

From the general theory as described in the last chapter a closer look is taken at the latent heat absorption through the wall by the PCM.

With a certain amount of energy (J) which enters the wall the temperature rises as visualized in figure 31. A part of the offered energy reaches point X_1 which is given in the figure. This gives a certain temperature rise at point X_1

If focused on this one point we must assume the following facts. If there is a normal concrete then a constant rise in temperature is noticeable at X_1 . If PCM is added, this is different. First because the density drops and so does the thermal conductivity. This results for an unmelted PCM a slightly quicker raising temperature. But secondly, at the moment the PCM starts to melt, the C_p rises, and this decreases the temperature rise. Therefore the red curve, which represents the concrete with added PCM, bends in Fig. 31 just above the melting temperature of the PCM. It shows that between

the dotted line and the actual line now there is an amount of latently stored heat. The dotted line represents the temperature rise of the concrete when the PCM does not melt.

For the calculation of the amount of heat which is stored latently the thermal diffusivities can be used. At a certain X in the concrete the temperature rises 1 degrees Celsius when there is added a certain amount of heat which can be calculated by the use of the K the density and the diffusivity. Above the 20 degrees the thermal diffusivity changes and the other factors stay the same. This gives another (higher) amount of heat that is needed for a temperature rise of one degree. The difference between the two specific heats is the amount of heat that is stored by latent heat. In this way the amount of latently stored energy can be calculated.

By calculating the maximum amount of latent heat which can be stored from the properties gained by the factory divided by the amount of sensible heat the room totally needs to rise 1 degree Celsius in temperature, the maximal temperature difference can be calculated which is possible in that one specific room.

During the process of heating a wall the energy distribution then actually results in figure 32 depending on the properties of the concrete PCM mixture. Figure 32 shows until what depth the latent storage capacity of the PCM is activated.

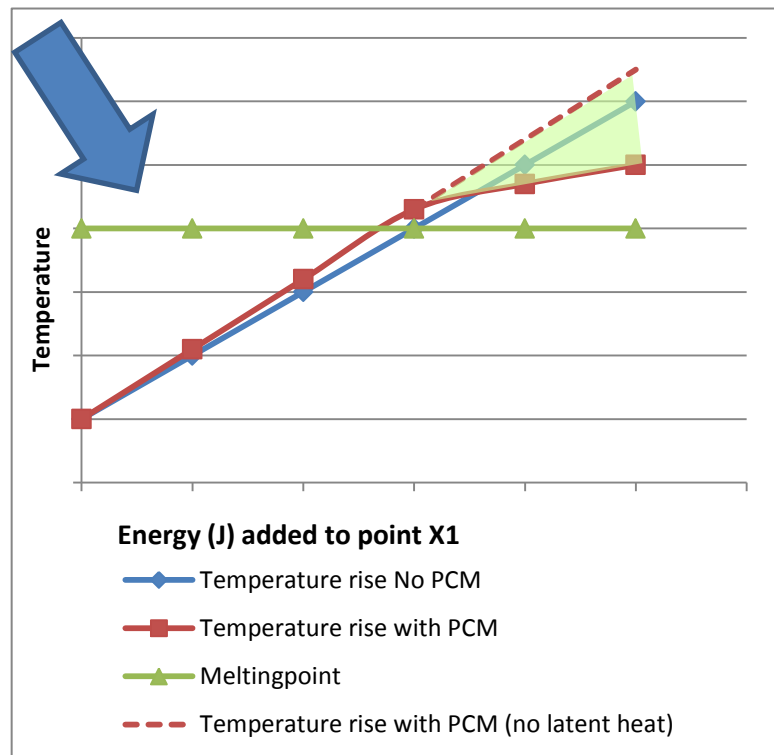
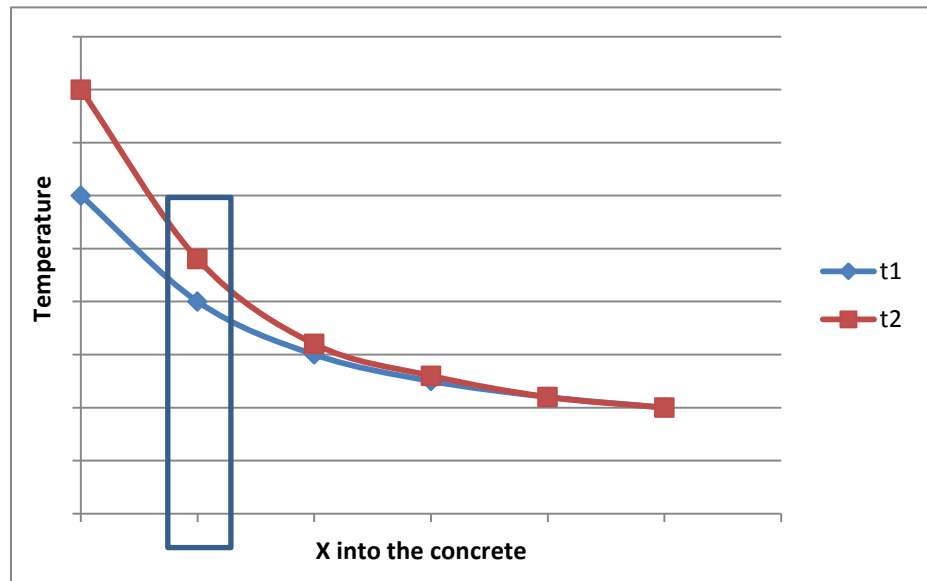


Figure 31: Temperature behavior through the wall (above) and specified at 1 point (below).

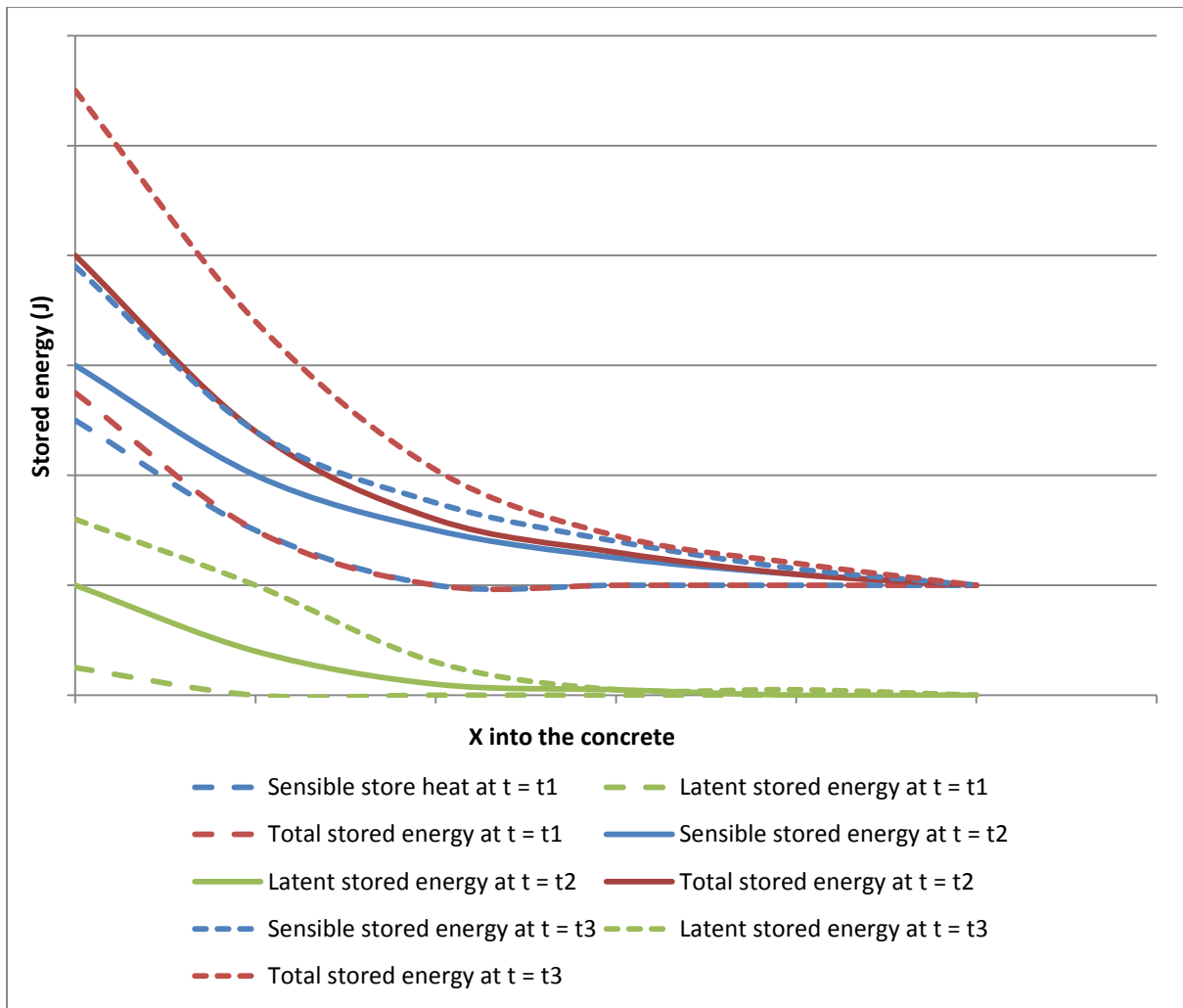


Figure 32: Graph with de heat absorbed by the different mechanisms for several moments in time

6.2. Composition of the samples

After the performed structural strength tests, was noticed that without special additions to the concrete, more than 10 Vol.% replacement of sand influences the workability too much to create a well-mixed PCM-concrete. Therefore the produced samples contain no more than 10 Vol.% of PCM. The mixtures contain cement, water, coarse aggregate and sand. The recipes are chosen by the use of several standard formulas given in the literature. These formulas can be found in the book *Betontechnologie van Souwerbren (1998)*. The resulting compositions of the samples are given in table 7. With the addition of PCM to the samples the sand particles are replaced by the PCM particles. The samples contain 5 Vol.% and 10 Vol.% PCM. Also several samples without PCM are made to compare the influence.

Table 7: mixture of the different samples used for thermal performance testing

Sample	Concrete	BASF 1 5 vol%	BASF 2 10 Vol.%	Salca 1 5 vol%	Salca 2 10 Vol.%
Cement (kg)	311	311	311	311	311
Water (kg)	165	165	165	165	165
Coars aggregate (kg)	780	780	780	780	780
Sand (kg)	1170	1073	975	1073	975
PCM (kg)	0	44	88	75	150
Water-Cement Ratio	0,53	0,53	0,53	0,53	0,53

The built samples have a diameter of 8 cm and a height of 10 cm. They are equipped with 5 thermocouples at 0,2,4,6 and 10 cm, which can measure the temperature through the sample. The chosen distance is done because it ensures no shortcut by the largest particles of 0.8 cm. The size of the sample is limited by the dimensions of the measurement equipment. Figure 33 shows the resulting samples with the thermocouples in place. Annex 4 explains how a specialized mold is made to implement the thermocouples into the sample.

Besides the sand replacement samples, another option is explored. This is the filling of lightweight aggregates with PCM. Figure 34 shows the setup used to fill the lightweight aggregates.

To ensure the PCM is liquid during the whole process, this is executed in a climate chamber at SGS INTRON. This chamber is kept at 30 °C and the PCM is placed in the chamber a day before the filling is executed. This ensures the PCM is completely molten before it is processed into the lightweight aggregates. First a vacuum box is created wherein the lightweight aggregates were placed and then the liquid PCM is pushed into the aggregates by the pressure difference. Table 8 shows the composition of the last set of samples in which the lightweight aggregates are used with and without PCM in it.

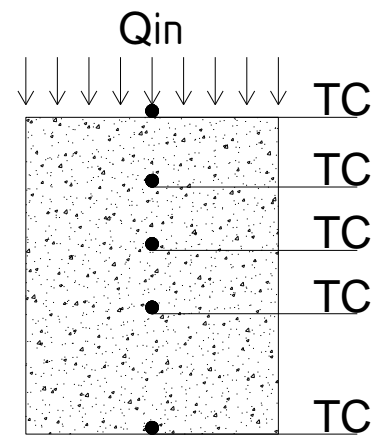


Figure 33: Layout of the sample with its thermocouples.

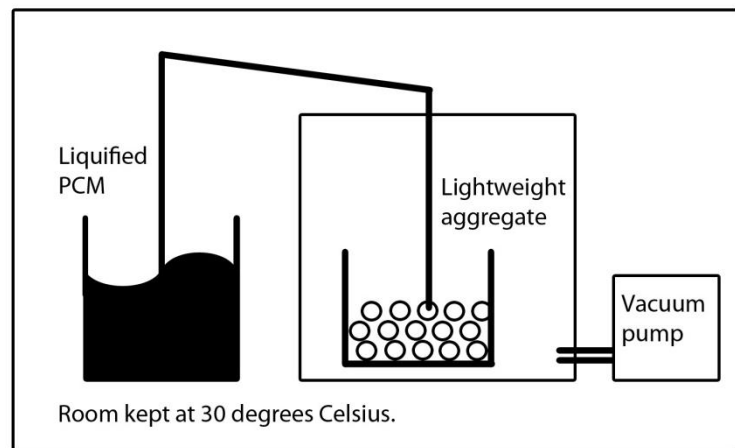


Figure 34: setup used for impregnating the lightweight aggregates with PCM

Table 8: mixture of the lightweight aggregate samples

Composition	LW1	LW2
Cement (kg)	311	311
Water (kg)	165	165
Light agg (kg)	4 tot 8 mm	190 +pcm
Sand (kg)	0 tot 4 mm	1170
Water-cement ratio	0,53	0,53

After filling the molds, these are placed in a room where the temperature is kept at 20 °C and the relative humidity at 65%. After 28 days the samples are taken from their mold and placed in the room where the measurements will take place. Here they stayed for a two weeks before the measurements took place to ensure the samples are acclimated.

The different materials have the following individual properties.

Table 9: properties of the different materials

Material	Thermal conductivity W/m ² .K	Specific heat J/kg	Heat of fusion J/kg
Concrete	2	840	-
BASF PCM	0.2	2000	110000
Salca PCM	0.6	1500	110000
Rubitherm PCM	0.2	2000	184000
Lightweight concrete	1.5	840	-

This results in the following combined properties if the individual properties are multiplied by its percentage and then added to each other.

Table 10: Resulting thermal properties of the PCM-concrete mixtures

Sample	Thermal conductivity W/m ² .K	Specific heat J/kg	Heat of fusion J/kg
BASF 1 5 Vol.%	1.91	898	5500
BASF 2 10 Vol.%	1.82	956	11000
Salca 1 5 Vol.%	1.93	873	5500
Salca 2 10 Vol.%	1.86	906	11000

6.3. Measurement setup

To measure the thermal diffusivity, the following setup is created. With this setup the speed with which the energy is distributed through the concrete can be determined and so the thermal diffusivity. By applying a thermal impulse, the reaction can be measured through the concrete. This setup is capable to apply various thermal impulses to test multiple temperature ranges.

To perform reliable measurements, a lot of effort is



Figure 35: Setup at the laboratory

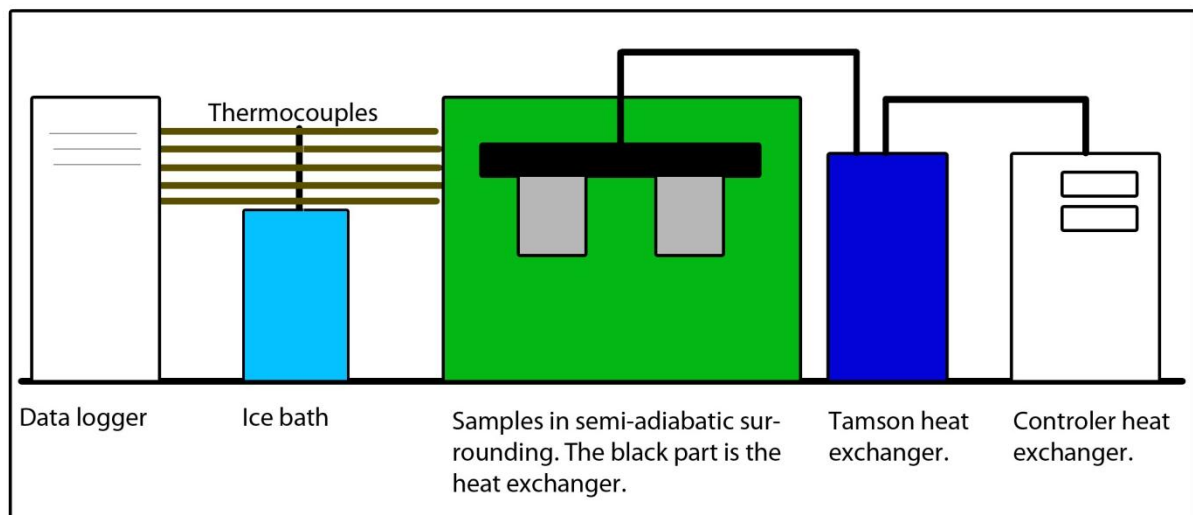


Figure 36: schematic view of the setup used for thermal measurements

used to build a proper setup. Figure 36 shows the schematic view of the setup used and figure 35 shows the setup in the laboratory. The setup exists of a box of 60 cm * 30 cm * 24 cm. The samples are placed in the middle and on top of the samples a conductive paste is applied to ensure a good contact with the heat flux meter on top of the sample. Above this all a heat exchanger is placed which is controlled by a computer.

The temperatures are measured every 66 seconds by a data logger who measures the voltage difference between melting ice and the sample in the positive as well as in the negative direction. This melting ice is continuously mixed to ensure a temperature of 0 °C.

The heat exchanger is tested for its well distributed temperature. In annex 5 the results of this test can be found.

6.4. Tests applied

With the samples in place, the following tests are done to obtain the temperature data which is used to characterize the PCM-Concrete mixtures, and calculate the thermal diffusivity.

6.4.1. Diffusivity calculation

The test series heats and cools the sample between 10 to 20 °C, between 15 to 35 °C and Between 30 to 50 °C. This boundary temperature is projected like a block graph on the sample. Chirdon (2007) has successfully used this method before. In this research, the intervals are for the first and third block 90 minutes and for the second block 180 minutes. Since there are three temperature ranges, the diffusivity is given for three ranges. There is given a thermal diffusivity before the melting trajectory, one during the melting trajectory, and one when the PCM is melted.

6.4.2. Sinus cycle

With the projection of a sinus shaped heating pattern on the sample, a simple simulation is tried to make to measure the influence on a room. The temperature goes from 15 °C to 30 °C and back to 15 °C. This cycle is made in 24 hours and represents a summer day.

The goal of this test is to characterize a general behavior of the PCM-Concrete in a room. Because PCMs are used for short time storage, what is mostly one day, the measurements show the effect of PCM over this period.

Afterwards this representation is not correct. Because the sample is heated by placing a plate directly on the sample, the heat is distributed by conduction. In a room however, heat is mainly transported by convection and radiation.

But with the results from the measurements some remarks can be made about the general behavior of the PCM-concrete mixture when compared to a normal concrete sample.

6.5. Calculation of the thermal diffusivity

With the measurements done, a calculation is performed by the use of equation (2), to find the best matching thermal diffusivity. This is done by the use of finite element software Comsol. Figure 37 shows how the calculation is done. The measurements of the thermocouple at two centimeter for a certain temperature range are projected on an 8 cm block and with use of equation (2) the temperature is calculated at the three points into the block of concrete.

This calculation is done with different thermal diffusivities. The results are used to perform a sum of squares of the differences between the calculated temperature and the actual measured temperature. At all three measurement points the differences between calculation and measurement are squared and then added. The diffusivity who gives the lowest value for this sum is the best fitting thermal diffusivity for that specific temperature range. Equation (6) shows the sum of squares.

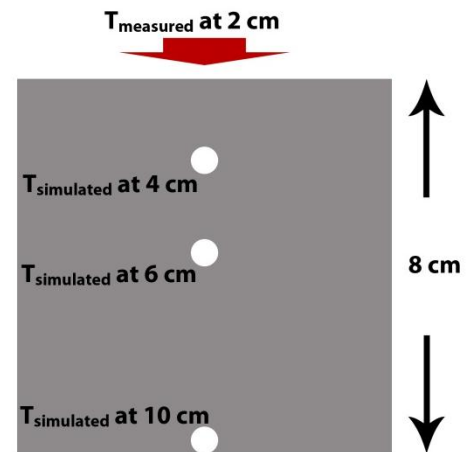


Figure 37

	$\sum_{m=1}^{m=n} (T_{simulation} - T_{measurement})^2$	Eq. 6
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When the diffusivity is determined equation (5) can be applied for every sample.

To control the quality of the diffusivity equation, a graph is made of the differences between measurement and simulation for every measurement point. This is the so called residue of the sum of squares. These are given in annex 7.

6.6. Results

The results are discussed in two parts. First the diffusivity measurements are discussed, and secondly the day cycle measurements.

6.6.1. Diffusivity measurements

To determine the thermal diffusivity, the samples are charged with three temperature cycles. As explained in chapter 8.4.1. Figure 38 shows the resulting temperatures through the samples. In this figure the sample which is taken, is an example with a PCM from BASF. As can be seen from figure 36b there are some irregularities in the temperature flow which indicate a PCM-moment, where heat is latently absorbed, is visible in the measurements.

These measurements are then used for the calculation done as explained in paragraph 8.5, to determine the thermal diffusivity.

Figure 39 and figure 40 show the calculated temperature and measured temperature at the different locations through two different samples. There is shown one sample with PCM from BASF and a sample with PCM from Salca.

Both samples show similar points which are discussed one by one. First the part between 10 and 20 °C is discussed. Here the simulation and the measurement match well. The reason for the difference is mainly caused by the initial temperature used in the simulation. Here is chosen to use the mean temperature over all the thermocouples. Because the most temperatures at the beginning of the measurements differ just 0.1 or 0.2 °C and with the used calculation program it was not possible to introduce a different initial temperature.

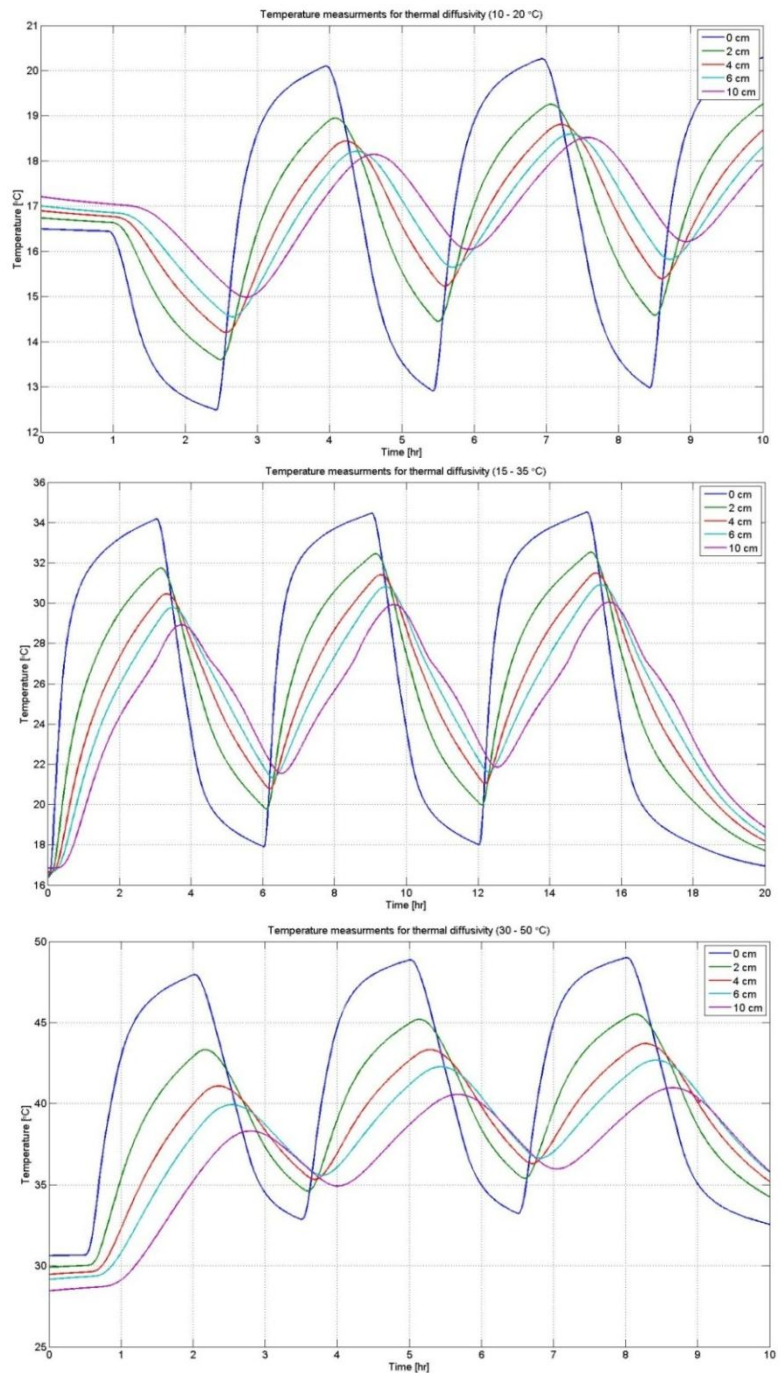


Figure 38: a: measurements between 10 and 20 degrees, b: measurements between 15 and 35 degrees, c: measurements between 30 and 50 degrees.

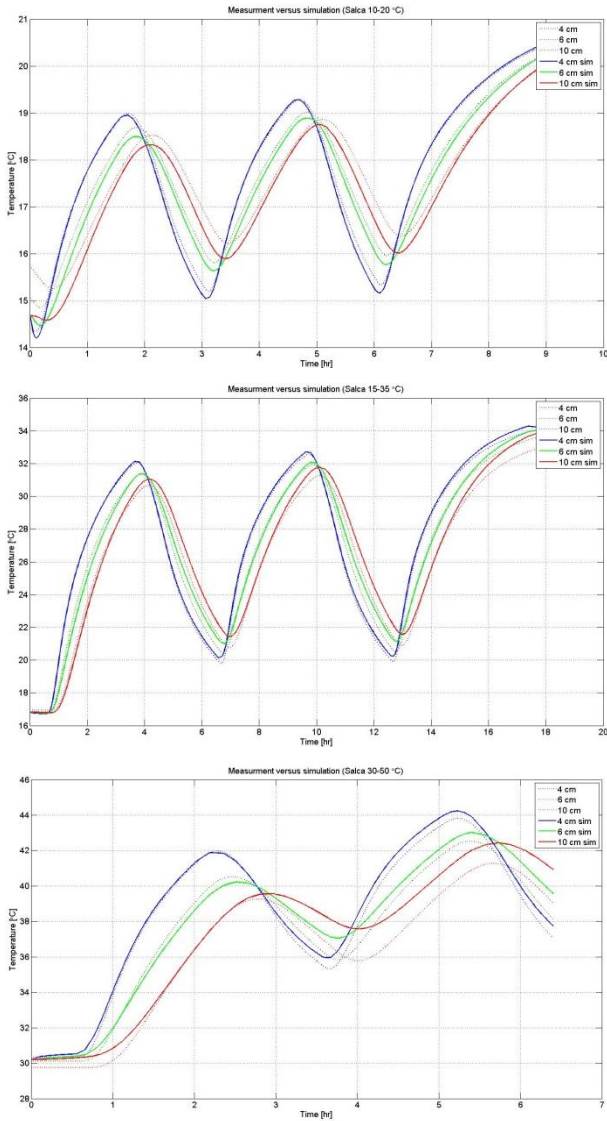


Figure 40: Measurement versus simulation of a sample with PCM from Salca.

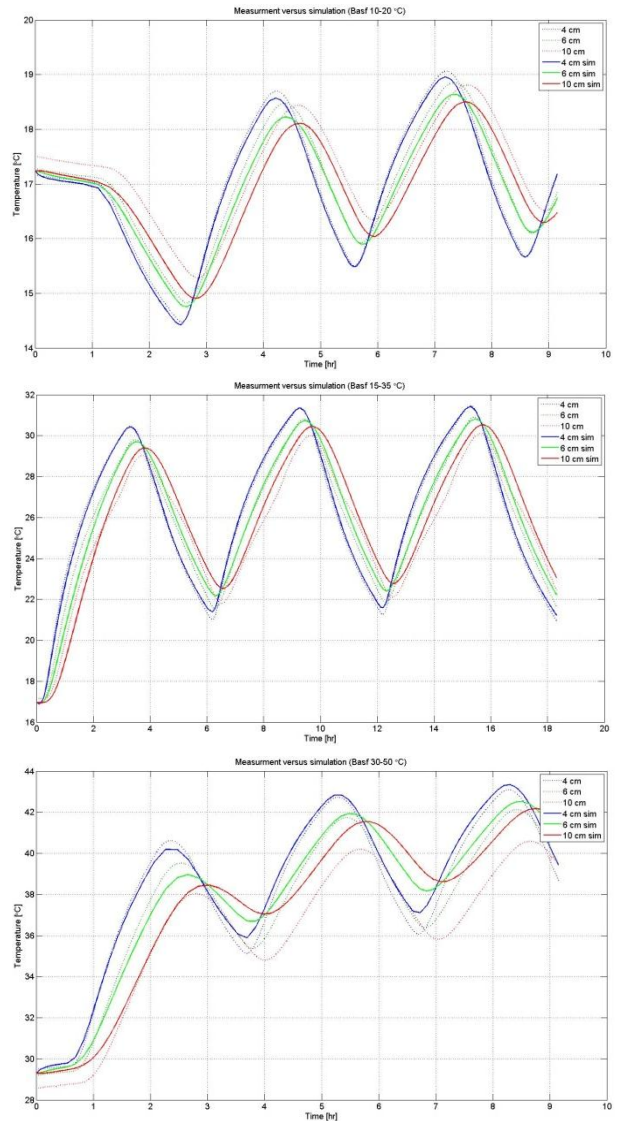


Figure 39: Measurement versus simulation of a sample with PCM from BASF.

The results between 15 and 35 °C are starting to differ more from each other. Here the simulation and measurement are showing slightly different lines, especially the sample with the BASF PCM. Here the moment the PCM starts to melt is clearly visible by the slower rising temperature around the melting temperature of the PCM. This show the PCMs stores a part of the heat latently which enters the room. Remarkable is the absence of a clear melting moment for the Salca PCM's.

Between 30 and 50 °C the gaps between simulation and measurement becomes bigger over time. Especially further into the concrete. This could indicate the PCM is still working during the higher temperatures.

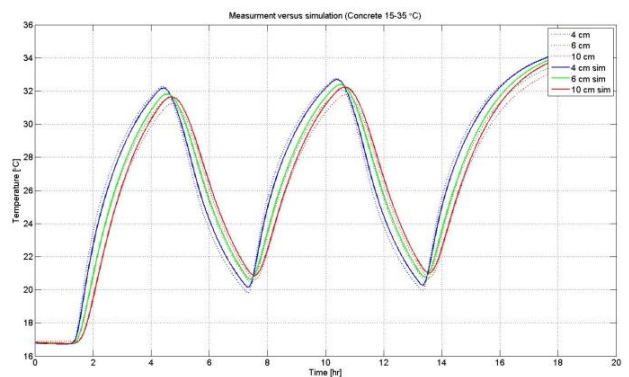


Figure 41: Measurement versus simulation of a non PCM sample.

To find prove for the hypothese the PCM is still melting during the mesurements between 30 and 50 °C, a closer look is taken at the results without PCM. This is shown in figure 41. Here we see a much better similarity between measurement and calculation between 15 and 35 degrees for concrete without PCM, what indicates the PCM is still influencing the measurements during the higher temperature measurements.

The last step in the process is making the residu graphs. Figure 42 shows the result from one of the samples with BASF PCM. Annex 7 shows the rest of the residu graphs. The first two graphs show just a little difference which is quite constant. The last graph about the measurements between 30 and 50 °C shows a decrease over the difference which indicate again the PCM is influencing this measurements. The graph shows the gaps between measured and calculated temperature are increasing.

The final result of the diffusivity measurements is table 11 which shows the thermal diffusivities of the different samples.

The table shows the unexpected low diffusivity for the temperatures between 30 and 50 °C.

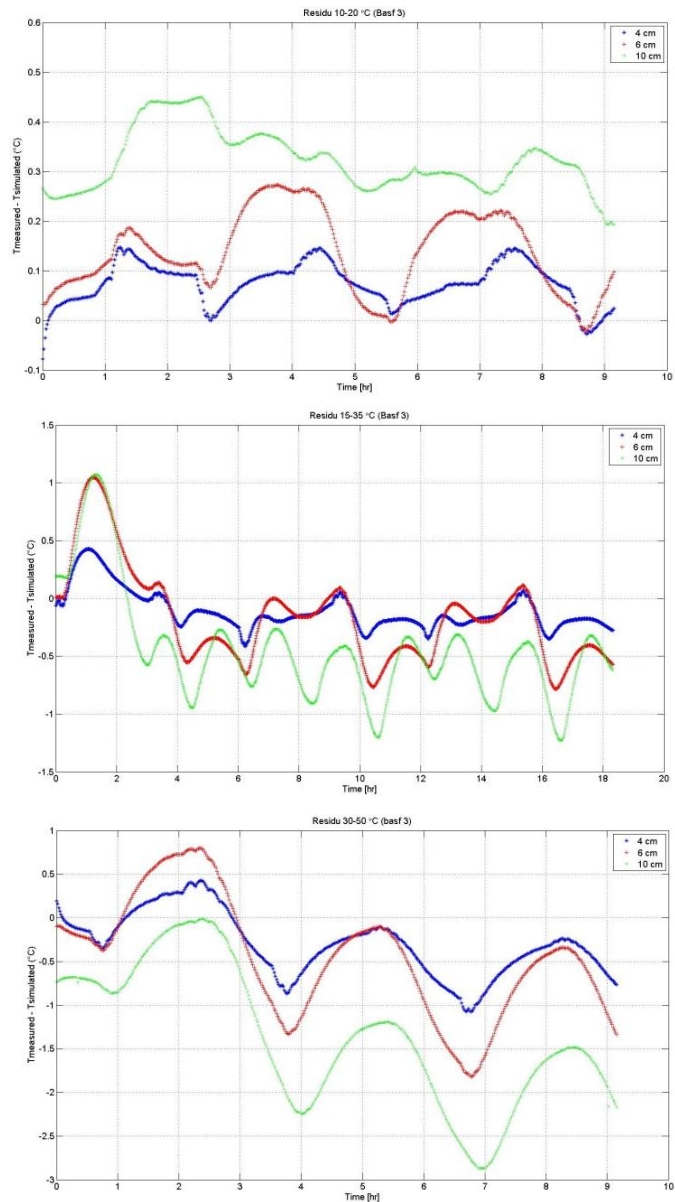


Figure 42: Residues of a sample for the three different temperature cycles.

Table 11: Resulting thermal diffusivities of the different samples.

Sample	α_1 (*10 ⁻⁷)	α_2 (*10 ⁻⁷)	α_3 (*10 ⁻⁷)	Sample	α_1 (*10 ⁻⁷)	α_2 (*10 ⁻⁷)	α_3 (*10 ⁻⁷)
Ca	17	14	12	BASF 1a	15	13	9
Cb	Bad sample	Bad sample	Bad sample	BASF 1b	13	11	9
Cc	13	12	11	BASF 2a	10	7	7
Cd	13	12	7	BASF 2b	9	7	6
Salca 1a	18	15	10	LW1a	10	7	9
Salca 1b	9	8	7	LW1b	10	8	8
Salca 2a	9	7	6	LW2a	12	12	10
Salca 2b	9	8	6	LW2b	14	14	11

6.6.2. Analysis of the unexpected result

After obtaining the thermal diffusivity for the different samples, the results were not as expected and therefore an analysis is performed to give an explanation for the results.

Before the tests were started the expectation was that the diffusivity would have about the similar number before and after the melting point of the PCM, and a significantly lower one during melting. The outcome contradicts this.

To ensure the unexpected result is not caused by other causes than the PCM, several possible interfering causes with the measurements are investigated. Looking back at the process of building samples and a setup, the following points could be weak spots in the process.

- Moisture in the samples
- PCM is not distributed equally over the Sample.
- Place of the thermocouples
- Quality of the setup
- Quality of the thermocouples
- Air gaps in the samples
- The assumption of the thermal diffusivity description is not correct.
- Heterogeneous material.

One by one these points will be explained, and with simple tests the plausibility is checked.

Moisture in the samples

After unmolding the samples, these are placed in the room where the measurements take place. This means they could slowly adapt to the prevailing moisture content of the surroundings. The moisture content in this room was about 35% at 20 °C. If this moisture is trapped in the concrete during the measurements, the relative moisture content changes with the temperature of the concrete. This could be the case because the material which is used to make the semi-adiabatic surrounding of the samples has a vapor diffusion resistance of about 150 – 300 kg/(m·h·Pa). This is a very high moisture isolating material what makes the moisture transport very slow. Therefore the assumption the vapor is trapped in the setup is very plausible.

Concrete exists of different types of pores which go from just a few micrometers until several millimeters. In every capillary there is a layer of water molecules against the sides, which increases rapidly with increasing relative humidity. Already at 30% relative humidity this layer closes the smallest capillaries, what introduces shortcuts through the concrete because water is a much better conductor instead of air (0.024 W/m.K for air against 0.58 W/m.K for water). With the introduction of temperature differences over the sample the relative humidity changes.

As can be seen in Figure 43, the moisture content highly influences the thermal conductivity and as a consequence the thermal diffusivity. In the article of Khan (2002) the relative moisture is varied, and for every change the thermal conductivity is measured. This shows the influence of the moisture is very well measurable. Figure 43 shows the ratio between moisture and conductivity. This figure shows the conductivity drops with around 0.4 W/m.K if the moisture drops with about 10%.

With the assumption the absolute humidity is constant over the sample and a temperature difference is introduced, the relative humidity differs through the sample. When we then look at the measurements of the samples, the temperature differs 4 to 5 degrees over the sample. This means there is a relative humidity difference between the warm and cold side of the sample of about 5 % relative humidity as can be learned from the literature. The relative humidity in the measurement room is about 30 to 40 % what means the difference in conductivity could be around 0.2 W/m.K to 0.3 W/m.K. This shows that also without PCM the thermal conductivity and diffusivity are influenced by the moisture content of the sample.

The thermal diffusivity changes by Equation (3), what means that if around 20 degrees the diffusivity is $2/2300 \cdot 850 = 1 \cdot 10^{-6} \text{ mm}^2/\text{s}$, the diffusivity around 30 degrees is $1.8/2300 \cdot 850 = 9.1 \cdot 10^{-7} \text{ mm}^2/\text{s}$. Here the density is 2300 kg/m³ and the conductivity at 20 degrees Celsius is considered 2 W/m.K. The specific heat is set at 850 J/kg. This finally results in a difference of $0.9 \cdot 10^{-7} \text{ mm}^2/\text{s}$ over 5 degrees.

With this phenomenon a clear influence on the diffusivity measurements is visible between the lower temperatures and the higher temperatures. Especially around the peak moments of the measurements the influence is present of the moisture content. It will not completely explain the found the difference between the expectations of the diffusivity measurements and the measurements.

Phase Change Materials are not distributed equally over the sample

Every type of sample is made twice. But the mixture for the two samples is made at once. This means the PCM could be unequal distributed over the two samples. From the difference in measurements between the similar samples is seen that the distribution of PCMs over the different samples did not work out

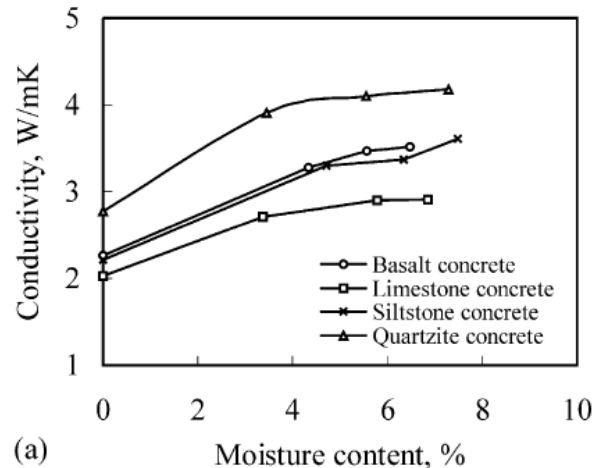


Figure 43: Thermal conductivity of several types of concrete at a certain amount of moisture. (percentage is x10)

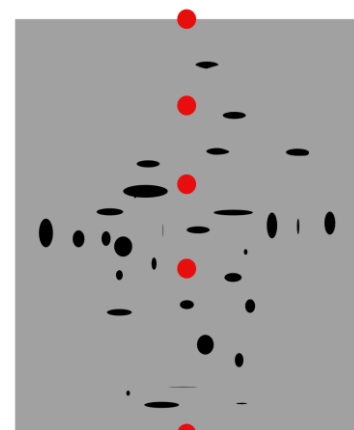


Figure 44: Fictive particle distribution over a sample

well, although this does not influence the thermal diffusivity difference between measurements before and after its melting point.

As can be seen in Figure 44 the black PCM particles are not distributed evenly over the sample. The red thermocouples than could measure different diffusivities between two different couples. This could explain the small differences between measurement and simulation, but the differences between the expectations for the thermal diffusivities and the results cannot be explained by this phenomenon.

Quality of the setup

With the setup is tried to make a semi-adiabatic surrounding for the samples. Due to the possibility to get wires out of this surrounding and because the isolation material is not a perfect thermally closed, there will be some leakage. But to get the best possible result, the cracks are taped up and there is used a thick layer of isolation material. This material is styrodur and has a λ -value of $0.038 \text{ W/m}^2\cdot\text{K}$. The thickness of the isolation is at least 120 mm thick. Figure 45 shows the taped up cracks.



Figure 45: setup with the taped up cracks

Quality of the thermocouples

The quality of the thermocouples have a great impact on the result and therefore these are made from the materials copper and constantan and the weldings are sealed to get no interaction between the welding and the ingredients of the concrete. Also the couples are calibrated to obtain the best possible result by the use of thermocouples. To test the sealing, the thermocouples were placed in a salt bath and checked if the measurements were disturbed. This way is assured the sealings are closed for any outside influence.

Place of the thermocouples

With the casting of the samples the couples are put into place. Much care is taken to get them on the right height without movement during the filling process of the mold. But during the drying process it is possible the couples have moved a bit and so the distance between the couples could be not exactly on the intended distance.

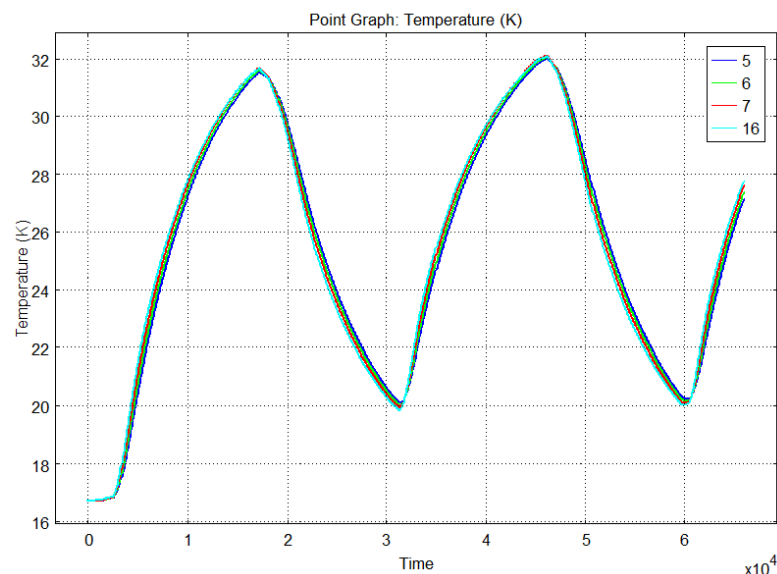


Figure 46: Simulation for three different locations in the sample which are 5 mm away from each other.

Figure 46 shows the graphs of the measurement, the calculation and two alternative calculations in which the placement of couples is 5 mm above and 5 mm below the intendant place. So if it moved 5 mm the difference is not more than 0.2 degrees. This could not explain the difference between the

measurements and the simulations. This phenomenon is only responsible for slight differences in the measurements versus the calculations. For example the differences between the measurements and calculations for the temperature range of 10 to 20 °C.

Air gaps in the samples

Air gaps in the samples could arise during the curing if the air is not removed properly by vibrating the mixture. To disturb the place of the thermocouple the air is taken out by just using a pestle. This could give a slightly worse result than using a vibrating plate, as is the case in most tests performed in laboratory.

If an air gap arises around a thermocouple the resulting measurement shows an aberrant temperature flow when compared with the other thermocouples, because of the isolating air layer around the couple. This layer of air is stagnant what means the thermal conductivity is very low in such an air gap. There is however no thermocouple that really shows a different flow over time what indicates this cause is not plausible.

The assumption of the thermal diffusivity is not correct

In this research the assumption is done of a constant thermal diffusivity for the three temperature ranges. The goal was to create a simplified tool for further simulations. But with the melting PCMs there is actually a more complex situation.

The thermal diffusivity is normally explained with the Equation (3) which can be found in chapter 8.1, where there is no transition from liquid to solid or vice versa and all the parameters are constant. But during the transition temperature of the PCM particles, the heat of fusion is introduced what results in a bigger specific heat around a specific temperature. This means the formula transforms into

$$\alpha (T) = \frac{k}{\rho \cdot C_p(T)} \tag{Eq. 7}$$

Figure 48 shows the form of the $C_p (T)$ This results in Figure 47, where the thermal diffusivity of the PCM is visualized. As can be seen the thermal diffusivity is more complex than just a three point representation. It seems this simplification is a bit too simplistic.

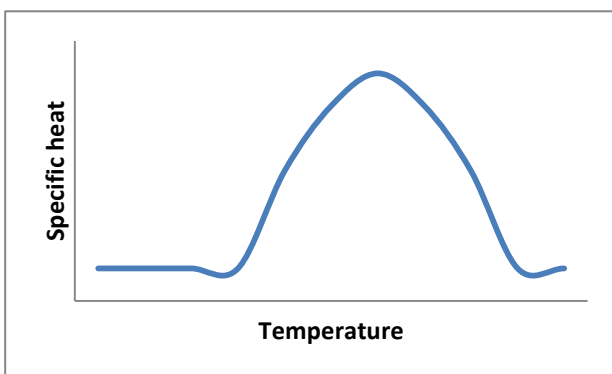


Figure 48: Specific heat of a PCM around melting temperature

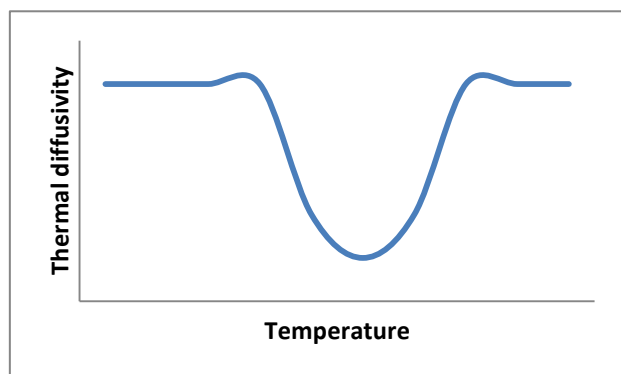


Figure 47: Diffusivity of a PCM around melting temperature

Heterogeneous material

A last influencing factor on the measured thermal diffusivities is an important one. The sample is made out of different materials which are mixed together and then treated as a homogeneous material. But especially during the melting cycles of the PCMs the heat does not travel through the material in a straight line. Figure 49 shows a simple model of the sample in which the heat enters the sample and is distributed constantly through the concrete. When the heat flow meets a PCM-particle, it partly disappears into the particle but also a part will travel around it because the surrounding concrete is much easier to increase in temperature. This means the energy will already be traveling through the concrete around a thermocouple although the storage capacity above this thermocouple is not fully used.

This phenomenon could explain the lower thermal diffusivity for the 30 to 50 degrees measurements. Although a higher temperature is measured the heat storage is not used fully what means heat is still entering the PCMs instead of heating the full sample.

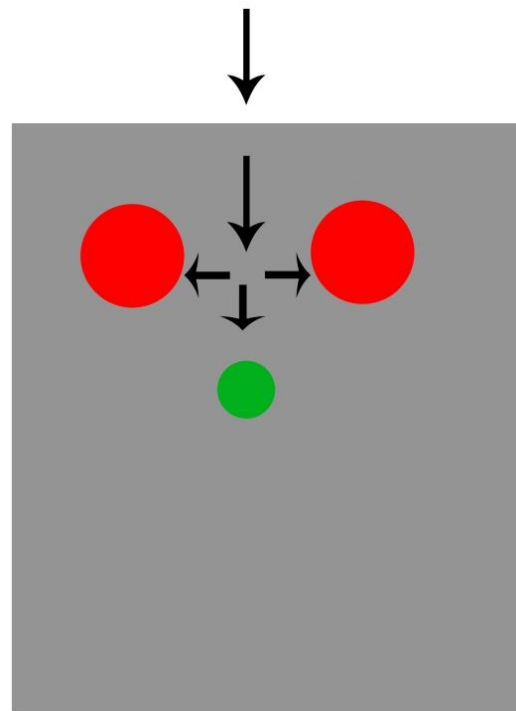


Figure 49: Section of the sample with the heat flow to the different parts

For a better insight in this phenomenon, some extra literature is found. Two articles showed the complexity of rightfully simulate the conductivity, which is part of the diffusivity, of a heterogeneous material. The first article is from Wang et al. (2006). Here the different types of mixtures are discussed with different simulating models. Also a new simulation method is introduced.

The second article is from Furmanski (1992) which describes the effective conduction of a heterogeneous material by the use of the particle size. This articles show the complexity of some mixtures. And of course not only the heterogeneity is present; also the latent heat factor adds complexity. To get a good simulation of this phenomenon the formula has to be more complicated to take into account all the influencing parameters.

Figure 50 shows a picture of simple simulation of this situation what already shows the problem.

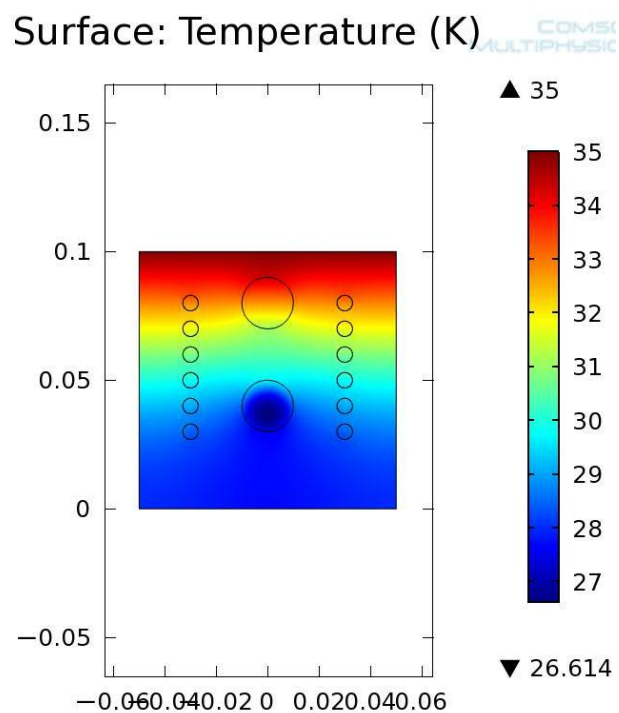


Figure 50: Model of the indicated error where heat travels around the PCMs.

6.6.3. Sinus measurements

The results of the sinus measurement per sample looks like figure 51. Here a BASF sample is displayed. During this research the choice is made to look at the mean results of the different similar samples. For every type of mixture two samples were produced, but it is done by making one mix to fill both moldings. This means there could be an uneven distribution of the PCMs over the two samples. Therefore the mean results of the two samples is calculated and used to analyze the effect of the specific PCM-Concrete mixture.

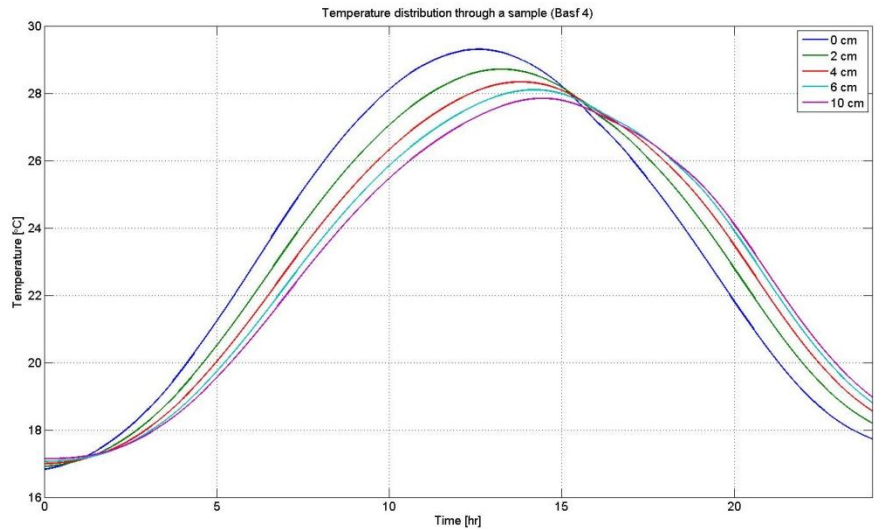


Figure 51: Measurements of the 5 different thermocouples in a BASF sample.

Figure 52 shows the mean results of the sinus measurements at 4 cm into the sample. The rest of the results at the different locations in the samples are displayed in annex 6. Several phenomena are visible and the most important are the lower peaks of the samples with PCM in it in comparison with the samples without PCM. Also most peaks occur later in time. A last point which takes attention is the little higher starting point of the concrete samples. Here the measurement was started a bit early what resulted in a not fully cooled down sample to the start point of 15 °C. At the other measurement points, similar phenomena take place.

Besides these phenomena some more detailed phenomena take place. Therefore an analysis is made of the most important phenomena.

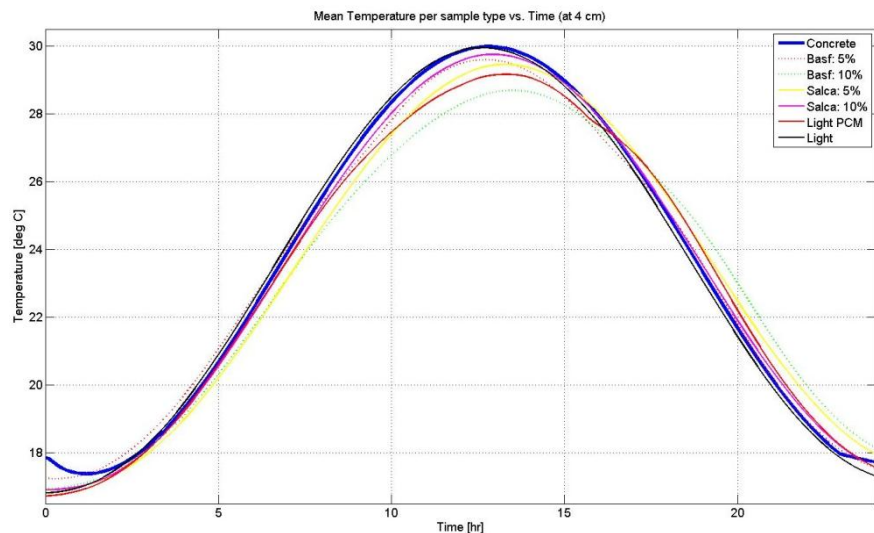


Figure 52: Mean results per sample at 4 cm.

6.6.4. General analysis of the sinus measurements

The analysis starts at the top of the samples. As mentioned earlier in this report the surface temperature is an important factor in the amount of heat which is able to enter the concrete. Therefore a closer look was taken at the measurement results at the top of the samples.

Figure 53 shows the measurements which represent the surface temperature. Here the most PCM-concrete mixtures have a lower surface temperature than the one without PCM. Only two types of samples show a higher mean surface temperature. This could mean the PCM is not distributed well through the sample and therefore no PCM is available at the top or at least around the thermocouple.

The second phenomenon is the inconsistent graph of several samples with PCM. Figure 54 shows such an inconsistent part of the graphs.

This inconsistent part shows the moment the

PCM starts to melt. Here the temperature changes slow down because of the latent stored heat instead of the sensible storage. The samples without PCM do not show this inconsistency but also the Samples with the PCM from Salca in it do not show this phenomenon. The explanation could be the melting temperature of the PCM. The PCM from Salca has its melting temperature around 28 degrees. And as can be seen in the different graphs, this temperature is exceeded just a very short time around the peaks. Besides, the melting of BASF PCM starts a few degrees above its actual melting temperature. Therefore can be concluded the PCM of salca is almost not activated during the measurements because the temperature around the PCM is to low and therefore the graph stays consistent. This could also explain the almost similar temperature for the 5 and 10 Vol.% samples.

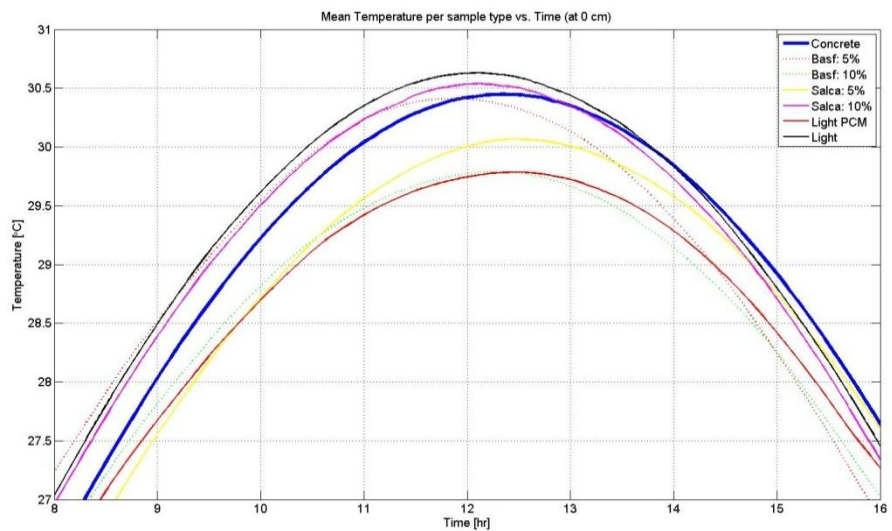


Figure 53: Surface temperature at the highest point during the measurements

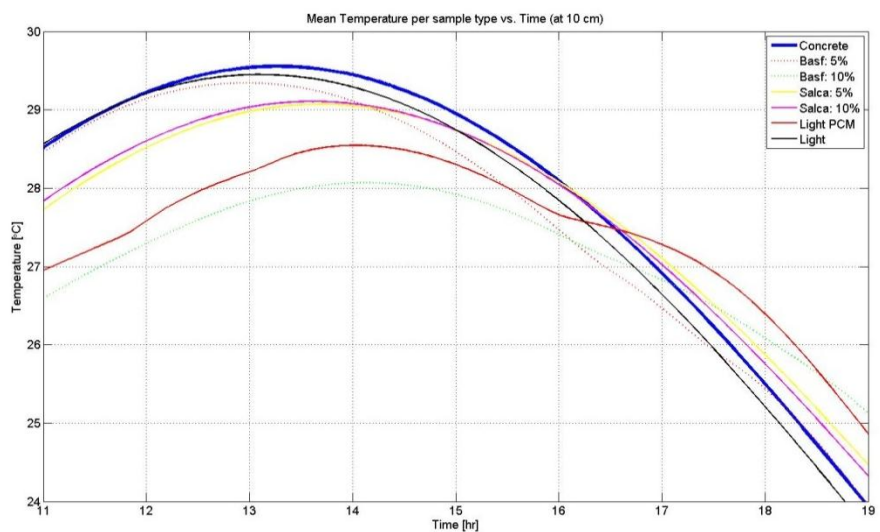


Figure 54: clear moment where PCMs slow down the temperature change

Besides the temperature measurements, also the heat flux of the samples is measured. Figure 55 shows the heat flux for every sample during the measurements. What can be seen is a start in which the samples go pretty similar. Around the peak, clearly more heat enters the lightweight sample filled with PCM and the sample with the two 10 Vol.% of PCM. The difference between the BASF and Salca version is due to the different melting temperatures. The samples with 5 Vol.% of Salca is the only one who clearly absorbs less energy than a sample without PCM. This could be explained by the lower mass and the high melting temperature again of the PCM.

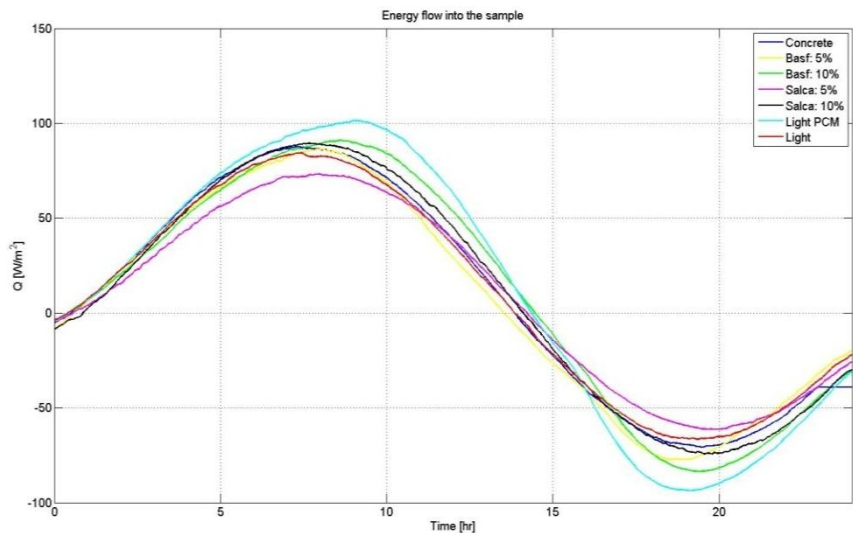


Figure 55: Heat flux into the samples.

The last graph shows the peak temperature distribution through the different sample types. As can be seen the energy is stored more and more in the first part of the sample. The temperature differences through the sample become greater. This indicates the thermal diffusivity is lowered by the addition of the PCMs. With the earlier explained theory about the desire to transport the heat as quickly as possible through the sample here can be seen the PCM has a negative influence on it. Especially the BASF PCM makes the heat travel slowly through the sample, what can be explained by its lower thermal conductivity. This again shows the PCM is only useful in the first centimeters of the concrete layer.

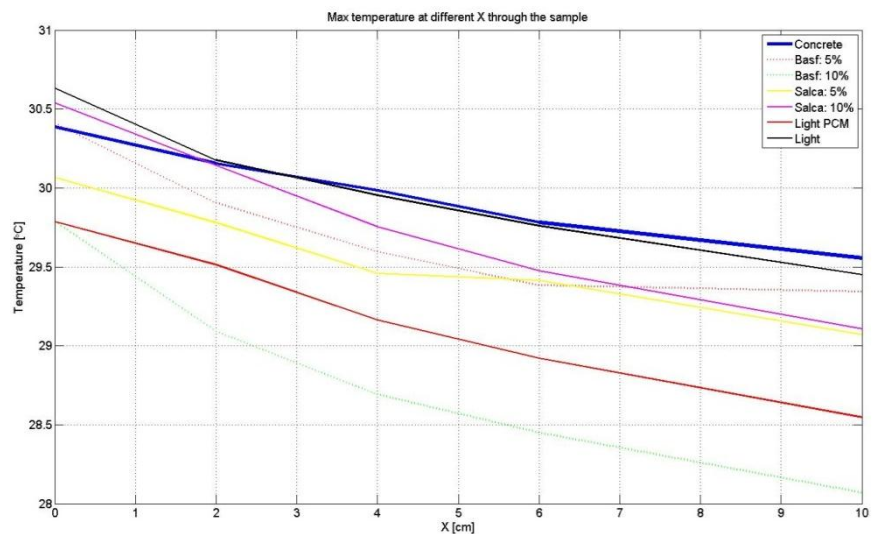


Figure 56: peak temperatures reached at different point through the sample

6.6.5. Simple calculation of the stored heat in the samples

To get an idea about how much heat can be stored in the samples, a simple calculation is made for the amount of heat the samples need to raise several degrees in temperature. Normally the heat needs time to reach all the material of the sample, but in this case is assumed the sample is evenly heated at all points. No time is needed for the heat to travel through the concrete what means the dependence of the depth into concrete is not taken into account. This is described earlier in the theory section and called the lumb method.

First the values of the samples are determined for the samples with the encapsulated PCM. The samples without PCM are not taken into account because this calculation is done to get an idea about the amount of heat which can be latently stored.

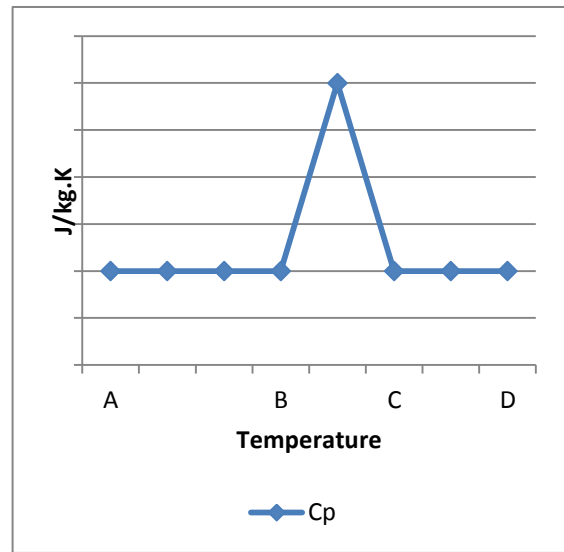


Figure 57: simple representation of the C_p

The C_p of a PCM-concrete sample transforms with the addition of the latent factor to figure 57. From A to B and from C to D there is just the normal C_p active but between B and C there is the melting point what means around that temperature the latent storage capacity is available. In table 12 the C_p between A, B, C and D are given.

Table 12: Data about the samples with encapsulated PCM

	Samples			
	BASF 5	BASF 10	Salca 5	Salca 10
1. Measured k-value of composite¹	1.20	1.10	2.10	1.50
2. Calculated k-value of composite²	1.91	1.82	1.93	1.86
3. Calculated C_p of composite without latent heat³	898	956	873	906
4. heat of fusion of composite (J/sample)	2212	4423	4147	8294
Simple C_p Graph				
A-B	898	956	873	906
B-C	3110	5379	5020	9200
C-D	898	956	873	906
5. Measured density (kg/m³)	1957	1837	1996	1887
Calculated mass sample (kg)	0.98	0.92	1.00	0.95

If then the samples are heated from 15 to 30 degrees, the following amount of energy is absorbed by the different samples which is displayed in table 13. Here the amount of absorbed heat by sensible storage and latent storage are separated.

¹ Measured using a device called isomet

² Calculated from the factory data by weighting the properties

³ Calculated from the factory data by weighting the properties

Table 13: amount of energy stored when heated from 15 to 30 °C

	BASF 5	BASF 10	Salca 5	Salca 10
C_p * 15 °C (J)	13470	14340	13095	13590
Heat of fusion (J)	2212	4423	4147	8294
Total (J)	15682	18763	17242	21884

After the determination of the thermal diffusivity earlier in this chapter, the situation as described above is not present. To get a more accurate approximation the measured thermal diffusivities and conductivities are used to determine the C_p over the different temperature ranges with the use of equation (3).

Table 12 shows the mean thermal conductivities and table 14 shows the thermal diffusivities for the three temperature ranges. From this data the C_p can be determined for the three used temperature ranges.

Table 14: Thermal diffusivity calculation

	Samples			
	BASF		Salca	
	5.00%	10.00%	5.00%	10.00%
Measured thermal diffusivities	14.00	9.50	13.50	9.00
(m²/s)	12.00	7.00	11.50	7.50
	9.00	6.50	8.50	6.00
C_p's from measured diffusivities and measured k-value	437.99	630.32	779.34	883.24
(J)	510.99	855.43	914.87	1059.88
	681.31	921.23	1237.77	1324.85

With this calculated data again the amount of heat needed to heat up the sample from 15 to 30 °C, is determined. Again the assumption is done that the samples reach completely 30 °C. The amount of latent absorbed heat is calculated by the different amount of the C_p per degree between the C_p from 15 to 20 °C and from 20 to 30 °C. From the factory data a maximal amount of latent heat can be calculated for the sample and this result in a percentage of stored heat.

Table 15: calculation results for the different samples

	15 to 20 °C	20 to 30 °C	Part which is latently absorbed (J)	Effective percentage of max amount of latent heat (%)
	(J)	(J)		
BASF 5%	2154.24	5026.55	718.08	32.47
BASF 10%	2910.11	7898.86	2078.65	46.99
salca 5%	3909.54	9178.91	1359.84	32.79
salca 10%	4188.79	10053.10	1675.52	20.20

In this table can be seen that during the sinus measurements where the temperatures are lower through the sample, just a small amount of the latent storage capacity is used to reach a lower temperature. This again gives an explanation of the temperature measurements between the 30 °C and 50 °C.

7. Conclusions

During this study the influence of PCM as an addition to structural concrete is investigated for the thermal and structural properties.

The goal of this thesis is to get insight in how to use the PCM into the concrete as effectively as possible. What are the advantages and what are the drawbacks.

The study is divided into two parts the strength and the thermal properties.

What is the effect on the mechanical strength?

After executing the prism and cube tests the following conclusions can be drawn:

- The addition of 5 Vol.% of PCM to the prisms reduces the compressive strength of BASF with about 14 MPa which is 30% of its original strength and 24 MPa for Salca which is about 50%.
- With more than 10 Vol.% of PCM added the workability has to be improved by additional plasticizers.
- The two layer concrete cubes show a reduction of 6 MPa for Salca and 6.5 MPa for the samples with BASF when 10 Vol.% of PCM is added to the first 5 cm of the cube. This resulted in a decrease of one strength class when added 10 vol% to the first 5 cm of a cube.
- During the prism test the samples with BASF performs better but with the cubes the Salca PCM performs slightly better when looking at the mean values.
- Salca tends to break apart during mixing, which means the salt could interrupt the hydration process of the concrete.

In general the strength is reduced by the addition of PCM. By careful mixing the broken shells can be reduced what improves the strength of the mixture. Especially with PCM made from salt hydrate, it is important to prevent the salt from being released into the concrete during hydration.

The dual layer concrete elements are an interesting compromise between improvement of the thermal properties and the reduction of strength.

What is the thermal effect of the mixture?

Two tests are performed. First the determination of the diffusivity

- The thermal diffusivity does not react as expected. The calculated diffusivity is still similar above the melting point as during the melting point.
- Reasons for the diffusivity
 - Moisture influences the conductivity and therefore the thermal diffusivity. It is slightly reduced over the different temperature ranges. With 5 degrees difference the diffusivity can be changed with $1 \cdot 10^{-7} \text{ m}^2/\text{s}$.
 - During the higher temperatures between 30 and 50 degrees Celsius the melting process of PCM is still working. Not all PCMs were melted when the measurements started.

- The description of the mixture by its combined thermal diffusivity is not suited to completely describe the behavior of the PCM-concrete because of the complex melting trajectory of the PCM.

The day simulation

- With the addition of PCM, the surface temperature decreases with 0.1 to 1 °C. Only exception is the Salca samples with 10 Vol.% which rises 0.2 °C. The exception is the cause of bad distributed PCM over the concrete.
- Most samples absorb and release more heat during the 24 hours than the samples without PCM. Salca samples with 5 Vol.% are the exception due to the high melting temperature. The most heat is absorbed by the lightweight concrete version.
- BASF and the lightweight aggregate perform better because of their lower melting temperature. The period in which the temperature exceeds the 28 °C is very short. Therefore just a little amount of heat is stored by latent heat.

Because during the higher temperature measurements the PCMs are still melting it is clear the melting temperature of the PCM should go down to use more of its latent storage capacity. The sinus measurements also show better performance of the PCM with the lowest melting temperature.

8. Discussion/advice

After performing several tests and some basic simulations some important points became clear.

- The shells of encapsulated PCM should be stronger
- Quicker heat entrance to the wall
- Further research should be done in simulation possibilities
- Implementation in active systems like HVAC.

Encapsulation of the shells

The shells of encapsulated PCM tend to break during the mixing procedure of the concrete. Also cases are known in which the shells just dissolves in the base environment. Since the sand particles are replaced by the PCM particles, the structural capability of the concrete is reduced, and this could be partly solved by stronger capsules.

Heat entrance to the wall

For maximum efficiency as explained in the theory of chapter 8, it is important to lead the heat as quickly as possible to the PCM. Therefore the heat entrance and the heat distribution, thermal diffusivity, should be as high as possible. Since the specific heat should be as high as possible, the conductivity should be high too. This allows heat to enter or leave the wall rapidly although a lot of heat is also captured during its way through the concrete.

Further research in simulation

To give a good advice about the advances of the added PCM to the concrete, more insight should be gained about the influencing factors for the efficiency of concrete. Little is known about the influence of several factors. If then the PCM can be easily added to the simulation of a building to predict its advantages, the possibility of using it on a large scale becomes more and more and option.

PCM implementation in active systems

In this research the PCM is implemented in the room to control it passively. But because of the greater possibilities in HVAC installations, it would be more desirable to use the PCMs in active manner. More heat can be stored in PCM in comparison with water, when placed in the same size container by making use of the right temperature and PCM. Also the interaction-problems with surrounding materials are not present and give more freedom in choosing the ideal PCM.

In general the PCM is a promising material what has a lot of potential in the built environment. For passive use it is interesting because it stores heat for later use instead of blocking it and consider it lost. But to use it to the full potential in structural concrete, it should be encapsulated in smarter capsules, which enlarge the heat flow to the PCM. The option of using it in an active HVAC system is much easier to implement in today's buildings and could result in greater efficiency.

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Annex 1: Possible PCMs with pro and contra's

Organic materials within the temperature range of 15 to 30 °C.

Compound	Melting temperature °C	Heat of fusion kJ/kg	Thermal conductivity		Density (kg/m ³)	
			<i>Solid</i>	<i>Liquid</i>	<i>Solid</i>	<i>Liquid</i>
<i>Paraffins</i>						
Dimethyl-sulfoxide (DMS)	16,5	85,7	n.a.	n.a.	1009	1009
Paraffin C16-C18	20-22	152	n.a.	n.a.	n.a.	n.a.
Polyglycol E600	22	127,4	0,189	0,187	1232	1126
Paraffin C13-C24	22-24	189	0,21	n.a.	900	760
1-dodecanol	26	200	n.a.	n.a.	n.a.	n.a.
Paraffin C18	28	244	0,358	0,148	814	774
1-tetradecanol	38	205	n.a.	n.a.	n.a.	n.a.
<i>Non-paraffins</i>						
Isopropyl stearate	14 – 18	140 – 142	n.a.	n.a.	n.a.	n.a.
Caprylic acid	16	148,5	n.a.	0,149	n.a.	901
Acetic acid (CH ₃ COOH)	16,7	184	n.a.	n.a.	n.a.	n.a.
Glycerin	17,9	198,7	n.a.	n.a.	n.a.	n.a.
Butyl stearate	19	140, 123 - 200	n.a.	n.a.	n.a.	n.a.
Dimethyl sabacate	21	120 – 135	n.a.	n.a.	n.a.	n.a.
Lactic acid	26	184	n.a.	n.a.	n.a.	n.a.
Vinyl stearate	27 – 29	122	n.a.	n.a.	n.a.	n.a.
Methyl palmitate	29	205	n.a.	n.a.	n.a.	n.a.
Capric acid	32	152,7	n.a.	0,153	1004	878

Inorganic materials within the temperature range of 15 to 30 °C.

Compound	Melting temperature	Heat of fusion	Thermal conductivity		Density	
			<i>Solid</i>	<i>Liquid</i>	<i>Solid</i>	<i>Liquid</i>
NaOH. 3,5H ₂ O	15	n.a.	n.a.	n.a.	n.a.	n.a.
Na ₂ CrO ₄ .10H ₂ O	18	n.a.	n.a.	n.a.	n.a.	n.a.
KF.4H ₂ O	18,5	231	n.a.	n.a.	1455	1447
Mn(NO ₃) ₂ .6H ₂ O	25,8	125,9	n.a.	n.a.	1795	1738
FeBr ₃ .6H ₂ O	27	105	n.a.	n.a.	n.a.	n.a.
CaCl ₂ .6H ₂ O	29-30	171 – 192	0,561	1,088	1802	1562
LiNO ₃ .3H ₂ O	30	296	n.a.	n.a.	n.a.	n.a.
Na ₂ SO ₄ .10H ₂ O	32	254	0,544	n.a.	1485	1458
Na ₂ CO ₃ .10H ₂ O	33	251,1	n.a.	n.a.	1442	n.a.
KFe(SO ₄) ₂ .12H ₂ O	33					
CaBr ₂ .6H ₂ O	34	115,5	n.a.	n.a.	2194	1956
LiBr ₂ .2H ₂ O	34	124	n.a.	n.a.	n.a.	n.a.
Na ₂ HPO ₄ .12H ₂ O	35,5	265 - 281	n.a.	n.a.	1522	n.a.

Eutectic materials within the temperature range of 15 to 30 °C.

Compound	Melting temperature	Heat of fusion	Thermal conductivity		Density	
			Solid	Liquid	Solid	Liquid
Capric-lauric acid (65-35%)	18	148	n.a.	n.a.	n.a.	n.a.
Capric-lauric acid (45-55%)	21	143	n.a.	n.a.	n.a.	n.a.
34% Mistriric acid + 66% capric acid	24	147,7	n.a.	0,164	1018	888
66,6% CaCl ₂ .6H ₂ O + 33,3% MgCl ₂ .6 H ₂ O	25	127	n.a.	n.a.	1590	n.a.
48% CaCl ₂ + 4,3% NaCl + 0,4% KCl + 47,3% H ₂ O	26,8	188	n.a.	n.a.	1640	n.a.
50% CH ₃ CONH ₂ + 50% NH ₂ CONH ₂	27	163	n.a.	n.a.	n.a.	n.a.
62,5% triethylolethane + 37,5% urea	29,8	218	n.a.	n.a.	n.a.	n.a.
67% Ca(NO ₃) ₂ .4H ₂ O + 33% Mg(NO ₃) ₂ .6H ₂ O	30	136	n.a.	n.a.	n.a.	n.a.
60% Na(CH ₃ COO).3 H ₂ O + 40%CO(NH ₂) ₂	31,5	226	n.a.	n.a.	n.a.	n.a.

The advantages and disadvantages of the different groups of materials of PCM.

Advantages	Disadvantages
<ul style="list-style-type: none"> -Freezing without much super cooling -Ability to melt congruently -Self nucleating properties -Compatibility with conventional material of construction -No segregation -Chemically stable -High heat of fusion -Safe and non-reactive -Recyclable 	<ul style="list-style-type: none"> - Low thermal conductivity when solid - Volumetric latent heat storage capacity is low - Flammable
Advantages	Disadvantages
<ul style="list-style-type: none"> -High volumetric latent heat storage capacity -Sharp melting point -High thermal conductivity -High heat of fusion -Non-flammable 	<ul style="list-style-type: none"> -Change of volume is very high -Super cooling is major problem in solid-liquid transition -Nucleating agents are needed and they often become inoperative after repeated cycling
Advantages	Disadvantages
<ul style="list-style-type: none"> -Eutectics have sharp melting point similar to pure substance -Volumetric storage density is slightly above organic compounds 	<ul style="list-style-type: none"> -Only limited data is available on thermo physical properties as the use of these materials are very new to thermal storage application

Annex 2: Materials used in tests


Cement

The cement that is used is standard Portland cement from the ENCI. The following figure is from the producer of the cement.

Portlandcement

CEM I

CEM I
EN12007



Productomschrijving
Portlandcement is een grijs cement dat verkregen wordt door het malen van de hoofdcomponent portlandcementklinker. In functie van een bepaalde maalbaarheid wordt een cement vervaardigd in de sterkteklassen 42,5 of 52,5. Afhankelijk van de sterkteklasse wordt dit cement gekenmerkt als een cement met een normale of hoge beginsterkte. Portlandcement CEM I voldoet aan de eisen zoals gesteld in de Europese cementnorm EN 197-1, inclusief wijzigingsblad A1. Deze norm geeft eisen ten aanzien van de samenstelling op bestanddelen, chemische eisen, mechanische en fysieke eisen.

Samenstelling
De eisen aan de samenstelling zijn uitgedrukt in procenten ten opzichte van de som van alle hoofd- en nevenbestanddelen. Dit totaal wordt nog vermeerderd met het nodige calciumsulfaat om het bindingsgedrag te regelen.



Cementsoort	Hoofbestanddelen (in massa %)	Nevenbestanddelen (in massa %)
	resterende (max. %)	
CEM I	95 - 100	
	0 - 5	

Mechanische en fysieke eisen
De sterkteklasse van een cement bepaalt de minimale druksterkte gemeten na 28 dagen op normprisma's. Voor elke normsterkteklasse zijn twee beginsterkteklassen opgenomen, een klasse met normale beginsterkte aangeduid met N en een klasse met een hoge beginsterkte aangeduid met R.
Het begin van de binding is een maat voor het opstijfgedrag van een cementpasta. Aan de eis van vormhoudendheid moet worden voldaan om aan te tonen dat een cementpasta niet gevoelig is voor expansie.

Sterkteklasse	Druksterkte in MPa				Begin van de binding (min.)	Vormhoudendheid (mm)
	Beginsterkte		Normsterkte			
	> 0 dagen	> 0 dagen	> 0 dagen	> 0 dagen		
42,5 N	≥ 10,0	–	≥ 42,5	≤ 62,5	≥ 60	–
52,5 N	≥ 20,0	–	≥ 52,5	–	≥ 45	≤ 10
52,5 R	≥ 30,0	–	–	–	–	–

ENCI
Technische Voorlichting
Postbus 3233
5203 DE 's-Hertogenbosch
Tel: 073 640 12 20
Fax: 073 640 12 18
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CBR Cementbedrijven
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Fax: 02 675 23 91
communication@cbt.be
www.cbt.be

Speciale eigenschappen

Cement dat voldoet aan de in EN 197-1 gestelde eisen is voorzien van een CE-markering. Daarnaast kan cement nog gecertificeerd worden op een aantal andere specifieke eigenschappen. Deze eigenschappen komen tot uiting in de naamgeving van het cement. De naamgeving is afhankelijk van de norm op basis waarvan de speciale eigenschap is gecertificeerd. CBR en ENCI brengen de volgende typen portlandcement CEM I op de markt:

- CEM I 42,5 N;
- CEM I 52,5 N;
- CEM I 52,5 R;
- CEM I 52,5 R HES;
- CEM I 52,5 R LA.

Portlandcement CEM I is leverbaar met de volgende certificaten:

Type cement	Certificaat		
	CE EN 197-1	ROMO NEN 3088	BDNR 77V 001
CEM I 42,5 N	*	*	
CEM I 52,5 N	*	*	*
CEM I 52,5 R	*	*	
CEM I 52,5 R HES	*		*
CEM I 52,5 R LA	*		*

Betekenis van de naamgeving:

Naamgeving	Betekenis	De	Norm
HES	Hoge aanvangsterkte	Bijkomende eis druksterkte op één dag ≥ 20 MPa	NEN B 12 - 110
LA	Begrensd alkaligehalte	Gehalte aan alkaliën uitgedrukt als $\text{Na}_2\text{O-eq} < 0,60$ (in massa %)	NEN B 12 - 109

Toepassingsgebied

Dit cement wordt toegepast bij het fabriceren van betonproducten en in sommige gevallen ook in stortklaar beton wanneer het zeer kort na het storten ontkt moet worden. In stortklaar beton kan dit cement bij koud weer ook gebruikt worden in combinatie met of ter vervanging van een hoogovencement om een voldoende sterkteontwikkeling te verkrijgen. Door het begrensd alkaligehalte is het cement van het type LA geschikt voor het gebruik met alle traditionele granulaten zonder risico voor een reactie tussen de alkaliën in het cement en de granulaten (ASR). Voor een optimaal resultaat bij het gebruik van dit cement in mortel of beton, moeten in elk geval de gangbare regels bij het aanmaken, het verwerken en de nazorg in acht genomen worden.



Aanvullende informatie

De in dit productblad gegeven informatie is zeer algemeen en bevat de minimale eisen waaraan het cement volgens de relevante normen moet voldoen. CBR en ENCI produceren de in dit productblad beschreven cementen op verschillende locaties. Op aanvraag zijn er, per cementtype en per fabriek, aanvullende informatiebladen beschikbaar bij de vermelde adressen.

PCMs

Two encapsulated Phase Change Materials are chosen. This is one from Basf and one from Salca. Figure 58 shows the information about the PCM from Basf. DS 5001 is the used PCM in this research.

Product designation	Product type	Melting point approx.	Application	Operational range	Overall storage capacity approx.	Latent heat capacity approx.	Solid content	Density	Apparent density	Visc.
DS 5000	Dispersion	26°C	Summertime excessive heating protection	10–30°C	59 kJ/kg	45 kJ/kg	Approx 42%	Approx 0,98		Approx 200–600 mPas
DS 5007	Dispersion	23°C	Stabilisation of the indoor temperature in the comfort zone Passive and active application	10–30°C	55 kJ/kg	41 kJ/kg	Approx 42%	Approx 0,98		Approx 200–600 mPas
DS 5030	Dispersion	21°C	Surface cooling systems	10–30°C	51 kJ/kg	37 kJ/kg	Approx 42%	Approx 0,98		Approx 200–600 mPas
DS 5001	Pulver	26°C	Summertime excessive heating protection	10–30°C	145 kJ/kg	110 kJ/kg	In powder form		Approx 250–350 kg/m ³	
DS 5008	Pulver	23°C	Stabilisation of the indoor temperature in the comfort zone Passive and active application	10–30°C	135 kJ/kg	100 kJ/kg	In powder form		Approx 250–350 kg/m ³	
DS 5029	Pulver	21°C	Surface cooling systems	10–30°C	125 kJ/kg	90 kJ/kg	In powder form		Approx 250–350 kg/m ³	

Figure 58: BASF PCM information

The PCM from Salca is made from Salt hydrates. The used PCM is Thermusol HD28SE. Information about this PCM is found in the following figure.


 THERMUSOL® HD28SE MICRO ENCAPSULATED SALT-HYDRATES	
Physical Properties	
Physical form	Fire resistant white powder
Density	1,5 kg/L
Bulk density	0,90 kg/L
Heat storage temperature range	T _m 20°C-30°C; T _c 20°C (isotherm 120 min.)
Latent heat storage capacity	110 kJ/kg
Volumetric latent heat storage capacity	165 kJ/L
Specific heat capacity	2,0 kJ/kg.K
Particle size	50-500 µm
Mechanical Strength	3
Oven Test (24 hours 50°C)	Passed
Water Resistance Test	Passed

Figure 59: Specification sheet of the PCM from Salca

Lightweight aggregate

Information about the lightweight aggregate is found in the following data sheet.

Product data sheet

Type	Liapor 4,5																													
General properties Type of material Shape	Expanded clay spherical																													
Geometrical properties Aggregate size Fines (< 0,063 mm)	2/10 < 1,5	mm M.-%																												
Physical properties Loose bulk density Particle density Water absorption w_{30} Water absorption w_{50} Crushing resistance Freezing and thawing resistance	450 ± 25 840 ± 50 10 ± 4 15 ± 4 > 3,0 < 2,0	kg/m ³ kg/m ³ M.-% M.-% N/mm ² M.-%																												
Chemical properties Chloride Acid-soluble sulfur Total sulfur	< 0,02 < 0,8 < 1,0	M.-% M.-% M.-%																												
Chemical composition SiO ₂ Al ₂ O ₃ Fe ₂ O ₃ CaO Trace elements	55 ± 5 24 ± 5 14 ± 5 5 ± 5 2 ± 2	% % % % %																												
Other Properties Thermal conductivity λ_R Fire resistance	n.n. A1 (DIN 4102)	W/(mK)																												
Grading (annual production statistics 2006)																														
<table border="1"> <caption>Approximate data points from the grading curve graph</caption> <thead> <tr> <th>Siebweite [mm]</th> <th>Mittelwert [M.-%]</th> <th>5% - Fraktile [M.-%]</th> <th>95% - Fraktile [M.-%]</th> </tr> </thead> <tbody> <tr> <td>0</td> <td>0</td> <td>0</td> <td>0</td> </tr> <tr> <td>2</td> <td>0</td> <td>0</td> <td>0</td> </tr> <tr> <td>4</td> <td>15</td> <td>5</td> <td>25</td> </tr> <tr> <td>6</td> <td>55</td> <td>35</td> <td>75</td> </tr> <tr> <td>8</td> <td>90</td> <td>85</td> <td>95</td> </tr> <tr> <td>10</td> <td>100</td> <td>100</td> <td>100</td> </tr> </tbody> </table>			Siebweite [mm]	Mittelwert [M.-%]	5% - Fraktile [M.-%]	95% - Fraktile [M.-%]	0	0	0	0	2	0	0	0	4	15	5	25	6	55	35	75	8	90	85	95	10	100	100	100
Siebweite [mm]	Mittelwert [M.-%]	5% - Fraktile [M.-%]	95% - Fraktile [M.-%]																											
0	0	0	0																											
2	0	0	0																											
4	15	5	25																											
6	55	35	75																											
8	90	85	95																											
10	100	100	100																											

Figure 60: Data sheet of the lightweight aggregate

Annex 3: Compressive/Flexure test results

The data which is collected by the Prism test and the cube test are collected here. First the prism samples and second the concrete blocks.

Salca prism's

Reference prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	6-4-11	13-4-11	40.03	40.92	160.4	581.5	2213.2	2.87	6.73	69.86	43.66
										69.5	43.44
2	6-4-11	4-5-11	40.6	40.88	160.4	578.2	2171.9	3.12	7.31	86.36	53.98
										87.62	54.76
3	6-4-11	4-5-11	40.33	40.23	160.45	573	2201.1	3.12	7.3	84.56	52.85
										85.86	53.66

3Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	28-4-11	5-5-11	40.35	41.35	160.41	549	2051.3	1.242	2.91	32.14	20.09
										34.81	21.76
2	28-4-11	26-mei	40.39	41.29	161.04	558.5	2079.6	1.831	4.29	56.83	35.52
										55.95	34.97
3	28-4-11	26-mei	40.33	41.84	160.45	559.9	2068.0	1.81	4.24	57.69	1
										52.81	33

5 vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	28-4-11	5-5-11	40.11	41.83	161.52	542.5	2001.9	1.01	2.37	28.27	-
										30.38	18.99
2	28-4-11	26-5-11	40.42	41.23	161.04	547.1	2038.6	1.432	3.36	46.52	29.08
										1	1
3	28-4-11	26-5-11	40.35	41.07	160.9	548.1	2055.6	1.715	4.02	47.53	29.7
										48.94	30.59

10 Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	28-4-11	5-5-11	40.08	41	160.51	529	2005.6	1.048	2.46	21.27	13.29
										20.57	12.85
2	28-4-11	26-5-11	40.61	41.23	160.62	535.8	1992.3	1.308	3.07	32.9	20.56
										1	1
3	28-4-11	26-5-11	40.52	41.15	160.68	533.6	1991.7	1.198	2.81	30.86	19.29
										30.7	19.19

20 Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	28-4-11	5-5-11	40.48	40.86	161.34	513.4	1923.9	0.769	1.8	14.6	9.12
										16.56	10.35
2	28-4-11	26-5-11	40.69	40.93	161.58	523.1	1943.9	0.932	2.19	14.15	8.85
										17.2	10.75
3	28-4-11	26-5-11	40.78	41.23	161.58	519.5	1912.2	0.792	1.86	18.12	11.33
										13.01	8.13

Data Basf prism's

3Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	6-apr-11	13-apr	40.07	40.54	160.23	558.6	2146.1	2.267	5.31	55.18	34.49
										53.66	33.54
2	6-apr	4-mei	40.07	40.53	160.23	560.9	2155.5	2.7	6.33	65.46	40.92
										65.85	41.16
3	6-apr	4-mei	40.25	40.14	160.31	563.7	2176.4	2.541	5.96	67.5	42.19
										67.32	42.08

5 Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	6-apr-11	13-apr	40.05	40.76	160.27	549.5	2100.2	2.183	5.12	47.8	29.88
										49.46	30.91
2	6-apr	4-mei	40.16	40.21	160.37	552	2131.5	2.403	5.63	59.41	37.13
										61.86	38.67
3	6-apr	4-mei	40.26	39.57	160.42	546	2136.5	2.446	5.73	58.93	36.83
										62.01	38.75

10 Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m ³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	6-apr-11	13-apr	40.05	40	160.38	528.9	2058.5	2.073	4.86	42.77	26.73
										42.30	26.44
2	6-apr	4-mei	40.14	40.32	160.45	534	2056.4	2.158	5.06	52.84	33.03
										53.25	33.28
3	6-apr	4-mei	40.32	39.94	160.53	531.2	2054.8	2.302	5.4	48.95	30.59
										51.24	32.03

20 Vol.% prisms											
Prism	Built	Tested	Width (mm)	Height (mm)	Length (mm)	Weight (g)	Density (kg/m³)	Tensile strength		Compressive strength	
								kN	MPa	kN	MPa
1	6-apr-11	13-apr	40.19	40.36	160.49	495.9	1904.9	1.555	3.64	30.39	18.99
										30.06	18.79
2	6-apr	4-mei	40.07	39.34	160.4	501.6	1983.8	1.788	4.19	35.92	22.45
										38.32	23.95
3	6-apr	4-mei	40.04	39.94	160.51	484	1885.6	1.348	3.16	30.09	18.81
										33.25	20.78

Results from the concrete block measurements

Sample	Depth (mm)	Width (mm)	Height (mm)	Volume (m³)	Mass (kg)	Pressure (kN)	Density (kg/m³)
B1-1	152,1	149,9	150	0,003419	8,218	1189,3	2403,7
B1-2	151,6	149,9	150,4	0,003416	8,172	1180,1	2392,1
B1-3	150,3	152,7	150	0,00344	8,216	1133,7	2388,1
Basf B2a-1	150,8	150,2	150,3	0,003404	8,106	1094,3	2381,1
Basf B2a-2	149,7	150,5	150,2	0,003384	8,061	1055,1	2382,1
Basf B2b-1	151,4	150,5	150,4	0,003427	8,124	979,8	2370,6
Basf B2b-2	150,2	150,6	150,4	0,003401	8,069	1063,5	2372,6
Salca B3a-1	151	150,5	150,4	0,003417	8,107	1137,7	2372,7
Salca B3a-2	152,3	150,5	150,2	0,003442	8,267	1165,2	2402,1
Salca B3b-1	151	150,5	150,2	0,003413	8,155	1078,7	2389,1
Salca B3b-2	150	150,1	150,3	0,003383	8,075	990,6	2387,0

Annex 4: building samples

To build samples with thermocouples on the right places a special mold is made. The basis is made of a wooden plate with a thin wooden plate with holes in it on top. These holes are made with a special round drill to ensure a perfect fitting shape. The sides are made from PVC. These pipes are available in standard measurements of \varnothing 80 mm.

These pipes are cut in parts of 10 cm which are cut in half again. Figure 61 shows the parts that are made of PVC in red. The green part is the sample with its thermocouples.

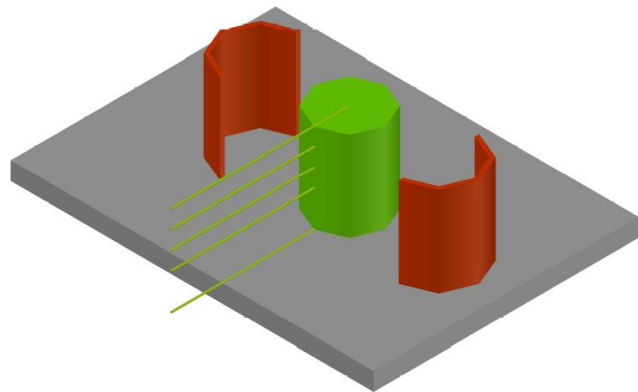


Figure 61: Exploded view of the mold

The two parts are held together by a PVC clamp which is normally used for attaching a rain pipe against a house. The PVC mold is then glued to the wooden plate where a plastic cover is placed over the basic plate.

For the placement of the thermocouples holes are drilled into the plastic mold. When a layer of concrete is casted, the thermocouple is laid on top of the concrete before a next layer of concrete is placed. In this way the sample is built.

To make sure the thermocouple does not move, on one side the couples are taped to the mold and with a very small fish line the couple is pulled to the middle of the mold. Figure 62 shows how this is done.

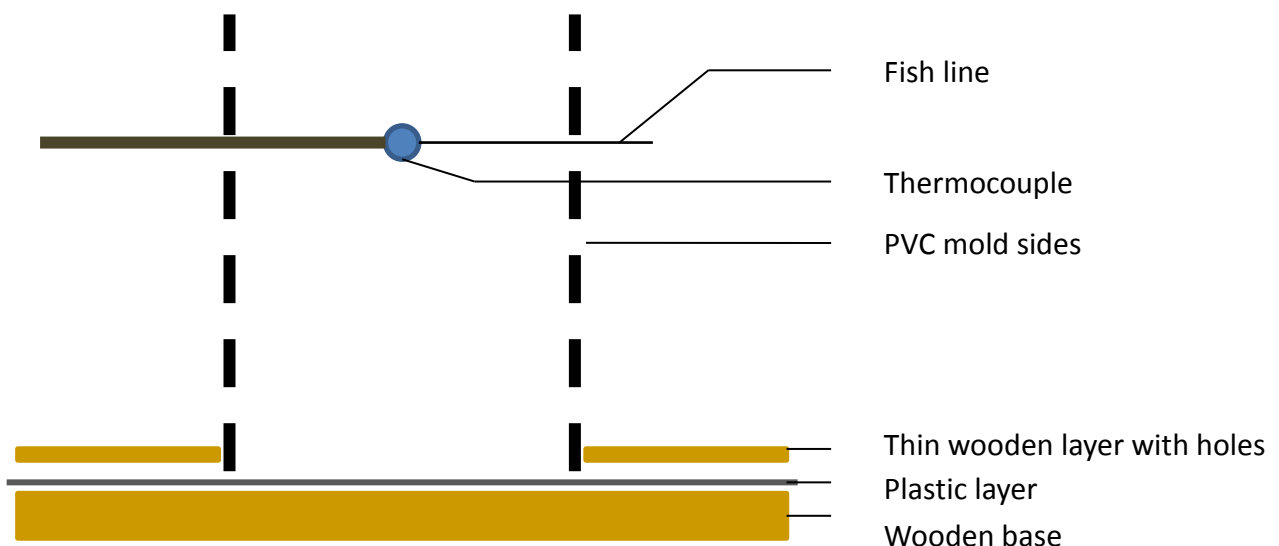


Figure 62: Section of the used mold for the samples

After the molds were filled they are placed in a room which had a constant temperature of 20 °C. The molds were covered by plastic foil to prevent too much moisture to evaporate.

Annex 5: Building of the thermal setup

In this setup is created a semi-adiabatic condition. This is done to get a very constant and predictable surrounding. With an adiabatic surrounding there is no heat loss to the surroundings and no air flow which could influence the results. To create this semi-adiabatic condition the samples are placed in a box made of styrodur. This highly isolating material has a very low k-value which means almost no heat can cross the material. Figure 63 shows the size of the box. In Figure 64 the box is opened.

From top to bottom it is a heat exchanger, heat flux measurement plates and the sample.

The heat exchanger is controlled by a Thomson heater which is shown in Figure 66. To regulate the heater, a computer is connected to the heater which controls what temperature the heat exchanger is set to.

For measurement of the thermocouple voltage a measurement device which is built at the university is used. Figure 65 shows the whole setup with the blue tower in which this device is placed. This device is connected to a computer to collect the data.

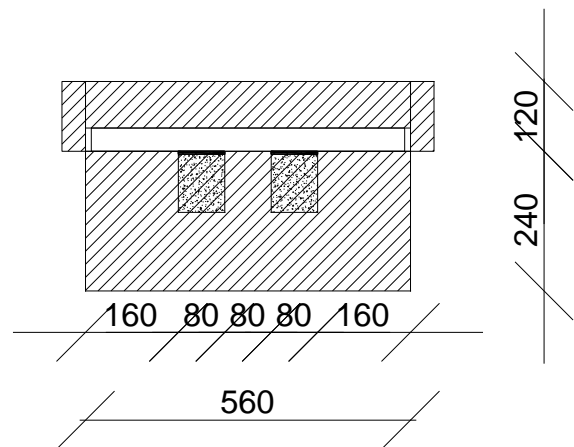


Figure 63: Section of the box with samples in it

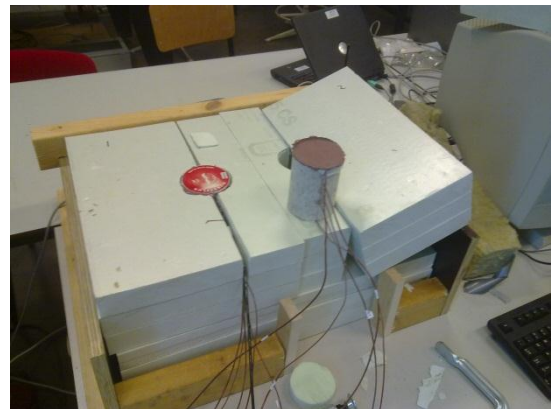


Figure 64: Created box used during measurements



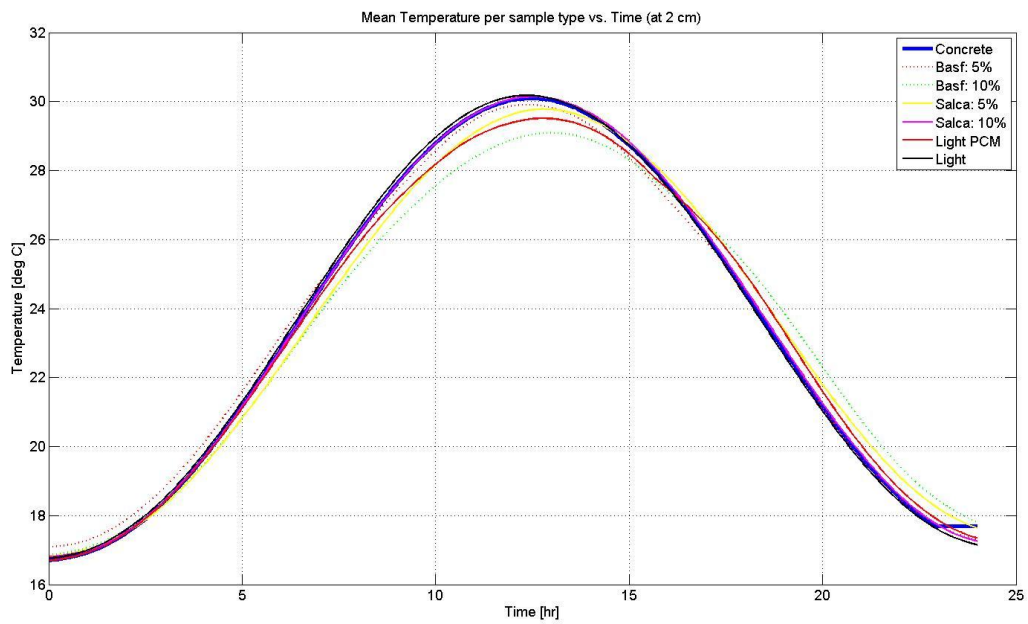
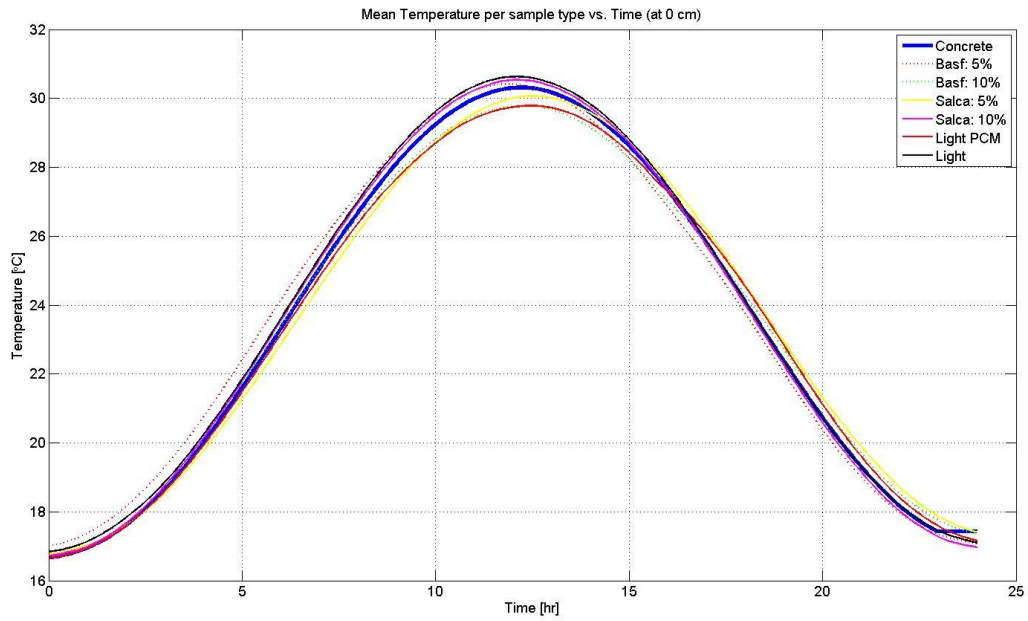
Figure 65: Complete setup as used at the university

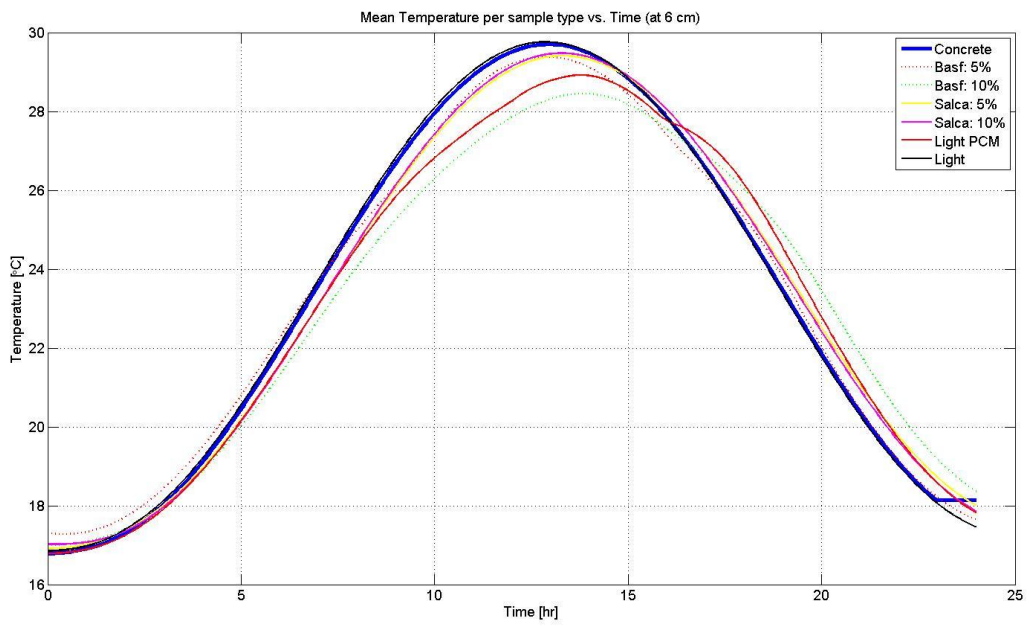
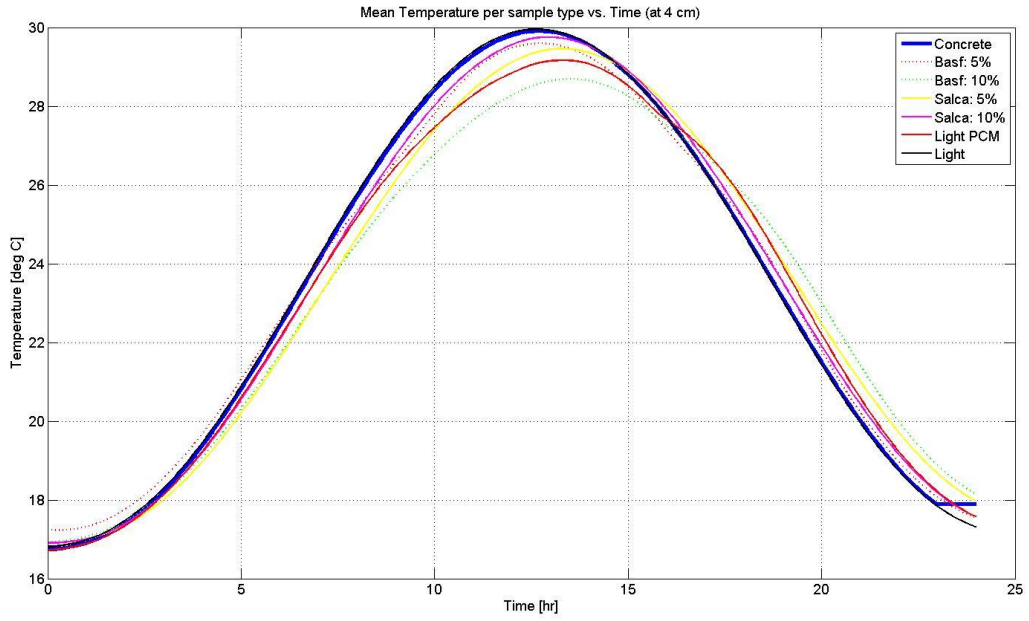


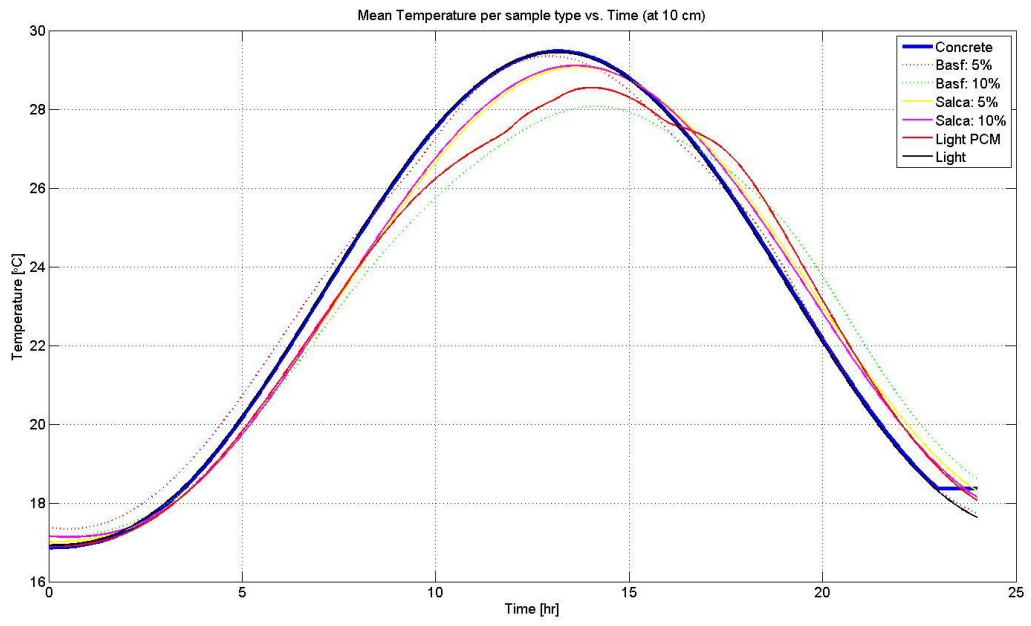
Figure 66: Thomson heat regulator

Annex 6: measurement results sinus

Mean measurement results of the different thermocouples in the samples.

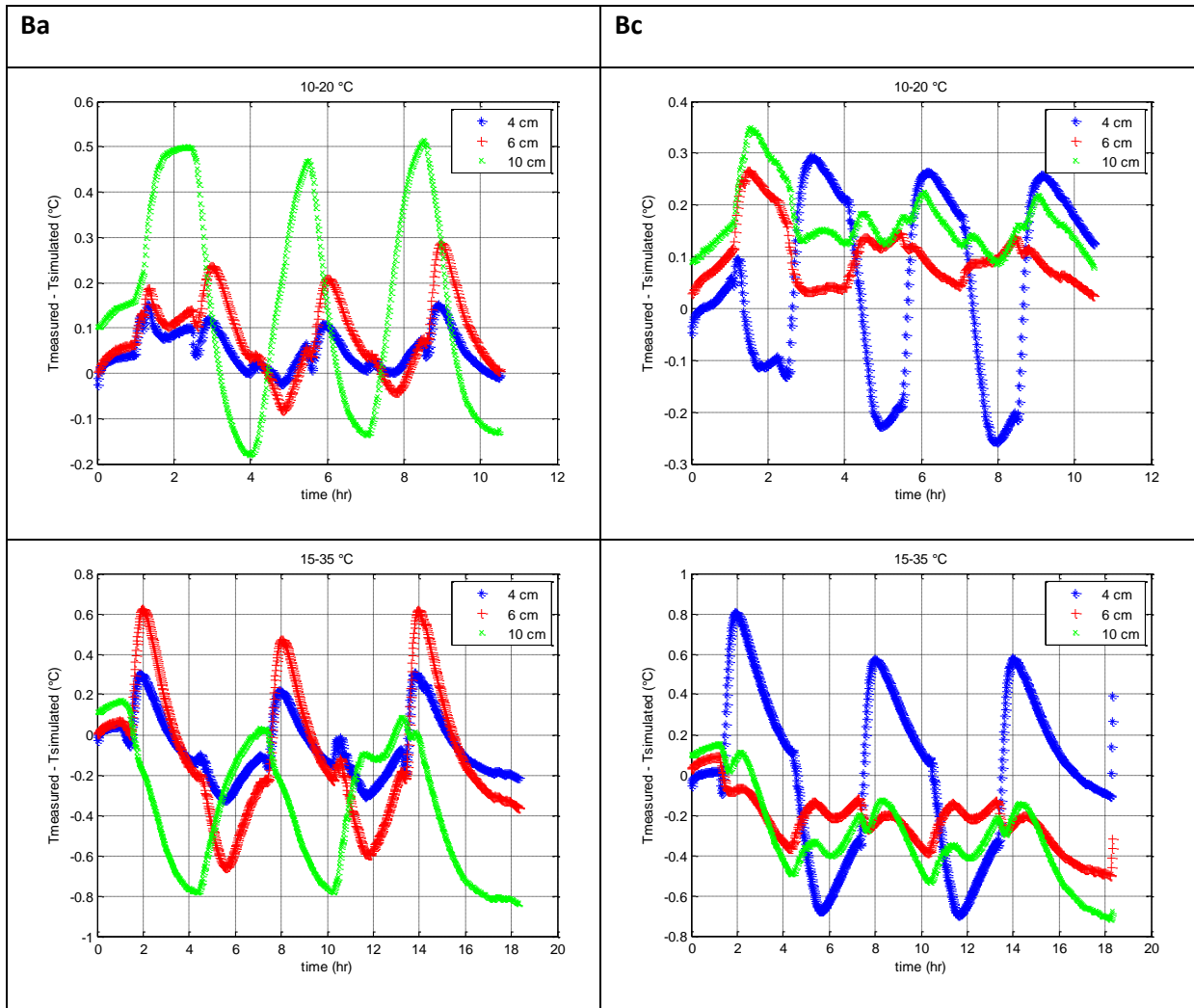




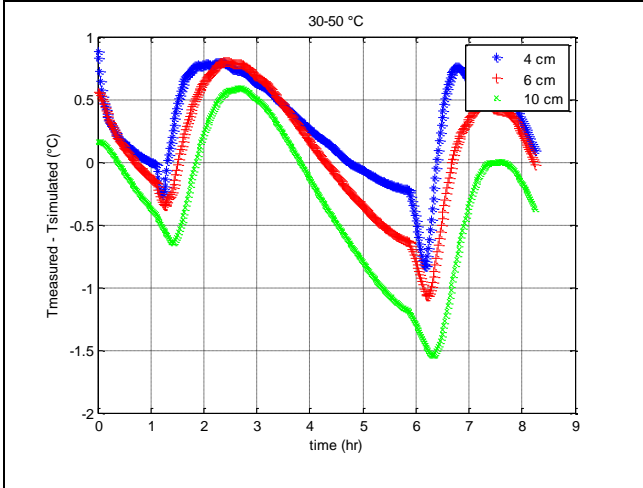
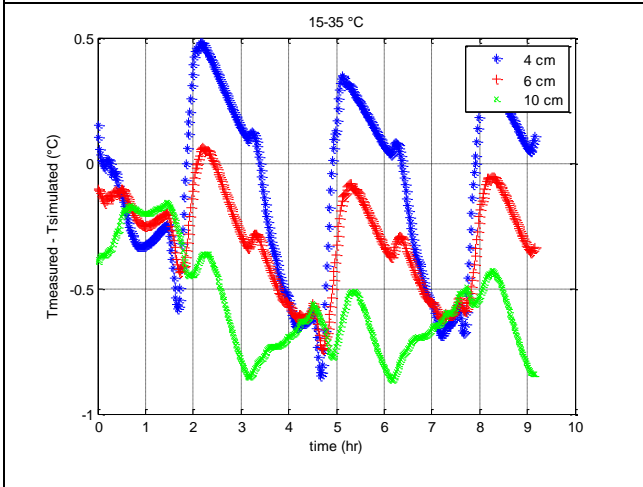
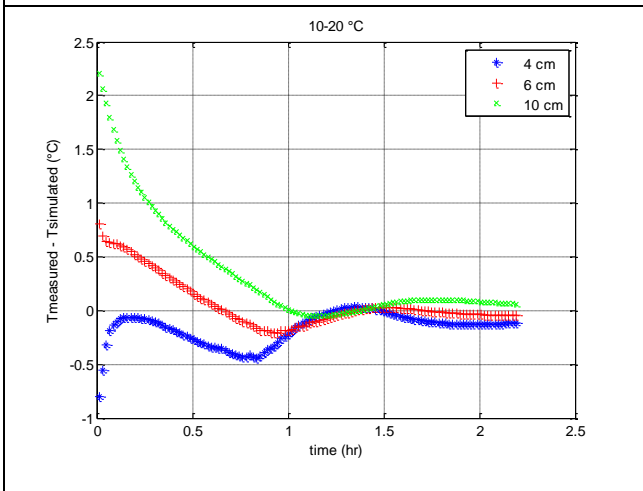


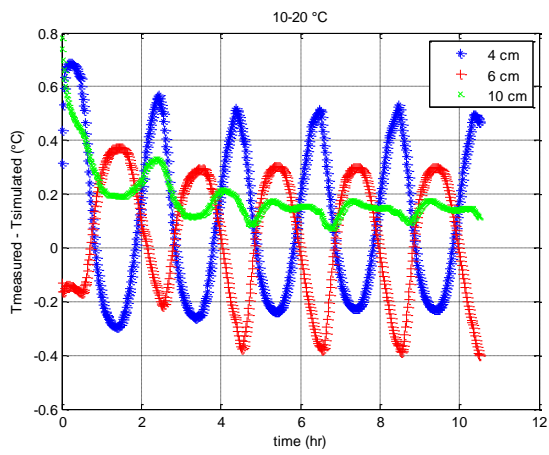
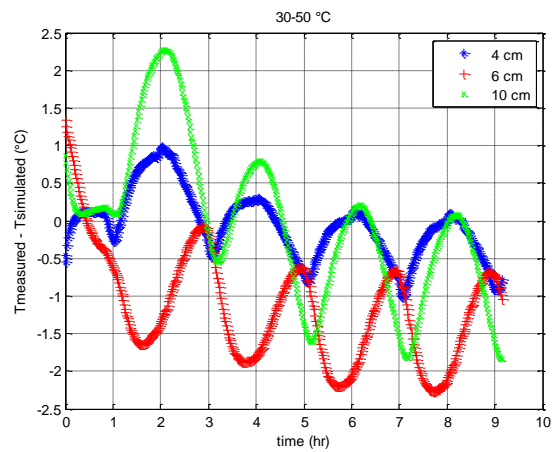
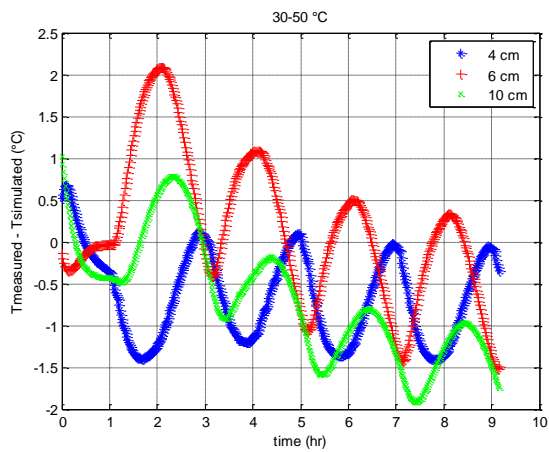
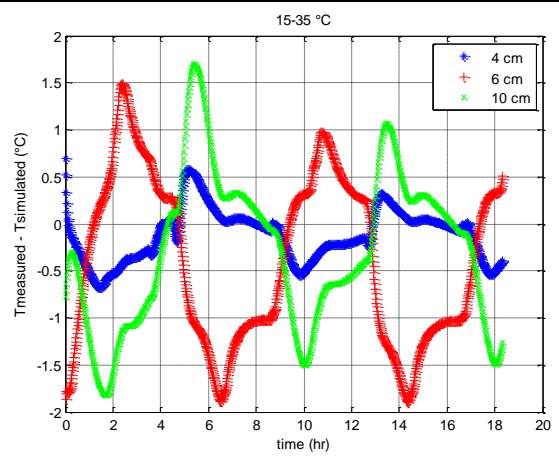
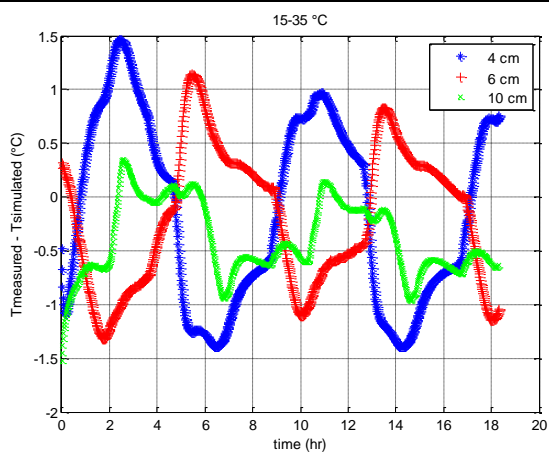
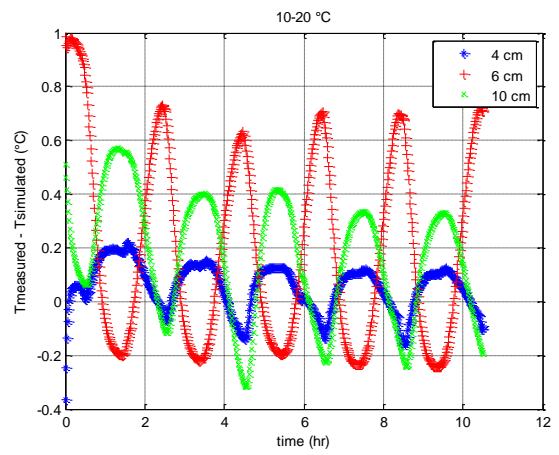
Annex 7: thermal diffusivity scatters

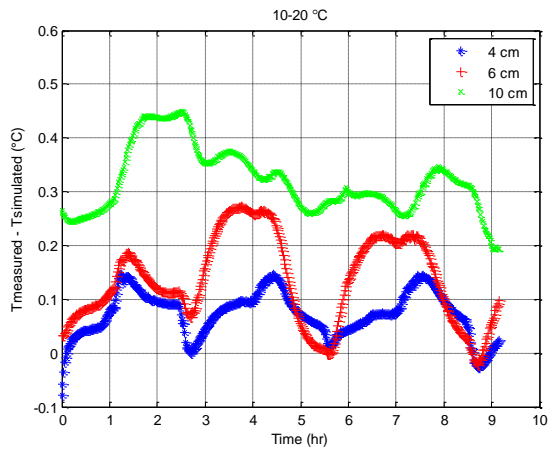
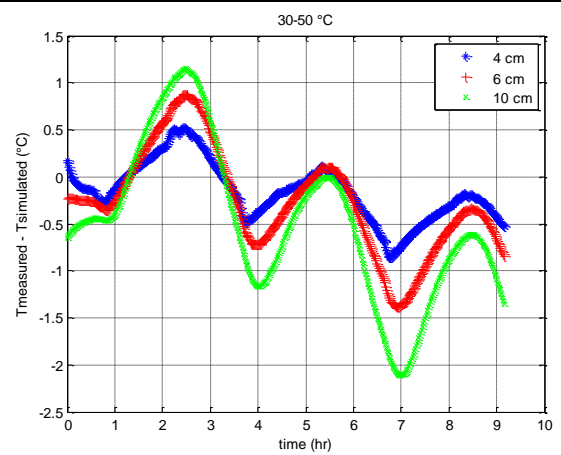
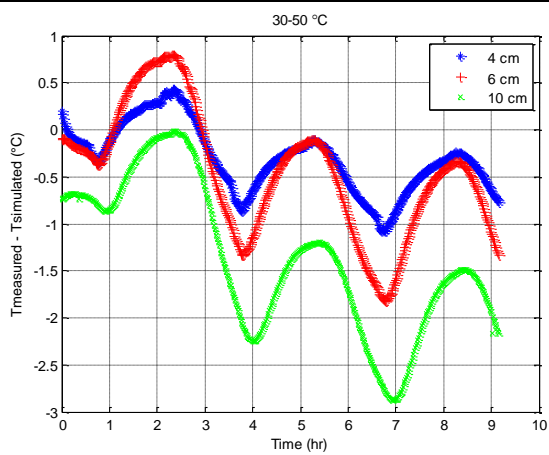
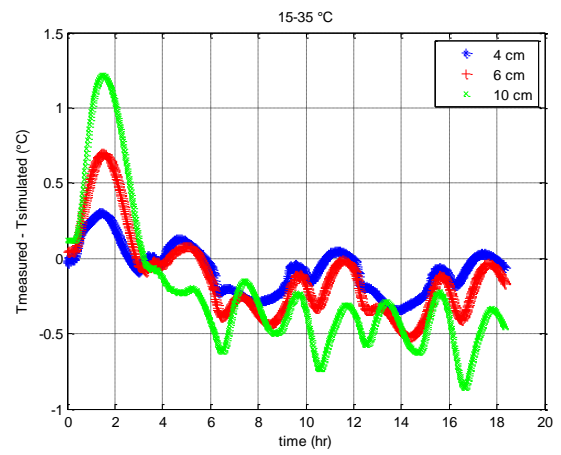
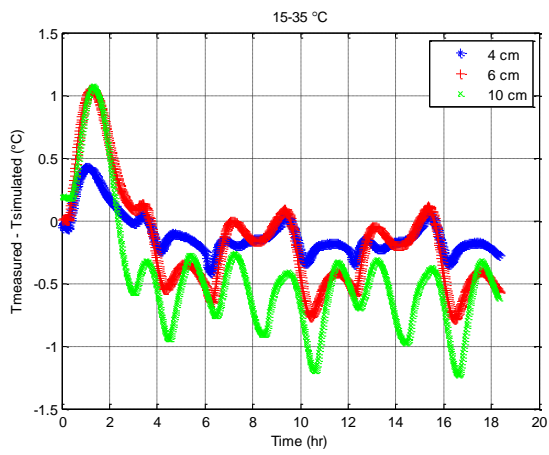
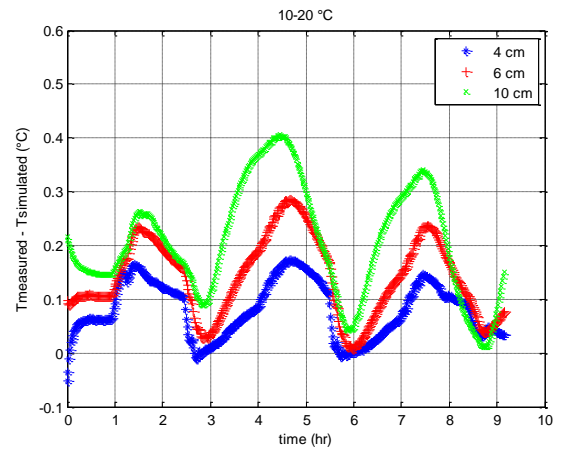
In the following graphs the differences between measurement and simulation are shown. Some data was not collected properly and is left away in this report.



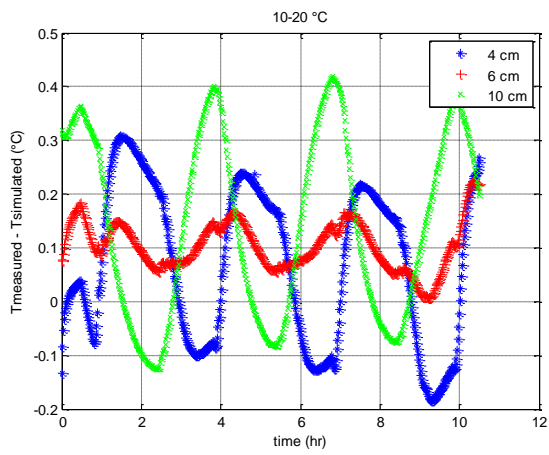
Bd



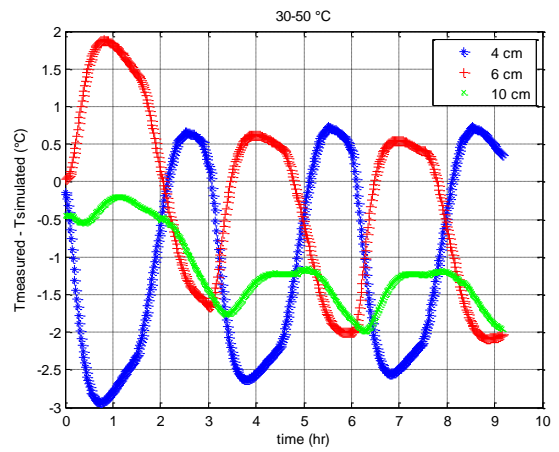
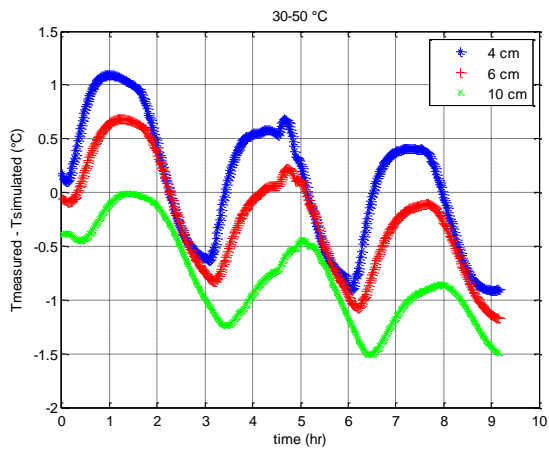
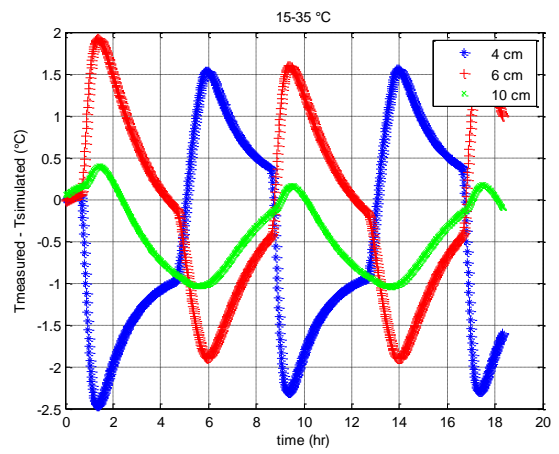
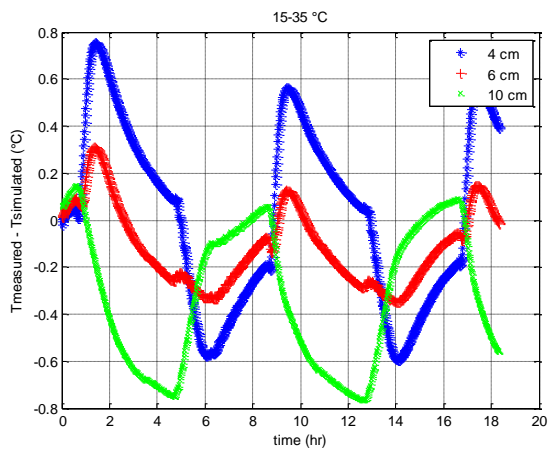
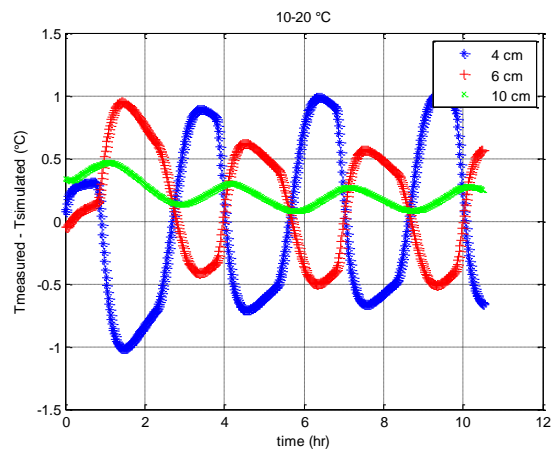
BASF 1a**BASF 1b**

BASF 2a**BASF 2b**

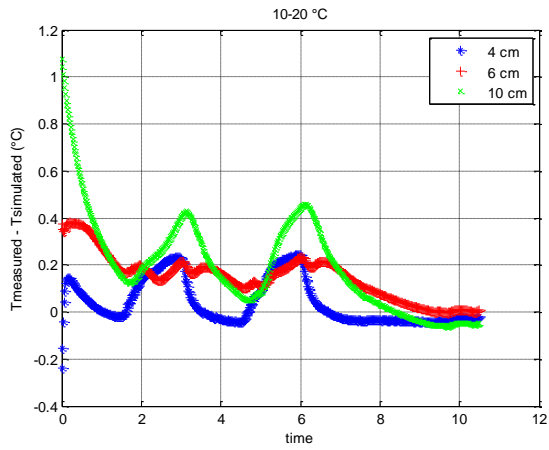
Salca 1a



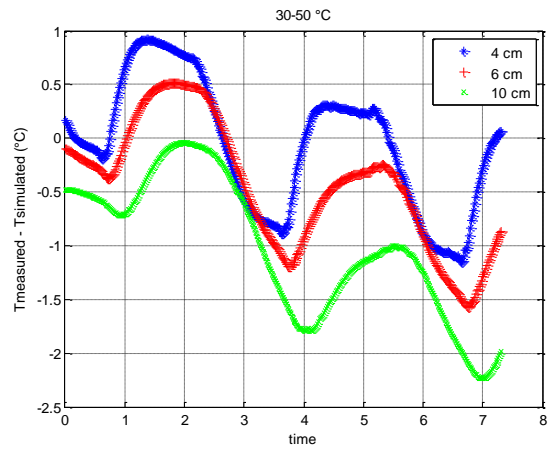
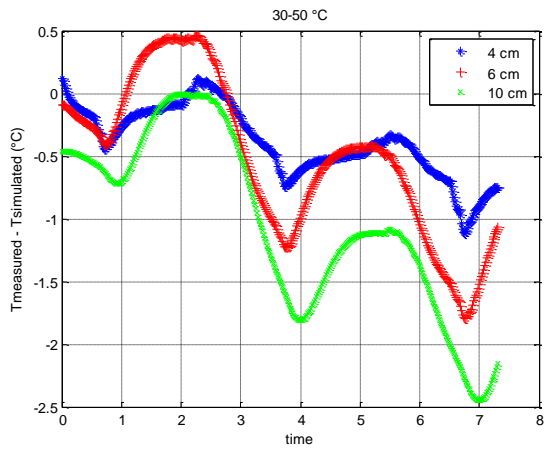
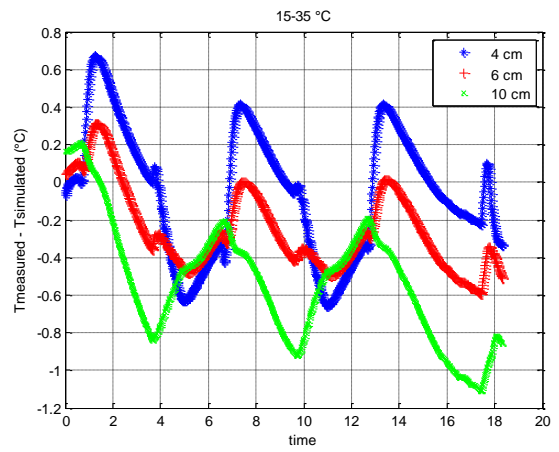
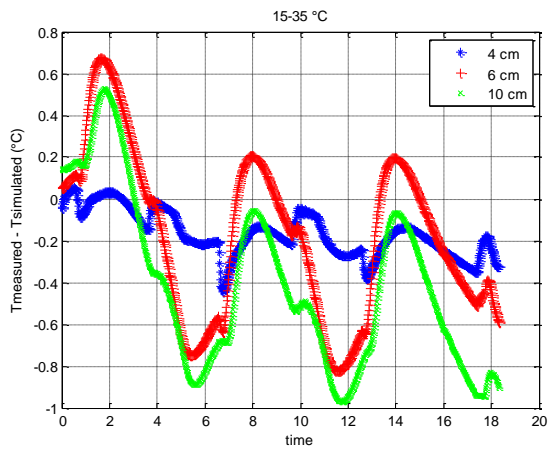
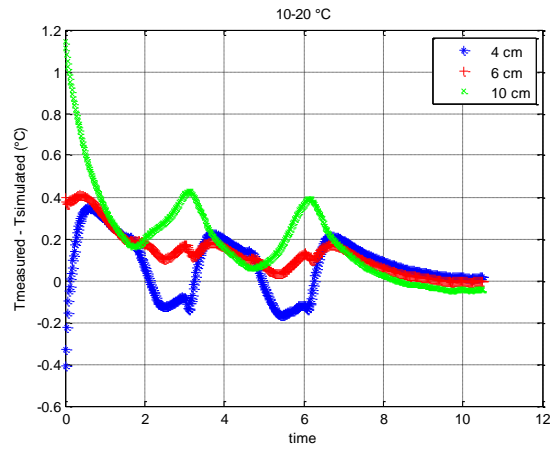
Salca 1b

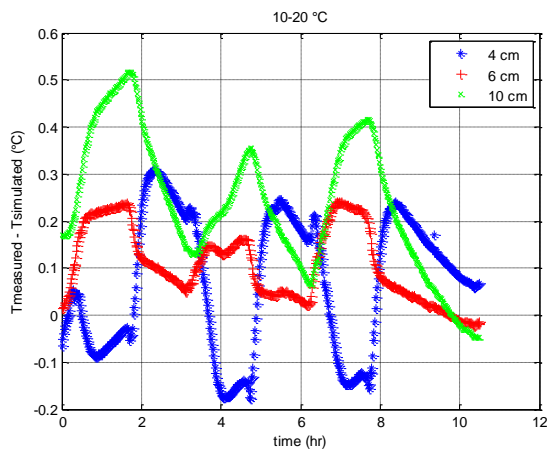
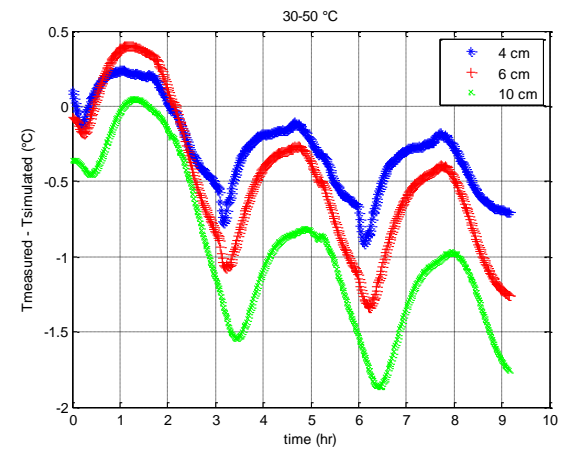
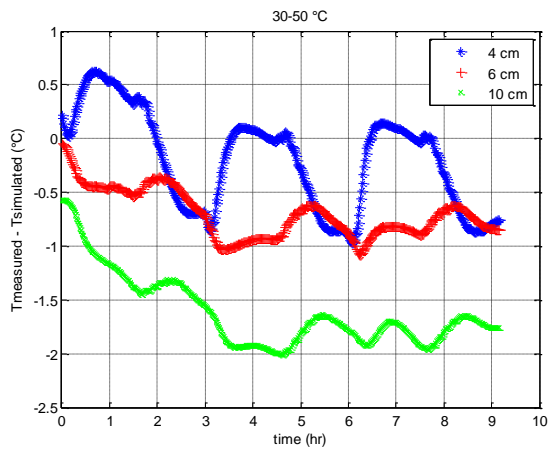
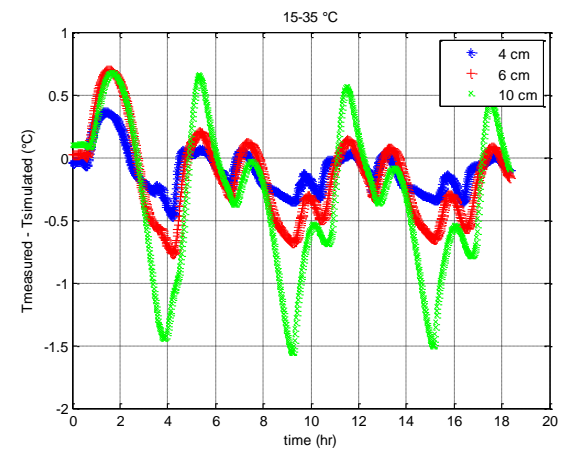
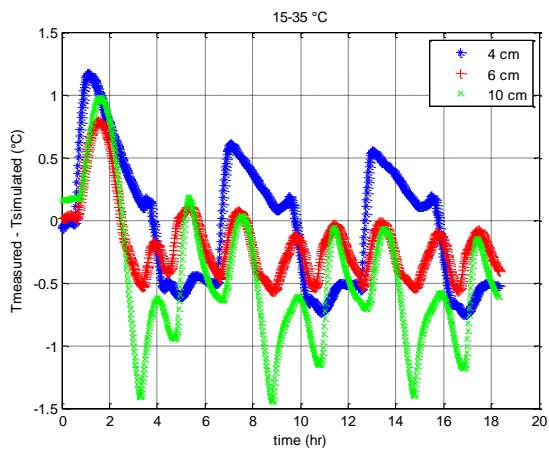
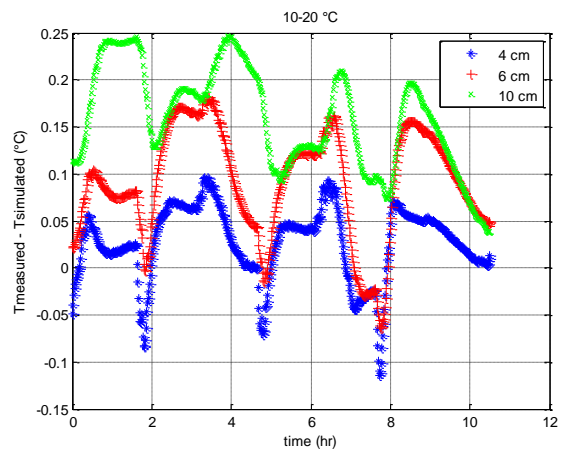


Salca 2a

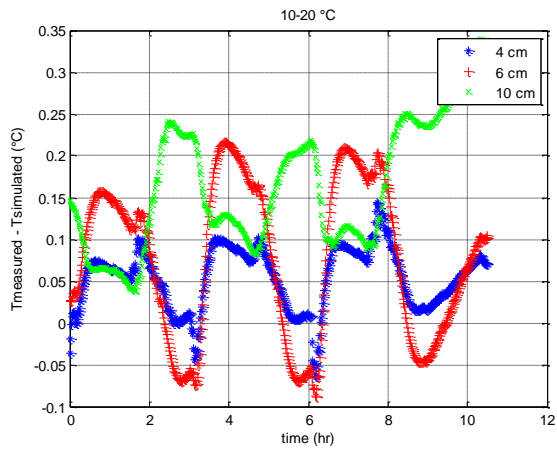


Salca 2b



LW1a**LW1b**

LW2a



LW2b

