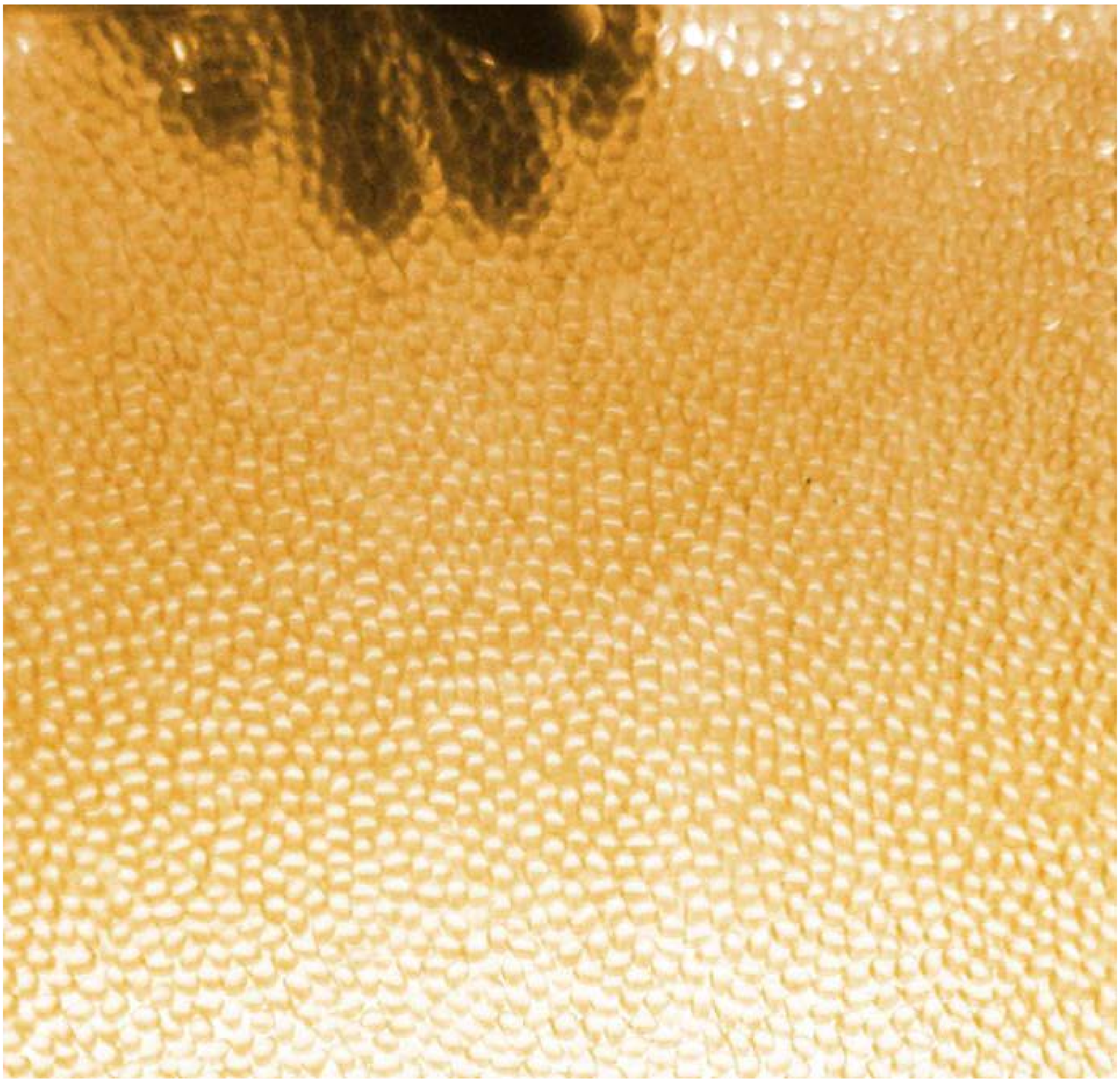
FACULTY OF ARCHITECTURE - DEPARTMENT OF BUILDING TECHNOLOGY



Research on the combination of translucent Glass Fiber Reinforced Polymers (G.F.R.P.) and Phase Change Materials (P.C.M.), for applications in architecture

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Graduation Report

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Contents

1 Introduction

PCMs

PCMs are materials that change from one state of the matter -phase (solid, liquid, gas) to another, at a temperature called Phase Change Temperature (T_{pc}) which is unique and different for each material.

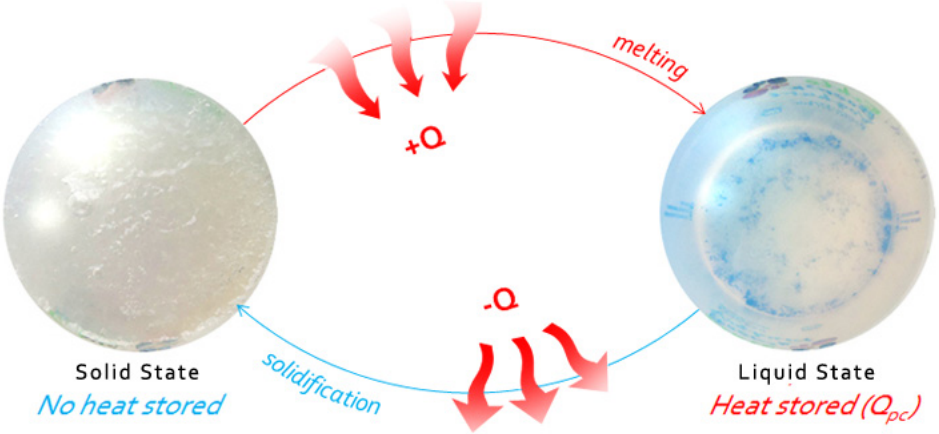

Figure 1: A PCM (Hydrated Salt, T_{pcm}=22°C) at its solid (left) and liquid (right) phase.

During the phase change process, high amounts of heat are absorbed or released from relatively small amounts of material. This fact classifies PCMs suitable for applications in fields where high heat storage demand in low mass, is required. Examples of commercial applications are: low temperature packaging, thermal protection for electronic devices, textiles for spacesuits and others.

Figure 2: Cool packaging using PCM for high storage in low weight, for transportation.
(source: left: www.techoeps.com/pcm/applications, right:www.activemsers.org/gear/testcoolingvests)

Many PCMs present different and distinct levels of translucency between their solid and molten phase. Some PCMs can turn from opaque to transparent while melting and from transparent to opaque while solidifying. A transparent PCM denotes that heat is absorbed, and an opaque PCM denotes that heat is released (Weinläder, 2004).

The most widely known natural PCM is water ($T_{pc\_liquid\text{-}solid}$=0°C and $T_{pc\_liquid\text{-}gas}$=100°C). Engineered PCMs include paraffin waxes, hydrated salts, fatty acids and others.

In modern buildings, PCMs are mainly used as a low-weight Thermal Mass.

Thermal Mass

It describes how construction materials can be used to absorb or release heat at their bodies, and therefore assist in energy-saving strategies for cooling/heating of spaces.

The quantity of heat absorbed or released in a space increases proportionally with the increase of the building weight-mass.

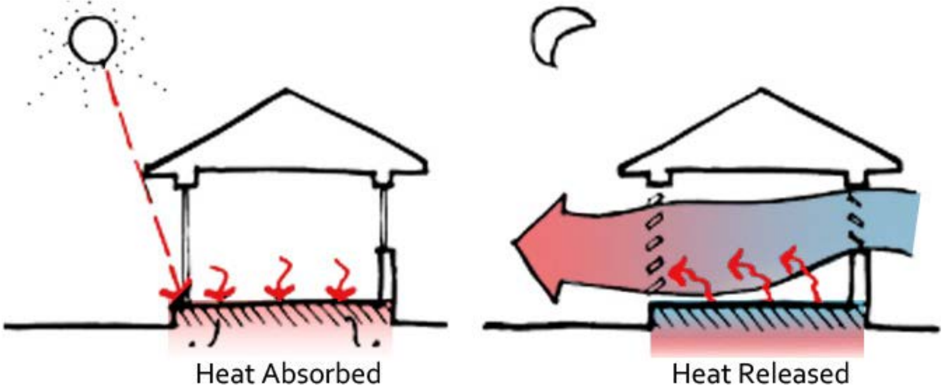

Figure 3: The thermal mass concept (source: http://www.theyellowhouse.org.uk/eco-prin/princip.html).

PCMs and Thermal Mass

PCMs can replicate the effect of thermal mass at lightweight structures or structures that require additional thermal mass.

Once the room temperature increases due to internal heating sources or solar gains, a PCM panel absorbs and stores the heat which releases when temperature drops in the evening and night hours

A PCM absorbs and releases big amounts of heat, while still being lightweight. This is the feature that makes a PCM system advantageous to concrete or other heavyweight building materials.

A PCM system can be used as a main or complementary measure to control temperature inside the building. It can be used in heating and cooling applications, for both passive and active systems. In order to do so, PCMs are panelized[1] in metal or plastic containers, and are installed behind ceiling, wall or floor coverings.

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[1] Panelization: is the procedure technique in which individual systems are prebuilt into panels in a factory setting. (source: www.notsobighouse.com/panelization.asp)

Figure 4: a. Installation of an ENERGAIN PCM panel at a wooden building's ceiling (source: www.offsite2007.com/progress-photos) **b. Installation of Deltacool PCM panels at a wooden building's floor** (source:www.webtarry.com/ideas)

Aesthetics and cost pressures often require modern buildings to be increasingly lightweight[2].

Figure 5: Lightweight Steel Frame and Cladding to assist a large cantilever
(source: Wilo Nederland industrial building, Westzaan (Benthem Crouwel Architects)

Figure 6: Lightweight Steel Frame and Cladding to assist floatation
(source: Floating Pavilion, Rotterdam (Public Domain Architects and Deltasync)

A lightweight material used more and more in contemporary lightweight architecture, is a Glass Fiber Reinforced Polymer (GFRP).

GFRP	Is a composite material made of a polymer matrix reinforced with glass fibers. This combination is called a laminate, and inherits its properties from the cooperative relationship between the matrix and fibers. In non-structural applications laminates are in form off sheets, whereas in structural are laminated to the sides of a foam core to create a sandwich composite

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[2] A lightweight structure can be termed as such, when, regardless of the type of material employed, the shape of the structure is determined through an optimization process to carry the loads from a critical loading case in an efficient way. Typical lightweight structures are wooden st., aluminum st., fabric st., glass fiber reinforced composite st. (source: http://www.lsaa.org/definition)

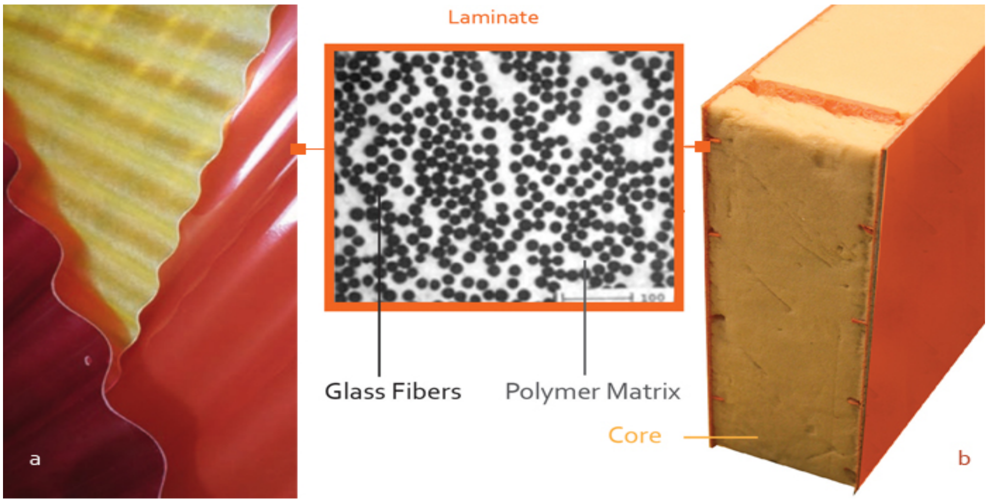

Figure 7: a. A GFRP corrugated laminate (source: www.scobalit.ch/pdf/scobanews), and b. a GFRP sandwich composite with a Polyurethane foam Core (source:www.mrl.columbia.edu/ntm/level2/ch05)

GFRP materials have originated in aviation and aerospace applications due to their very high strength to weight ratio, comparing to other lightweight materials. Their good chemical resistance, low maintenance demands, durability in time and their ability to be fabricated in one-piece at complex shapes, have made them particularly attractive in architecture.

Figure 8: a1. A lightweight (14 kg/m^2) GFRP façade and a2. Its interior (source: www.scobalit.ch/pdf/scobanews), b1. A self-bearing GFRP sandwich composite modular house and b2. Its interior ((source: mocoloco.com/archives)

Another advantage of GFRP composite materials, often overshadowed by their structural, durability and fabrication advantages, is the possibility to be transparent. Transparency can be achieved at the laminate if special transparent resins are used.

Due to the presence of glass fibers, the GFRP laminate is always translucent. This means that objects behind the laminate will look less distorted the closer they are, and more distorted the farther they are.

Figure 9: A translucent GFRP laminate using an Epoxy resin as its polymer matrix.

As mentioned already, lightweight structures present a lack of thermal mass. This means that they can easily overheat in the summer and cannot retain heat in the winter.

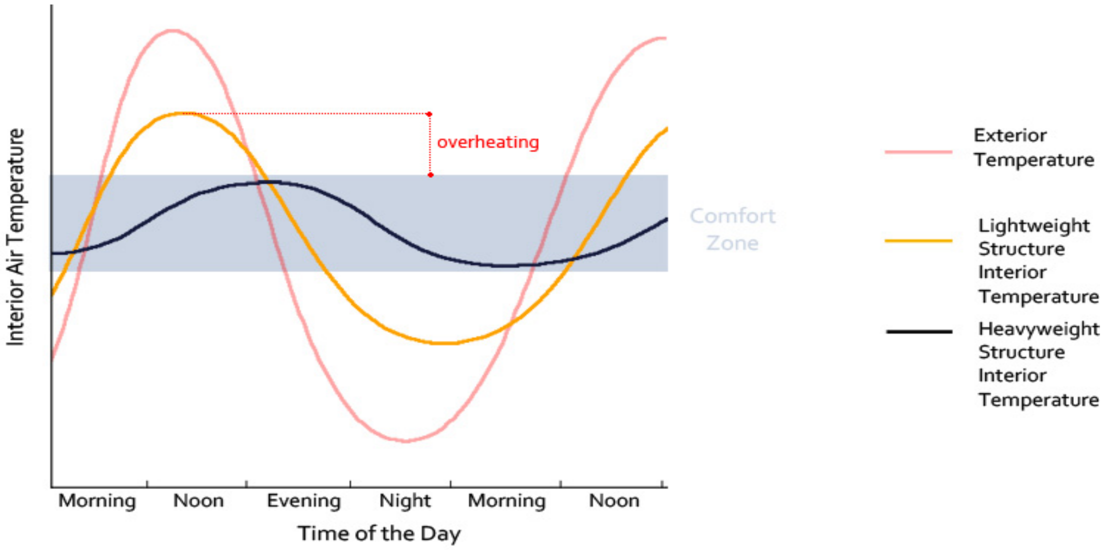

Chart 1: Interior air temperature profile within a Lightweight and a Heavyweight structure.

Solutions that increase the thermal mass of a building without increasing the structural weight are therefore particularly desirable. (Richardson and Woods, 2008)

The question appeared from if the combination of PCMs as lightweight thermal mass materials, translucent GFRPs as lightweight building materials, could be combined into one element that exploits best their individual thermal and structural/fabrication properties.

Moreover, could that element exploit the Optical qualities that appear of its constituent materials -that appear to be of a secondary importance in conventional applications- and add an additional esthetical value to a PCM system?

These questions were synthesized and formed the main Research Question.

1.1 Research question

Main research question:

How can the combination of a GFRP and a PCM be developed into a panel[3] that exploits both their translucency, and what are its potentials as a product in architecture?

This question can be divided in several sub-questions:

- What components can constitute such a panel?
- How do these components affect the optical performance of the panel?
- Can they be combined and create a unitized product? With which methods?
- How can the product exploit the advantages of its subcomponents?
- What are the potentials of such a product in architectural applications?

These questions will be answered in this report.

1.2 Research contribution

The contribution of this research is twofold, providing:

1) An analysis framework for further exploration on the combination of a PCM and a GFRP, in respect to their basic properties and focusing on their optical properties. The framework occurs from the qualitative and quantitative findings collected via literature study, calculations and experimentation.

2) A guideline and recommendations for synthesizing the above findings into design parameters for potential architectural applications.

Altogether, this thesis is a scouting on the possibilities of combining PCMs and GFRPs into one transparent element, which could upgrade the aesthetical values of a non-transparent PCM-GFRP system.

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[3] Panel: a distinct portion, section, or division of a wall, ceiling, door, shutter, fence, etc., especially of any surface *sunk below* or *raised above the general level* or *enclosed by a frame or border (*source: www.thefreedictionary.com/panel)

1.3 Methodology

This research has been designed in three parts.

- The first part of identifies the main research subject and defines the primary objectives of the research.
- In the second part, an analysis framework is generated through interplay between literature on PCM – GFRP, calculations and experimentation on self-made prototypes. The analysis is done at first for the PCMs and GFRPs, individually, and at second for the combinations.
- In the first half of the third part of the thesis, a list of possible applications in presented, based on observations and conclusions from the analysis, with some being further analyzed. In the second half, a reflection and recommendations for further research are made.

The research is based on literature study, calculations and experiments on PCM and GFRP samples.

Literature Study	was used to establish a theoretical background on the properties of PCM and GFRP. For the PCM, the focus was on the optical properties and the melting/solidifying process. For the GFRP, the focus was on the optical properties, fabrication processes and structural behavior. For the combination, the focus was on the existing applications, and on concepts currently under research.
Calculations	were conducted for PCMs in order to get an understanding of the parameters that affect the phase change process, and to roughly estimate the thermal performance of the proposed PCM systems and their variations. Calculations were conducted for the GFRP in order to compare their structural behavior, and prepare the quantities for manufacturing the prototypes.
Experiments	on PCM and GFRP samples as well as combined versions of them, focused on evaluating and documenting the optical properties, since information in literature was limited. Small additional tests helped in getting an overview on the relations between the optical state change and thermal performance of a PCM system, as well as its dynamic structural behavior. The experiments were also useful for a better understanding on the GFRP composite fabrication processes and on challenges that occur when working with those materials.

2 Phase Change Materials (PCM)

Introduction

PCMs melt and solidify at T_{pc} at a broad range of temperatures. For this research, we are interested mainly in PCMs that present a phase change within the range of architectural applications.

The material classes that can theoretically cover this range are many. However, two are actually used in a commercial way: hydrated salts and paraffin (waxes). (Mehling and Cabeza, 2008)

Salt hydrates are salts with a large and defined amount of crystal water, and are inorganic[4] compounds. Paraffin is an organic compound[5] consisting of a mixture of hydrocarbons, obtained from crude petroleum.

Figure 10: A Hydrated salt (Inorganic PCM) on the left, and a Paraffin Wax (Organic PCM) on the right, both at solid state (source: (left) blogs.indium.com, (right) www.hellotrade.com)

Both hydrated salts and paraffin PCM are engineered materials, meaning that their composition –thus properties- can be customized during production.

A Polymer micro-encapsulated Paraffin (PEP) is a recently developed PCM, a subcategory of Paraffin waxes. Microencapsulation is the encapsulation of solid or liquid particles of 1µm to 1000µm diameter with a solid shell. Currently microencapsulation in commercial scale is applied only to PCMs that are not soluble to water, such as paraffin. PEP is translucent.

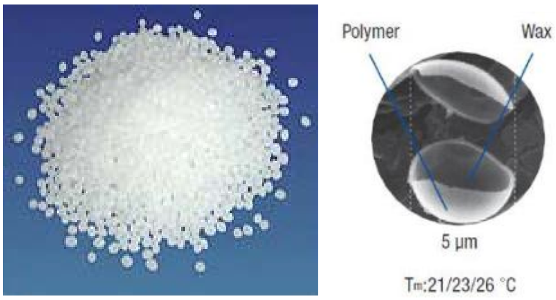

Figure 11: Polymer microencapsulated Paraffin by Rubitherm PK (left) and by Micronal (right) (sources: www.rubitherm.de, www.micronal.de)

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[4] 'Inorganic compound, any substance in which two or more chemical elements other than carbon are combined, nearly always in definite proportions.' (source: www.britannica.com)

[5] 'Organic compound: any of a large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen, or nitrogen.' (source: www.britannica.com)

2.1 Properties

Overview

The basic advantages and disadvantages for the PCMs are presented in the next table.

	Advantages	Disadvantages
Hydrated Salts	- Higher l_{pc} than Paraffin - Generally cheaper than Paraffin - Non flammable	- Corrosive to most materials - Phase separation - Subcooling - Leakage
Paraffin	- Inert to most materials - Chemically and thermally stable - Low or no Subcooling	- Lower l_{pc} than Hydrated Salts - More expensive than Hydrated Salts - Flammable - Leakage
Polymer encapsulated Paraffin (PEP)	- Inert to most materials - Chemically and thermally stable - Low or no Subcooling - Low flammable - No leakage	- Lower l_{pc} than Paraffin and Hydrated Salts - Less conductive - More expensive than Paraffin and Hydrated Salts

Table 1: Comparison between Hydrated Salts (Inorganic), Paraffin (Organic) and microencapsulated (PEP) PCM. (source: Cabeza et al. (2005))

The thermal properties that describe a PCM the best are

a) its Phase Change Temperature (T_{pc}), and
b) its specific latent heat capacity (l_{pc}).

a) Phase Change Temperature

The suitability of depends on the application of PCM, as we will see in a later chapter. The T_{pc} can be distinct (e.g. T_{pc}=21°C) or given within a range (e.g. T_{pc}=21-23°C), and for most substances is equal for melting and solidifying.

An ideal melting behavior exists when both the melting and solidifying process occur at one T_{pc}. Any deviation from the ideal melting raises the perplexity of a PCM system design.

The most common deviations in ideal melting are Hysteresis and Subcooling.

Hysteresis	Is the effect where the solidification process (liquid->solid) shifts at a lower T_{pc} than (solid->liquid). In other words, the PCM presents two different T_{pc}: T_{pc_melt} and T_{pc_solid}.
Subcooling	Means that the material does not solidify at its T_{pc} but at a temperature that can be much lower. After the solidification sets-in, the temperature increases until it reaches the T_{pc}, after when the process continues normally.

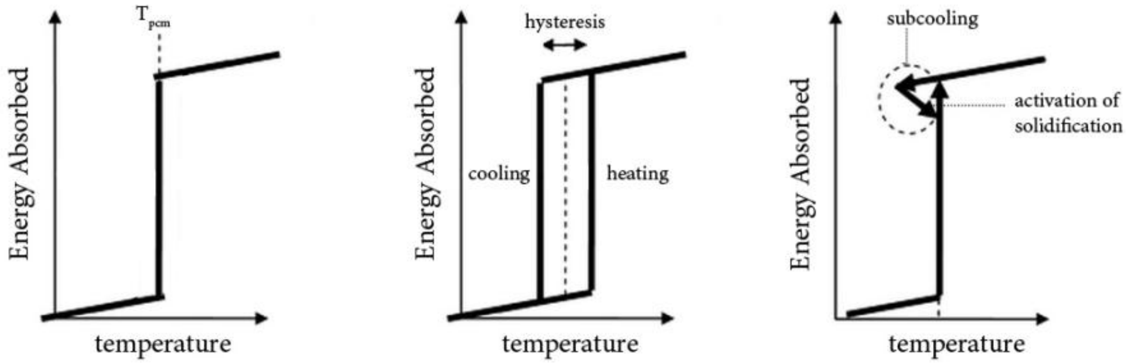

Chart 2: Ideal melting (left), Hysteresis (center) and Subcooling (right) in PCMS. (source: Mehling and Cabeza (2008))

Hydrated salts are more prone to Subcooling than paraffin. (Cabeza et al., 2005)

b) Latent Heat Capacity

Latent Heat

Is the heat absorbed or released by the material when it undergoes a phase change. (McMullan, 2002). The phase change process is isothermal, meaning that during heat absorption or release the temperature of the material remains constant.

The quantity of heat by regards to the mass is given by the formula:

$$Q_{pc} = m \cdot l_{pc}$$

where: Q_{pc} [J] is the quantity of the latent heat, m [kg] is the mass of substance, l_{pc} [J/kg] is the latent specific heat of that substance

Either wise, if we want to calculate by regards to the Volume, we substitute m for V·ρ

$$Q_{pc} = V \cdot \rho \cdot l_{pc} \cdot \Delta T$$

where: Q_s [J] is the quantity of the latent heat, ρ [kg/m^3] is the density, l_{pc} [J/m^3] is the latent specific heat of that substance, ΔT [K] is the temperature change

Sensible Heat[6]

Is the heat transferred to the storage medium and leads to increase of its temperature.
When a substance changes temperature, the amount of sensible heat absorbed or released is given by the following formula:

$$Q_s = m \cdot c_p \cdot \Delta T$$

where: Q_s [J] is the quantity of the sensible heat, m [kg] is the mass of substance, c_p [J/kg·K] is the sensible specific heat of that substance, ΔT [K] is the temperature change

To understand the difference between sensible and latent heat storage for different materials, we can depict the amount of mass needed to absorb a certain amount of energy. For this example we will observe Concrete (Sensible Heat Storage) and a PCM (Latent Heat storage) material.

	m *mass*	c_p *specific heat*	l_{pc} *specific latent heat (T_{pcm}=22^{o}C).*	Q *Energy stored For ΔT=23^o C*
	kg	*kJ/kg*	*kJ/kg*	*kJ*
PCM	1	2.50	170.00	242.00
Concrete	8.6	0.88	0.00	242.00

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[6] Since the temperature change can be detected by a sensor/thermocouple, the heat is called *sensible*.
Latent as a term that derives from the Latin 'latere' (to lie hidden), since there is no temperature change and it cannot be detected.

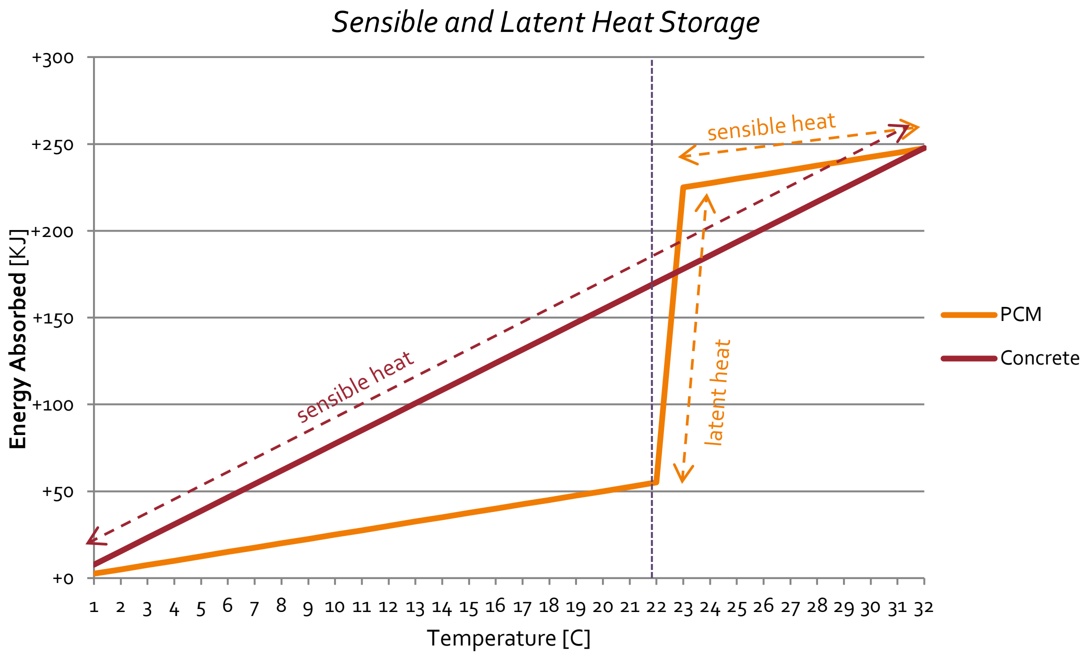

Chart 3: 1.0kg of PCM or 8.6kg of concrete is required to store 250 kJ of heat, at a temperature range of ΔT=32°C. The red dotted line denotes the T_{pc} for the PCM.

When the ambient temperature around the PCM is lower than the T_{pc}, latent heat is released. When the ambient temperature around the PCM is higher than the T_{pc}, latent heat is absorbed.

Hydrated salts have higher latent heat storage capacity than Paraffin PCMs.

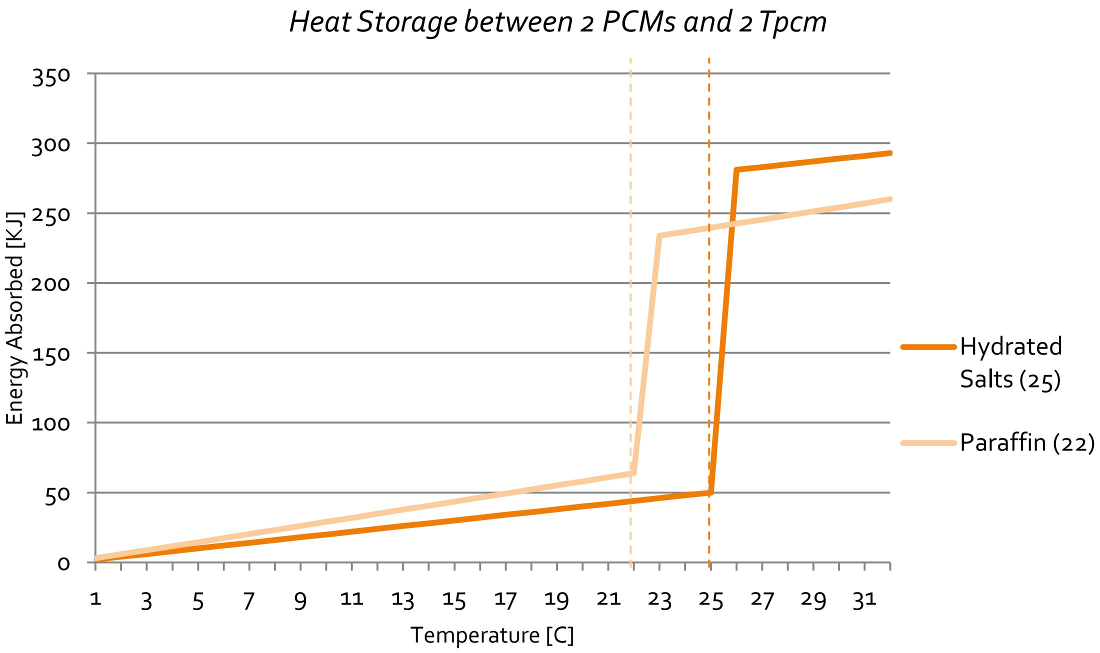

Chart 4: Comparison between the heat storage capacity of the 2 PCM classes, m=1kg 1) Hydrated Salts: T_{pc}=25°C, l_{pc}=231 kJ/kg, c_{psolid}=1.5 kJ/kg, $c_{pliquid}$=2.4 kJ/kg, Paraffin: T_{pc}=22°C, lpc=170 kJ/kg, c_{psolid}= $c_{pliquid}$ =2.1 kJ/kg (source: Cabeza et al. (2005)

They also present better conductivity (λ) than paraffin. This means that in a given volume they respond (melt or solidify) faster.

Thermal inertia (I_t)	Is a measure of the responsiveness of a material to variations in temperature. It demonstrates how slow a temperature of a body approaches that of its surroundings, and is mostly used to compare different materials.

$$I_t = \sqrt{\lambda \cdot l_{pc} \cdot \rho} \qquad \text{or} \qquad I_t = \sqrt{\lambda \cdot c_p \cdot \rho}$$

where: I_t [J*s$^{-1/2}$/m^2*K] is the Thermal Inertia, l_{pc} [J/kg] is the latent specific heat of that substance, c_p [J/kg·K] is the sensible specific heat of that substance, ΔT [K] is the temperature change

Materials with high thermal inertia show slow body changes in temperature, compared to those with low thermal inertia. A high l_{pc} is necessary in order for a PCM system to be advantageous compared to a sensible heat system. From the two basic classes, hydrated salts have generally larger l_{pc} (per volume and per mass) than paraffin.

An overview of the thermal performance of PCMs in comparison to some building materials is presented at the following table:

Materials	ρ [kg/m^3]	c [kJ/kg·K]	T_{pc} [°C]	l [kJ/kg]	λ_{solid} [W/m·K]	λ_{liquid} [W/m·K]	I_t [kJ·s$^{-1/2}$/m^2·K]
Water	917	4.20	0	330	2.18	0.58	47
Hydrated Salts							
*SHREG**	1400	3.00	22	150	1.20	0.55	340
*CLIMSEL**	1380	3.60	21	144	0.70	0.50	315
CaCl2·6H2O	1562	4.20	29	171	1.08	0.54	380
Paraffin (pure)							
n-Heptadecane	776	2.10	19	200	0.21	0.21	181
Paraffin (μencapsul)							
*PEP**	865	2.10	21.7	70	0.18	0.14	92
Aluminium (7000)	2650	0.87	-	-	164.00	-	615
Polyester	1130	1.67	-	-	0.28	-	23
Epoxy	1140	1.67	-	-	0.35	-	26
Concrete	2400	0.75	-	-	0.30	-	23
Cement Fiber Board	1300	1.55	-	-	0.24	-	22
PU foam	40	1.50	-	-	0.021	-	1

Table 2: Thermal and Physical properties of selective PCMs also compared to some encapsulating materials.

3 sponsored[7] PCM* were used at hands-on experiments for this research:

1. SHREG

Hydrated
Salts
Soild-Liquid

Figure 12: SHREG PCM at its crystallized state.

2. CLIMASEL

Hydrated
Salts
Soild-'Solid'

Figure 13: CLIMASEL PCM at its 'Solid' (molten) state

3. PEP

Polymer
Encapsulated
Paraffin
Soild-'Solid'

Figure 14: PEP PCM at its 'Solid' (molten) state

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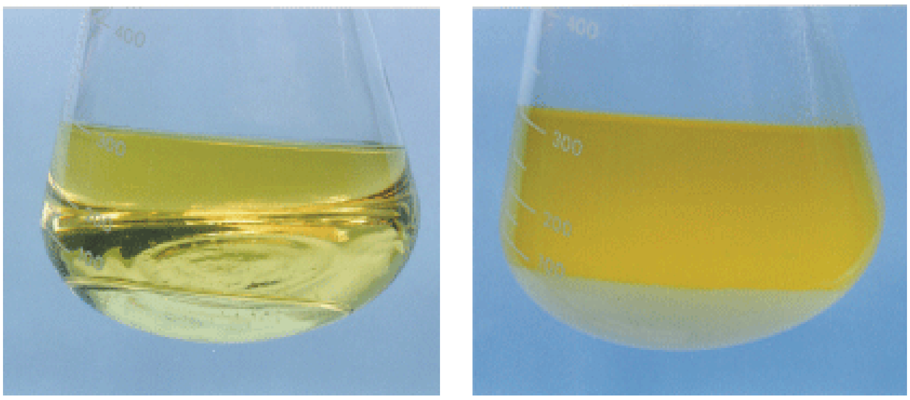
[7] See appendix for manufacturing companies, and sponsoring contacts.

Some properties that usually define the successful or not successful applicability of a PCM in architecture, and mentioned often in literature are chemical stability and compatibility, flammability and cost.

Chemical Stability	Hydrated salts are composite PCMs (water and salt) and they often present phase separation problems. This means that one of the components can melt/solidify in a different T and result in a non-homogeneous mix.  **Figure 15: Example of phase separation in a 'water + gasoline + ethanol' liquid. Homogeneous mix (left) and 'water ethanol'-'gasoline' separation (right)** (picture courtesy of Scott Irwin, source: www.enertechlabs.com) Paraffin does not present phase separation problems because is a one-component material.
Chemical Compatibility	Hydrated Salts can be corrosive to metals. However, in-depth research on their compatibility with other materials has not been conducted yet, thus their exact behavior is still unknown and can only be estimated (Cabeza et al., 2005). Paraffin is inert with most materials, and is insoluble to water (water repellent) (Mehling and Cabeza, 2008).
Flammability	Paraffin is combustible at low temperatures, but does not burn easily, contrary to common belief. Mehling and Cabeza (2008) state that it is a slow burner, like a candle. However, protection with a non- or low-flammable macro-encapsulating material is necessary to apply to standards. Hydrated Salts are inflammable, due to their high composition in water.
Cost[8]	Pure PCM costs range from 3€/kg to 10€/kg (Mehling and Cabeza, 2008). Paraffin is generally considered more expensive. The cost rises not only due to its raw material and production process, but also from transportation costs due to its flammability factor.

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[8] for a list of PCM cost look at the appendix.

2.2 Phase Change Parameters

Introduction

It is important to understand the influence of the parameters that influence the melting process. To do so we will examine the calculation models that describe the PCM behavior by Mehling and Cabeza (2008).

Note: Calculation Model Restrictions

The calculation models describe how the PCM melting front moves at a distance (s) through a PCM layer during the melting/solidification process (for a specific period of time (t), for specific boundary conditions (α_{over})). The temperature at melting front is always equal to the $T_{pc.}$

The restrictions that are taken into consideration for these models are:

- Heat is stored only as latent heat. The sensible heat stored in the PCM is negligible compared to the latent.
- Heat transfer within the PCM occurs only by conduction and not convection[9].
- At t=0, the T_o is homogeneous throughout the surface and equals to T_{pc}.
- Exactly after t=0, T_o changes to $T_{ambient}$ and remains constant at all times.
-

Three different boundary conditions are analyzed in three models:

i. the solid boundary,
ii. the liquid boundary and the
iii. no boundary model

By doing so we will see that the *time (t)* it takes the PCM to melt or solidify, depends mostly on two parameters:

1. the *quantity* of PCM, and
2. the *rate* energy is transferred to or from the surface of the PCM system.

The orientation (vertical or horizontal) of the PCM system and the type of PCM, affect mostly the *direction* of the melting/solidifying. The direction of the phase change process plays a crucial part in the optical performance, as we will see at a later chapter.

Apart from those parameters, the *melting speed* design can be determined from the desired ΔT between the PCM T_{pc} and its system surface temperature (T_o). Consequently, the T_o is related to the temperature around the PC system $T_{ambient}$. The difference between the T_o and the $T_{ambient}$ is called design temperature.

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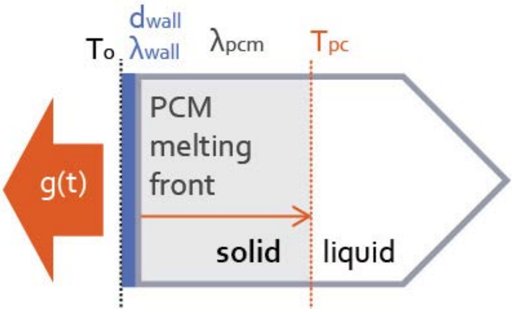
[9] As we will see at a later chapter, this simplification is valid in most applications, since the PCM system thicknesses are too low to allow convection (when the PCM is in liquid form).

i. Solid Boundary model

This model describes how heat is released from the system where a PCM is encapsulated by a solid container of a certain thickness (d_w) and conductivity (λ).

The blue border depicts the container layer, the grey area depicts the solidified PCM, the red dotted line depicts the molting phase front, and the red arrow the direction of the heat flux (g).



Scheme 1: Representation of the Boundary model during solidification of a PCM.
(Mehling and Cabeza, 2008)

The heat flux density for the system is:

$$q(t) = \frac{1}{R_{wall} + R_{pcm}} \cdot (T_{pc} - T_0)$$

where: q(t) [W/m^2] is the heat flux per area, R_{wall} and R_{pcm} [m^{2}K/W] are the heat resistances of the enclosing layer and PCM respectively, T_{pc} [^{o}C] is the phase change temperature, T_o [^{o}C] is the constant temperature at the surface of the system.

For a displacement of the melting front at a distance (s) from the surface it becomes:

$$q(t) = \frac{1}{\frac{s(t)}{\lambda_{pcm}} + \frac{d_{wall}}{\lambda_{wall}}} \cdot (T_{pc} - T_0)$$

where: s(t) [m] is the thickness of PCM, λ_{pcm} [W/m·K] is the thermal conductivity of the PCM, d_{wall} [m] is the thickness of the enclosing layer, λ_{wall} [W/m·K] is the thermal conductivity of the wall

The time (t) needed for a PCM, of thickness (s), to melt is:

$$t = \frac{l_{pc} \cdot s^2}{2 \cdot \lambda_{pcm} \cdot (T_{pc} - T_0)} \cdot \left(1 + 2 \cdot \frac{\lambda_{pcm}}{\alpha_{over} \cdot s}\right)$$

where: t [sec] time, l_{pc} [J/m^3] is the latent specific heat (volumetric), and s[m] thickness, and $\alpha_{over}=\lambda_{wall}/d_{wall}$ the overall heat transfer coefficient of the border.

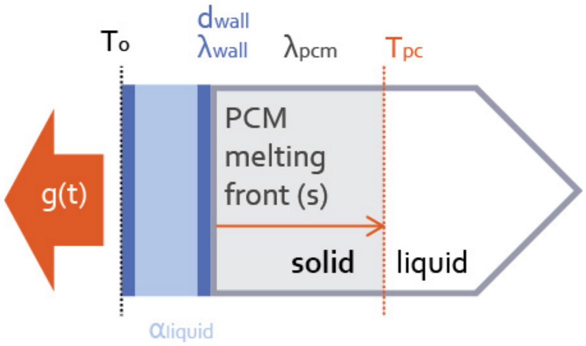
Or the thickness(s) according to the desired melting time (t):

$$s(t) = \frac{1}{2 \cdot l_{pc} \cdot \alpha_{over}} \cdot \left(-2 \cdot l_{pc} \cdot \lambda + 2 \cdot \sqrt{l_{pc} \cdot \lambda \cdot \left(l_{pc} \cdot \lambda + 2 \cdot \alpha_{over}{}^2 \cdot t \cdot (T_{pc} - T_0)\right)}\right)$$

ii. Liquid Boundary model

This model describes how heat is released from the system where a liquid boundary condition is added.

The blue border depicts the container layer, the light blue border a liquid in motion, the grey area depicts the solidified PCM, the red dotted line depicts the molting phase front, and the red arrow the direction of the heat flux (g).



Scheme 2: Representation of the Liquid Boundary model during solidification of a PCM. **(Mehling and Cabeza, 2008)**

The basic difference with the previous system is that the overall heat transfer coefficient changes to:

$$\frac{1}{\alpha_{\text{over}}} = \frac{d_{\text{wall}}}{\lambda_{\text{wall}}} + \frac{1}{\alpha_{\text{liquid}}}$$

as it takes into consideration the heat transfer $\alpha_{\text{liquid}} = \alpha_{\text{cv\_liquid}} + \alpha_{\text{cd\_liquid}}$ at the surface of the PCM by a liquid in motion. The liquid can be air, water or any other liquid. This model is used mostly for heat exchangers.

The heat flux density for the system is:

$$q(t) = \frac{1}{R_{\text{wall}} + R_{\text{pcm}} + R_{\text{liquid}}} \cdot (T_{\text{pc}} - T_0)$$

where: R_{liquid} [m^2K/W] is the heat resistances of the liquid in motion

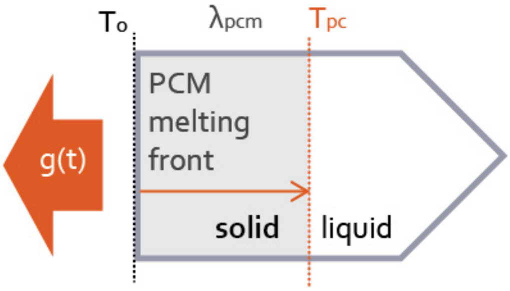
which for a displacement of the melting front at a distance (s) from the surface becomes:

$$q(t) = \frac{1}{\frac{s(t)}{\lambda_{\text{pcm}}} + \frac{d_{\text{wall}}}{\lambda_{\text{wall}}} + \frac{1}{\alpha_{\text{liquid}}}} \cdot (T_{\text{pc}} - T_0)$$

where: α_{liquid}[$W/m^{2\cdot}K$] is the boundary heat transfer coefficient if it is of liquid form

iii. No Boundary model

If the resistance of the encapsulation material is too small (for example if d_{wall} is too small) it can be neglected.
The grey arrow depicts the PCM; the red dotted line depicts the molting phase front, and the red arrow the direction of the heat flux (g).



Scheme 3: Representation of the No Boundary model during solidification of a PCM. (Mehling and Cabeza, 2008)

Then the time (t) needed for a PCM, of thickness (s), to melt is:

$$t = \frac{1}{2} \cdot \frac{l_{pc} \cdot s(t)^2}{\lambda_{pcm} \cdot (T_{pc} - T_0)}$$

If we want to calculate the thickness (s) in relation to a desired melting time (t)

$$s(t) = \sqrt{2 \cdot \frac{\lambda_{pcm} \cdot (T_{pc} - T_o)}{l_{pc}} \cdot t}$$

The heat flux density then becomes:

$$q(t) = \sqrt{\frac{(T_{pc} - T_o) \cdot l_{pc} \cdot \lambda_{pcm}}{2 \cdot t}}$$

The total heat flux, for an area A, can be calculated by the formula:

$$Q(t) = A \cdot q(t)$$

where: Q(t) [W] or [J/sec] is the total heat absorbed in an area A, A [m^2] is the area, q(t) [J/m^2] is the heat flux per area, as a function of time

The selection between the models depends on which parameters we want to examine. For example if we want to focus on the melting process within a PCM melting process of we will use the no- boundary model, but if we want to see the influence of the encapsulating layer, we will use the solid boundary model.

Using the calculation models, we can describe the 4 basic parameters that influence the melting process concerning:

1. Speed	a. PCM quantity,	b. Heat transfer Means
2. Melting/Solidifying Pattern	a. System Orientation,	b. PCM type

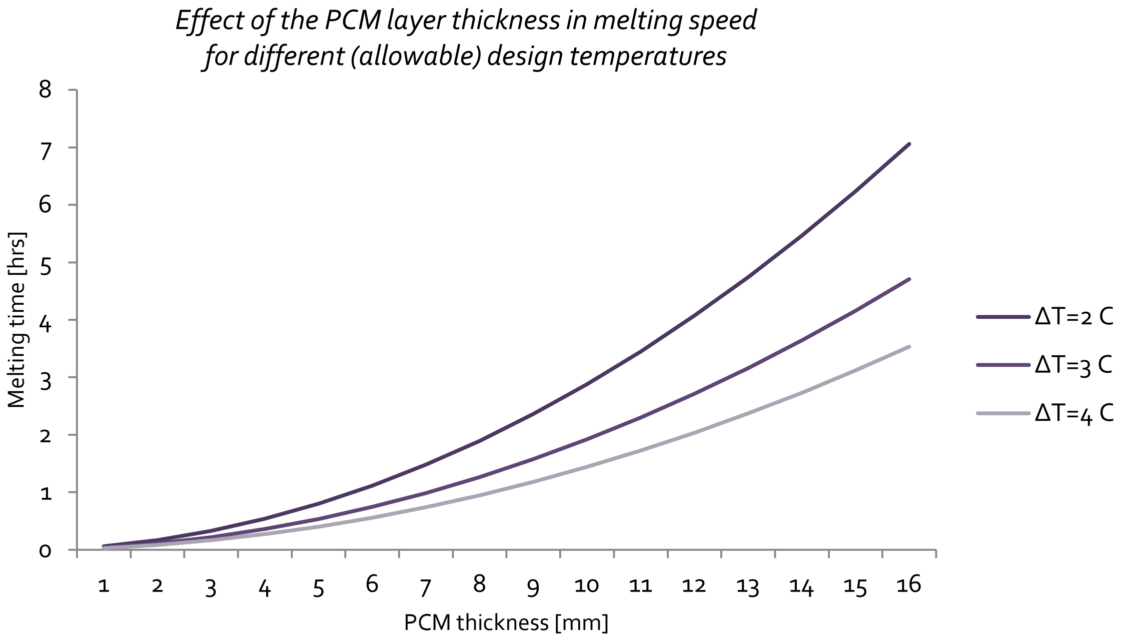
1. a. PCM quantity: *Bigger PCM quantity, slower melting speed.*

More PCM means that more heat [Q] can be stored or released from its body. Thus, the bigger the quantity of PCM the more energy is required to melt or solidify.

Since a PCM system exchanges heat [q] with the environment when its surface T_o differs from the T_{pc}, the bigger this ΔT is, the faster the phase change will occur.

Thermal conductivity [λ] of the PCM also affects the heating process since it controls how easy heat is transferred within the PCM.

Using the no-boundary model, we can estimate the melting thickness of a PCM. An example for Paraffin encapsulated Polymer PCM is presented:



ΔT [°C]	Time [hrs]															
2	*0.06*	*0.17*	*0.33*	*0.54*	*0.80*	1.12	1.48	1.90	2.36	2.88	3.45	4.07	4.74	5.46	6.24	7.06
3	0.04	0.11	0.22	0.36	0.53	0.74	0.99	1.26	1.58	1.92	2.30	2.71	3.16	3.64	4.16	4.71
4	0.03	0.08	0.16	0.27	0.40	0.56	0.74	0.95	1.18	1.44	1.73	2.04	2.37	2.73	3.12	3.53
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	PCM thickness [mm]															

Chart 5: Melting and solidifying time of PCM according to the temperature on its surface. Calculated with the no Boundary model, l_{pc}=70kJ/kg, ρ_{pcm}=865kg/m^3, λpcm=0.16 W/m^{2}K.

It is important to mention that thickness (s) and not the volume (V) or the mass (m) of a PCM defines the time (t) it takes for a complete phase change.

Volume	Volume[10] and mass are related to the total heat capacity of the system Q_{pc} and, similarly to ΔT, it is determined by the design parameters set by the application.
Thicknesses	In architectural applications, PCM layer thicknesses are small and vary within a range of 5 - 50mm. Their choice is influenced not only by thermal performance, but also by practical factors such as weight and cost.
ΔT	As mentioned earlier the calculation models assume that T_o remains constant during the phase change (Mehling and Cabeza, 2008). This is more true in active-strategy architectural applications (like a water-based cooling ceiling), as we will see at a later chapter. In passive-strategy applications, however, T_o is increasing or decreasing depending on the changing temperature surrounding the PCM system. Chart 6 communicates this dynamic nature of the PC process at a PCM system. If the ΔT is set by an application and we still want to achieve faster/slower PC speeds, we should consider reducing the quantity of PCM used, or changing the way that heat is exchanged at its external surface.

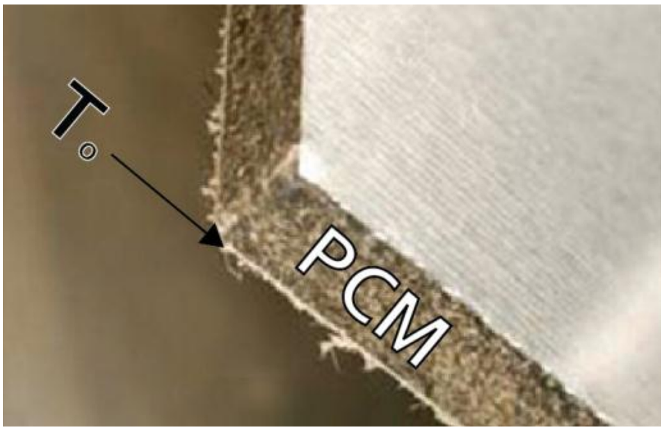


Figure 16: Example of a PEP panel, of 5mm thickness, encapsulated in two 0.1mm aluminum sheets.
(source: www.greenspec.co.uk/thermal-mass.php)

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[10] If Volume is used as the means to measure quantity, then Volumetric c_p or l_{pc} should be used.

1.b. Heat Exchange Mechanisms: *Easier heat transfer, results to faster phase change process*

We already saw the influence of varying T_o in melting speed. Most PCM systems consist of an encapsulating container and an encapsulated PCM. T_o is usually the temperature of the container surface, which exchanges heat with the surrounding space.

In architectural applications, the space is usually the air inside a room. Therefore, we can say that the encapsulating surface and its surrounding space is the PCM's border condition.

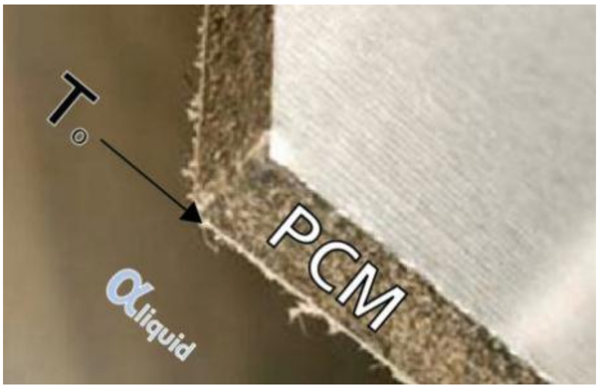
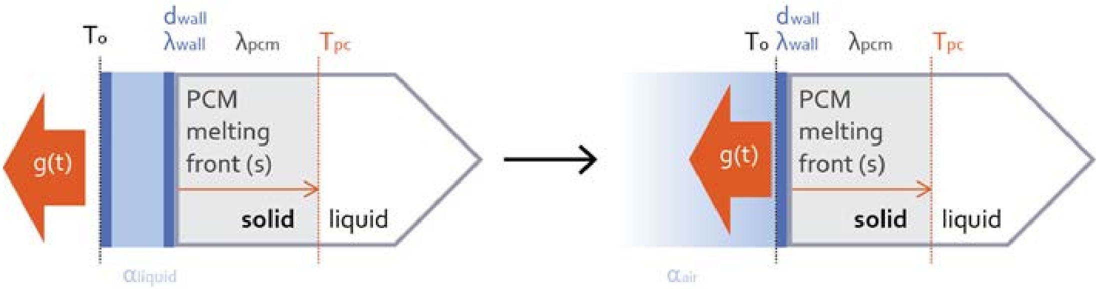


Figure 17: Border Conditions T_o and $\alpha_{liuid,}$ at a 5mm PEP PCM encapsulated in two 0.1mm aluminum sheets. (source: www.greenspec.co.uk/thermal-mass.php)

The border condition can be numerically described by an overall heat transfer coefficient, α_{over} $[W/m^{2}K]$. It includes the conductive heat transfer of the surface $\alpha_{wall}=\lambda_{wall}/d_{wall}$, and the overall heat transfer of the surrounding space α_{liquid} .which is a summation of the convective, α_{liquid_cv}, radiative, α_{liquid_rd}, and conductive, α_{liquid_cd}, heat transfer.

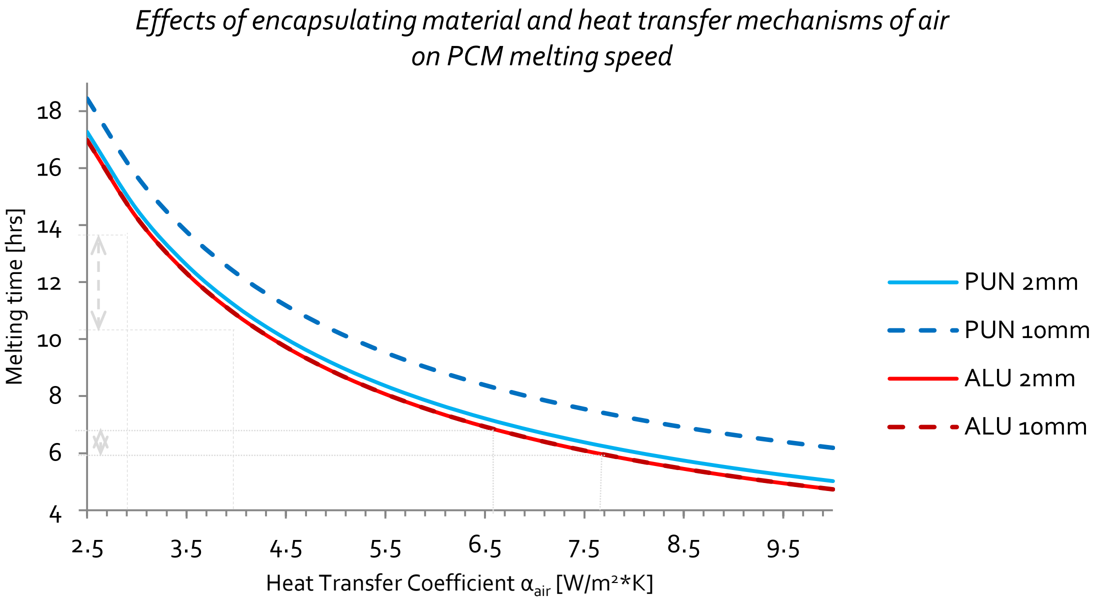
Using a simplified version of the liquid border model is a good way to visualize the effect of different border conditions heat transfer mechanisms



Scheme 4: At the right a simplified 'liquid border' model

We can compare the PCM melting speeds between a highly conductive and a poorly conductive encapsulating material at varying thicknesses, and see the effect on them, by increasing the α_{liquid}. The liquid medium, in our case will be air (α_{air}).

It is a good opportunity to see how a GFR Polyester (PUN) container thermally performs compared to an Aluminum (ALU) one. The conductivity of PUN is similar to Polycarbonate, which, along with aluminum, is widely used as commercial PCM encapsulating containers.



	Thickness [mm]	Materials	Heat Transfer Coefficient [W/m2K]							
			2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
Melting Time [hrs]	2mm	PUN	17.3	12.6	10.0	8.4	7.2	6.4	5.7	5.2
		ALU	17.0	12.3	9.7	8.1	6.9	6.1	5.4	4.9
	10mm	PUN	18.4	13.8	11.2	9.5	8.4	7.5	6.9	6.4
		ALU	17.0	12.3	9.7	8.1	6.9	6.1	5.4	4.9

Chart 6: Melting speed comparison between an ALU and PUN encapsulation layer at 5 mm paraffin PCM, for various α_{liquid} heat-transfer coefficients. $\Delta T=2^{\circ}C$, $l=70$ kJ/kg, $\lambda_{pcm}=0.16$ W/m·K, $\lambda_{PUN}=0.28$ W/m·K, $\lambda_{ALU}=164.00$ W/m·K

A higher α_{air} causes faster phase change process.

It is interesting to see that within a low α_{air} range (2,5- 5,0) a small increase of 1,0 W/m^{2}K, can lead to a 3,5 hrs reduction of the phase change period. In contrast, within a higher α_{air} range (7,0- 10), the phase change period is increasing much slower.[11]

A very thin encapsulation layer nullifies the effects of low layer conductivity.

A 2 mm Polyester container behaves almost the same as a 2mm Aluminium. Only if a thick encapsulating layer is required (> 2mm), e.g. for structural reasons, the container conductivity becomes an important parameter.

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[11] This observation also leads to the conclusion that the boundary conditions should be carefully estimated as input parameters, because a slight misjudgment can lead to serious deviations from the calculated melting times.

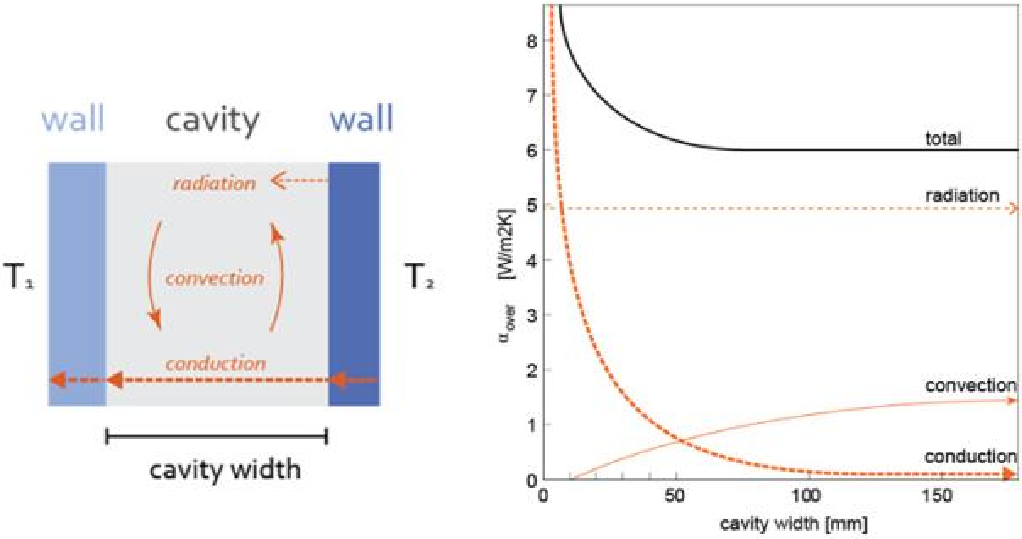
2.a. PCM system orientation: *Inhomogeneous melting at vertical systems*

In most PCM systems, heat transfer within the PCM is dominated by conduction (Zalba et al., 2003). We can visualize a PCM system as a cavity construction, with a PCM at a liquid state replacing the cavity air. Both conduction and convection occur at the liquid of the cavity.

However, the intensity depends on the width of the cavity. Convection flows develop less easily in a thin cavity, reducing the α_{cv}, while at the same time, the α_{cd} increases because the layer is thinner (Linden and Zeegers, 2007).

If the PCM is encapsulated within two layers and the layers have different T_o ($T_1 \neq T_2$) , then radiation should occur. However, in most applications heat transfer within liquid PCM though radiation is neglected.

When the PCM is solid, of course, no convection occurs.



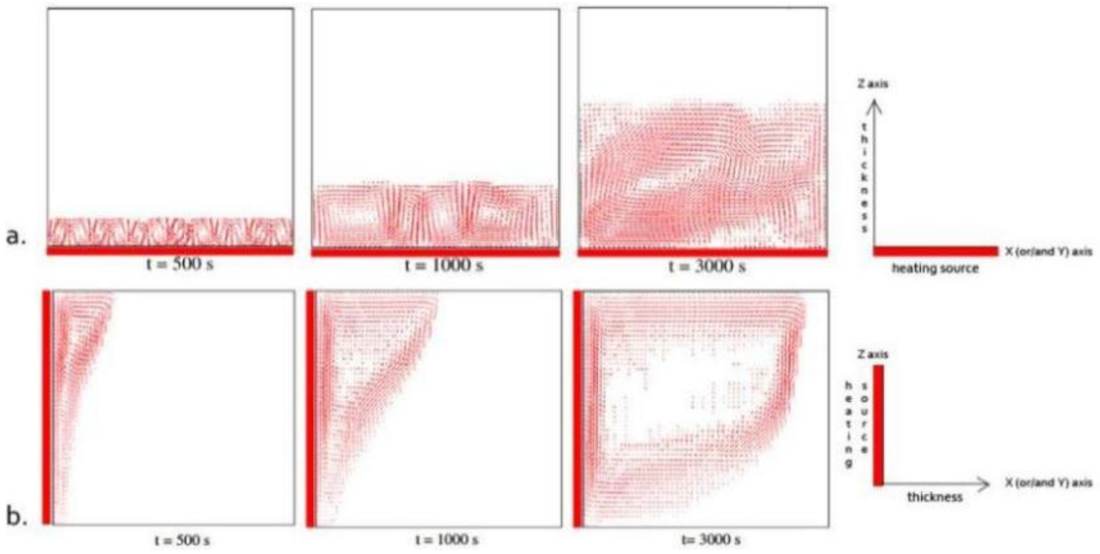
Scheme 5: Left: A vertical cavity construction. Right: Heat transfer as it occurs through conduction, radiation and convection, depending on width of cavity: approximate indication of transfer coefficient α_{over} of an air cavity. (source: (Linden and Zeegers, 2007))

Research projects that investigated the visual phase change process of PCMs, verify this comparison. Arasu and Mujumdar (2012) observed that the phase change process depends on the relationship between the heating source *orientation* and the system *thickness*.

It also depends on whether the PCM is melting or solidifying:

Heat Source orientation	Solidifying Process	Melting Process
Horizontal	*Homogeneous*	*Homogeneous*
Vertical	*Homogeneous*	*Inhomogeneous*

This occurs because the convection heat transfer causes recirculation inside the molten PCM: The warmer liquid-PCM flows to the top, and the colder liquid-PCM flows to the bottom. Since the top liquid-PCM is always warmer, the solid-PCM on top melts faster ($T_{o\_top} > T_{o\_bottom} => \Delta T_{top} > \Delta T_{bottom}$).



Scheme 6: Melting pattern for a horizontal heating from the bottom (left) and side (right) for paraffin wax with 2% Al2O3. The heating source is illustrated in a red line, the thickness line shows the heat source orientation. (source (Arasu and Mujumdar, 2012))

During the solidification process, on the other hand, the PCM is solidifying parallel to the heat transfer source (Jegadheeswaran and Pohekar, 2009). This is because the liquid volume shrinks during solidification, making the process conduction dominant.

The melting process at a vertical heat source is fundamentally the same, regardless of geometry. What changes is the melting pattern, which depends on the shape of the container.

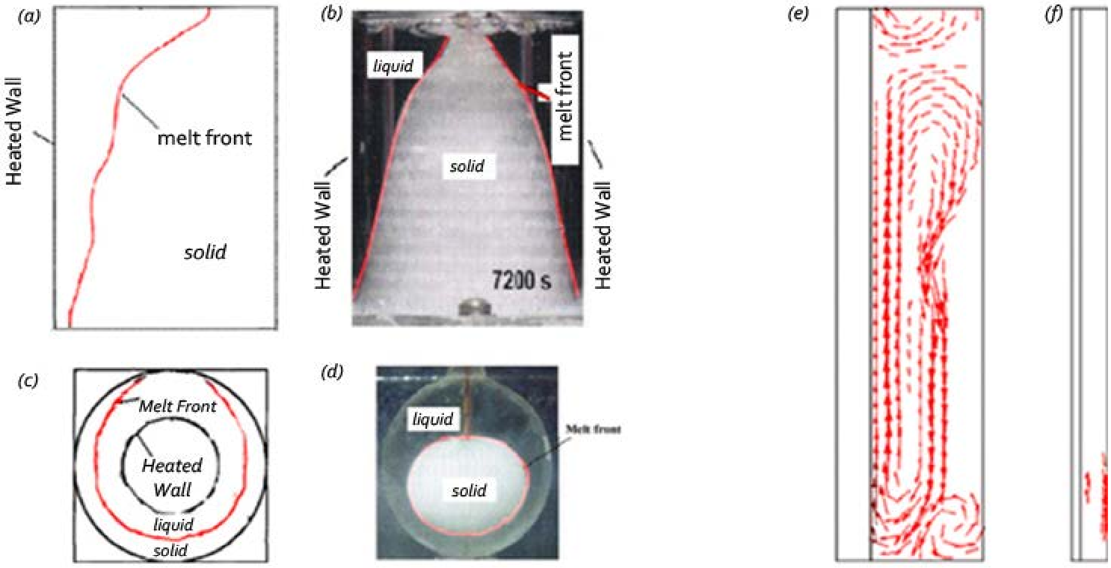


Figure 18: (left) Hydrated Salts natural convection dominated melting process: a. Rectangular System, b. Cylindrical system, c. Cylindrical annulus, d. Spherical System. (right) Paraffin fluid motion during melting: a. Wider system, b. Narrow system (source: (Jegadheeswaran and Pohekar, 2009)).

Similar to ice cubes melting in water, the salt hydrate and paraffin PCMs also communicates its melting behavior through a pattern. When the solidifying/melting is conduction dominated, the pattern is linear and more easily predictable. When the melting is convection dominated, the melting pattern it is not linear and therefore less predictable.

2.b. PCM Type: *Macro-encapsulated PCMs melt in-homogeneously, microencapsulated PCMs melt homogeneously*

The composition of the PCM affects differently the homogeneity of the phase change process.

Weinläder (2004) has verified this while examining the optical properties of paraffin[12] and a hydrated salts[13] PCM, encapsulated in polycarbonate sheets:

Paraffin	solidifies into small flakes. The flakes being denser objects, they sink within the molten PCM.
Hydrated Salts	crystalize during solidification. The crystals form at the heat source front and expand until they cover the entire thickness.

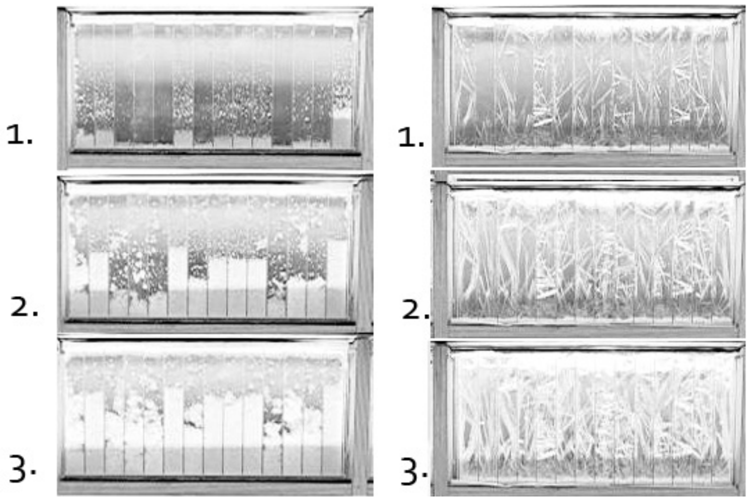
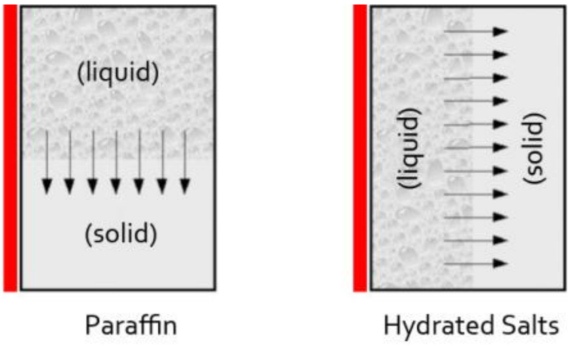


Figure 19: Solidification process (reading from 1 to 3) for a 12.0 mm Paraffin (left) and a 8.6 mm Hydrated Salts (right), encapsulated at transparent polycarbonate sheets. (source:(Weinläder, 2004))

The melting process also differs from class to class. The crystalized hydrated salt, having stronger internal bonds due its crystals, melts more homogeneously towards the heat source direction than paraffin. (Weinläder, 2004)



Scheme 7: Representation of the difference between paraffin and hydrated salts melting, exaggerated. (source: (Weinläder et al., 2005)

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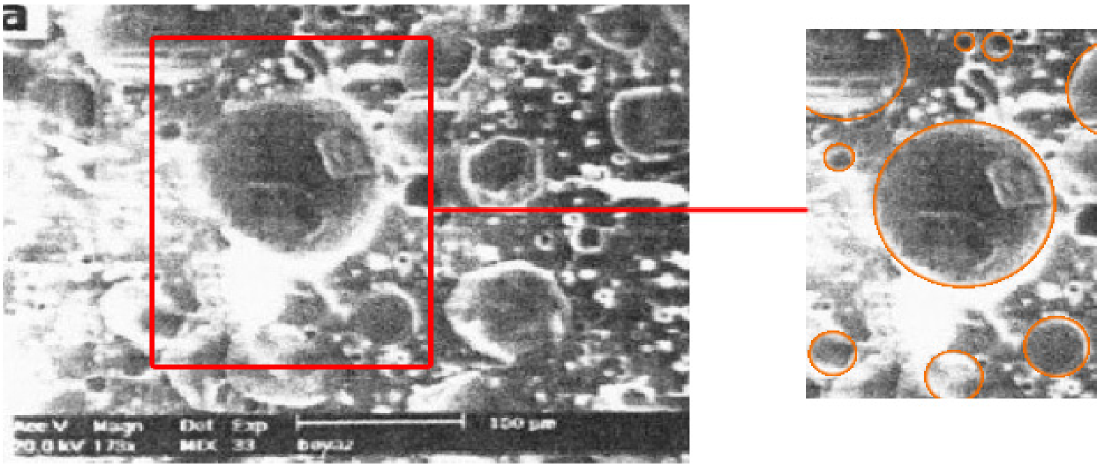
[12] Paraffin: RT25 wax from Rubitherm

[13] Hydrated Salt: S27 from Cristopia, which is based on CaCl2Æ6H2O

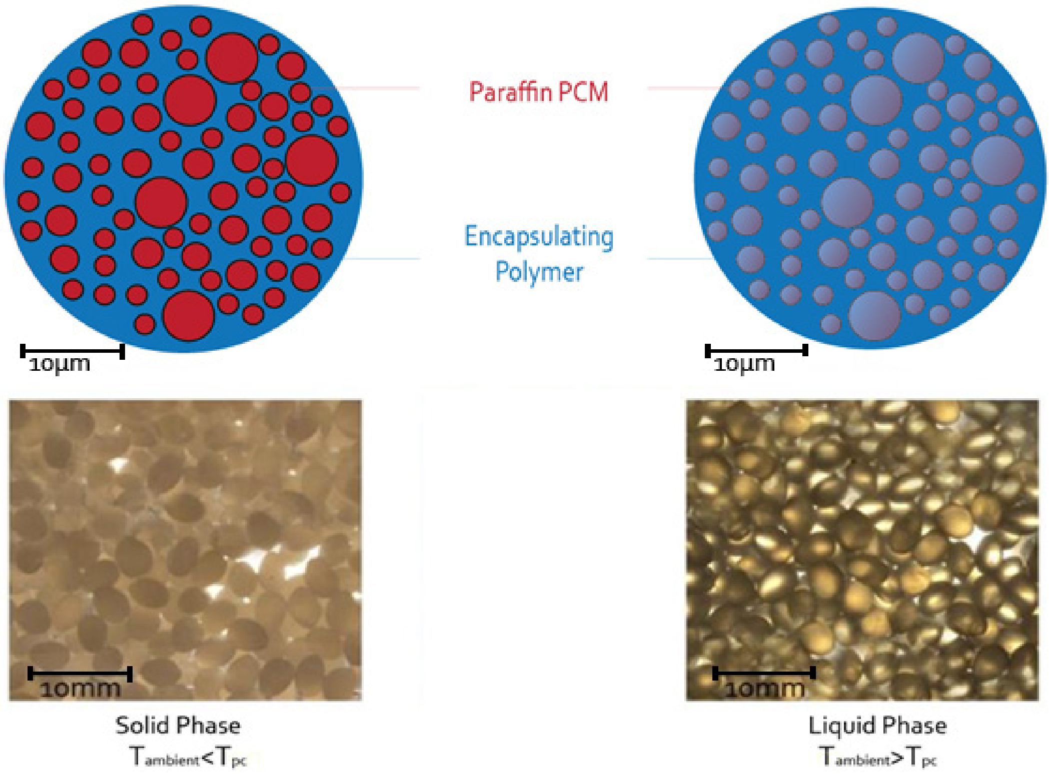
No research papers on the melting pattern of microencapsulated PCMs (PEP) were found. This is probably because PEP are relatively new products (Mehling and Cabeza, 2008).

A research by Cayli and Kusefoglu (2004) on the relationship between strength and the phase change process of a Polyester-Paraffin composite, can be helpful in defining the melting mechanism for PEP. The samples they tested showed that the paraffin underwent phase change ,while the composite remained in the same solid state.



Scheme 8: SEM image of 30 percent paraffin filled polyester sample (magnificationx173). In orange circles, the paraffin is visible, in spherical concentration. (source: (Cayli and Kusefoglu, 2004))

Judging from the conclusions mentioned in the report of Cayli and Kusefoglu (2004), and from the previous discussion about the effect of the PCM thickness in reduction on convection, we can assume that the melting process within PEP is also conduction dominated.



Scheme 9: (top) Schematic representation of a PEP and (bottom) PEP pictures, at its solid and liquid phase.

2.3 PCM Optical Performance

Introduction

To describe the optical performance we should first understand what the term 'translucency' means and how it affects the visual perception of an element.

To understand the term translucency we can look at the definition:

> "*Translucency is the descriptive of a material that transmits light but diffuses it in a way that an image cannot be seen through the material clearly* (McGraw-Hill Dictionary of Architecture & Construction)".

Therefore, translucency can be described as partial opacity or a state between complete opacity and complete transparency. (Yu and Lee, 2008)

Literature research has pinpointed that there is no internationally accepted translucency-level unit (see appendix).

Since the elements we are examining in this report will be used in architectural applications, we should adapt the definition and measurements for translucency to our demands.

A way to describe the translucency intensity of an element, can be by pinpointing its light Transmission values and record the Image Distortion it causes to projected shapes:

2.3.1 Theory and Experiments

1. Light transmission

The term transmission generally refers to the physical process of radiation passing through a substance. The property of a substance that permits the transmission of visible light-radiation[14], with some or none of the incident light being absorbed or reflected in the process, is called transparency[15].

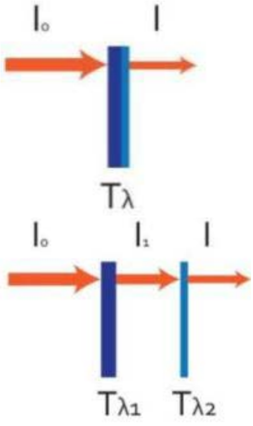
Transmittance [T_λ] is the unit of measuring transmission and is defined as the ratio between the intensity of the radiation coming out of the sample I [lux] to the intensity of the incident visible light on a sample, I_o [lux]:

$$T_\lambda = \frac{I}{I_o}$$

T_λ is measured in a scale of 0.0-1.0. In practice, however, the term 'transparency levels' is used instead of transmittance, and is usually displayed in the scale 1-100%.

At a 2-component composite, with $T_{\lambda 1}$ and $T_{\lambda 2}$ the components' light transmittance values, the composite's T_λ can be calculated as:

$$T_\lambda = T_{\lambda 1} \cdot T_{\lambda 2}$$



Measuring Light transmittance

The I levels were measured under a 40W bulb (2700°K), at a vertical distance of 250mm using a digital lux meter[16]. The center of the light sensor disk was oriented vertically to the lamp bulb.

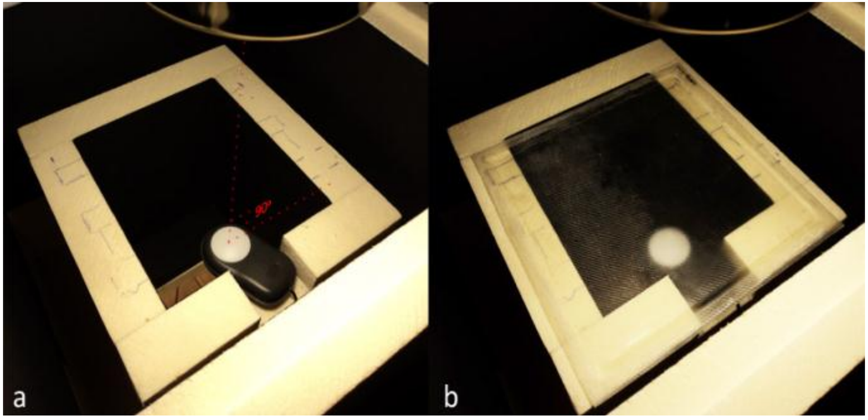


Figure 20: LUX level measurement. A. Measuring intensity before placement of sample. B. Measuring intensity after placement of sample

A measurement for each sample was taken 2 times, and the average values were inserted at an Excel file, where the T_λ was calculated.

---

[14] *Light* or *visible light* is electromagnetic radiation that is visible to the human eye, and is responsible for the sense of sight. Visible light has wavelength in a range from about 380 nanometers to about 740 nm, with a frequency range of about 405 THz to 790 THz. In physics, the term light sometimes refers to electromagnetic radiation of any wavelength, whether visible or not. source: CIE 1987. *International Lighting Vocabulary*, CIE.

[15] Transparency depends on the wavelength; for instance, a glass pane can transparent to the visible wavelengths of light, and opaque to Ultraviolet wavelengths.

[16] Accuracy: 5.0%, Resolution: 1 Lux, Shanghai Handsun Electronic Co., Ltd.

2. Image distortion (ID)

Image distortion (ID) is an effect caused by the diffusion of the transmitted light through an object. It is a characteristic, which denotes if a material that allows light transmission is translucent, or not.

Image Distortion

One of the ways of defining the ID that a material causes, is by comparing the image of a graphic pattern to the image of the same pattern projected behind the material. The declination between the pattern outlines denotes the amount of ID.

This method has been patented by Merkel and Task (1991), who used an orthogonal grid as the comparison pattern, that had the possibility to be digitized and be further examined.

It is also important to state that the ID increases as the distance from the tested pattern increases (Merkel and Task, 1991) .

Figure 21: Example of Image distortion caused by a translucent panel (source: Asvgis, Vray manual)

Measuring Image Distortion

To measure image distortion, photographs of the pattern given by an 'outline specimen' taken behind the panels were compared, to the photographs of that specimen taken behind a 100% transparent panel.

The pattern was given by an element composed of 3 steel sheets, 40% perforated with holes, placed at a vertical distance d=30mm from each other.

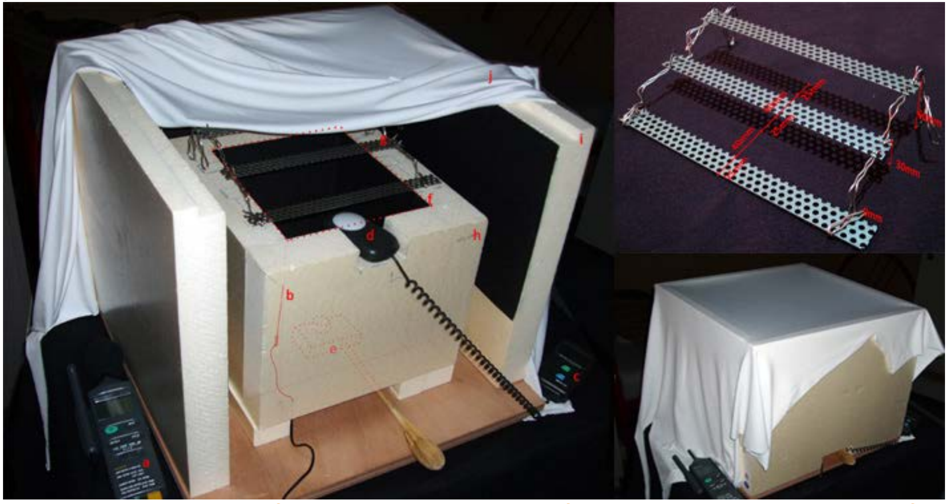


Figure 22: The setup used for recording the optical performance and melting behavior of the test panels. a. Volcraft temperature meter, b. Voltcraft Temperature sensor Chromel/Alumel tcoubple, c. LX-1010B Lux meter, d.External sensor surface, e.Olympus Camedia c-605M, f.sample border, g.outline specimen, h. Interior box, I Exterior box, j. Stretchable fabric for light diffusion

2.3.2 Light Transmission at PCMs

Weinläder (2004) examined the change of light transmission during the phase change process for the two main classes of PCM. To do so, he compared the light transmittance of 12mm thickness PCMs.

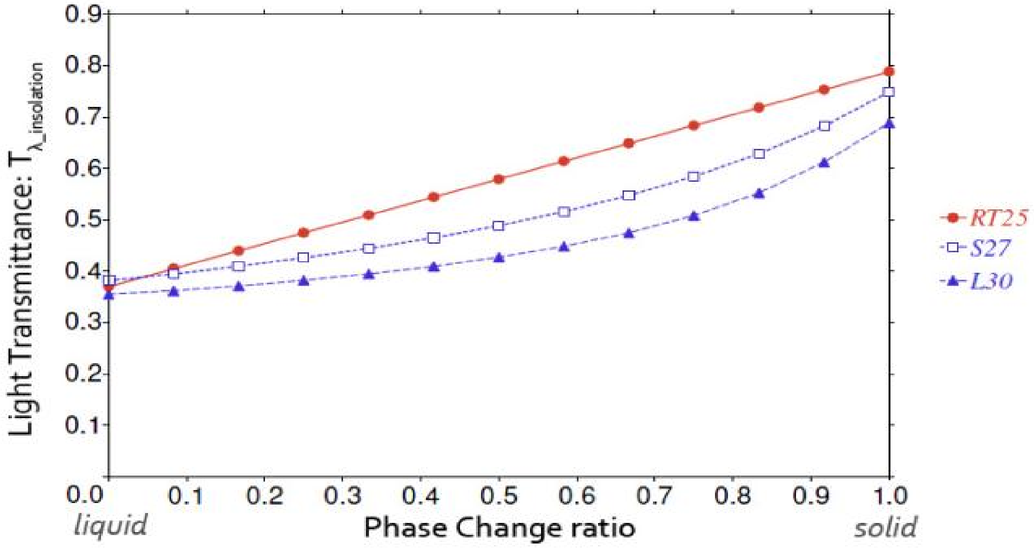


Chart 7: Calculated values of Transmittance at a 12 mm thick PCM layer, as a function state of charge.(source: (Weinläder, 2004))

His general observations state that in liquid state, the PCMs are "non-scattering[17], clear and transparent homogeneous fluids". In liquid state, all the samples presented equally high transmittance values in the visual range of about 0.9. In solid state, the transmittance decreased to about 0.5 in the visual range. This is mainly due to scattering processes within in the materials, that also cause image distortion (Weinläder, 2004).

The transmittance in the visual spectral range is nearly independent of wavelength, so there is no change in color during the PC process.

In order to have a more general picture on the light transmittance of PCMs, the T_λ values for the three PCMs (PEP, CLIMASEL and SHREG) were examined. In order to be comparable to Weinläder (2004) the PCM thickness was adjusted to 12mm:

Average Transmittance Values (Transparency Percentage)

	PEP	CLIMASEL	SHREG	RT25	S27	L30
PCM	Microencapsulated Paraffin	Hydrated Salts		Paraffin	Hydrated Salts	
Liquid	0.64 (64%)	0.57 (57%)	0.82 (82%)	0.78 (78%)	0.75 (75%)	0.68 (68%)
Solid	0.50 (50%)	0.54 (54%)	0.44 (44%)	0.37 (37%)	0.38 (38%)	0.35 (35%)

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[17] Light scattering is a form of scattering in which light is the form of propagating energy which is scattered. (Wikipedia). In other words, they do not cause image distortion or they are not governed by a pattern.

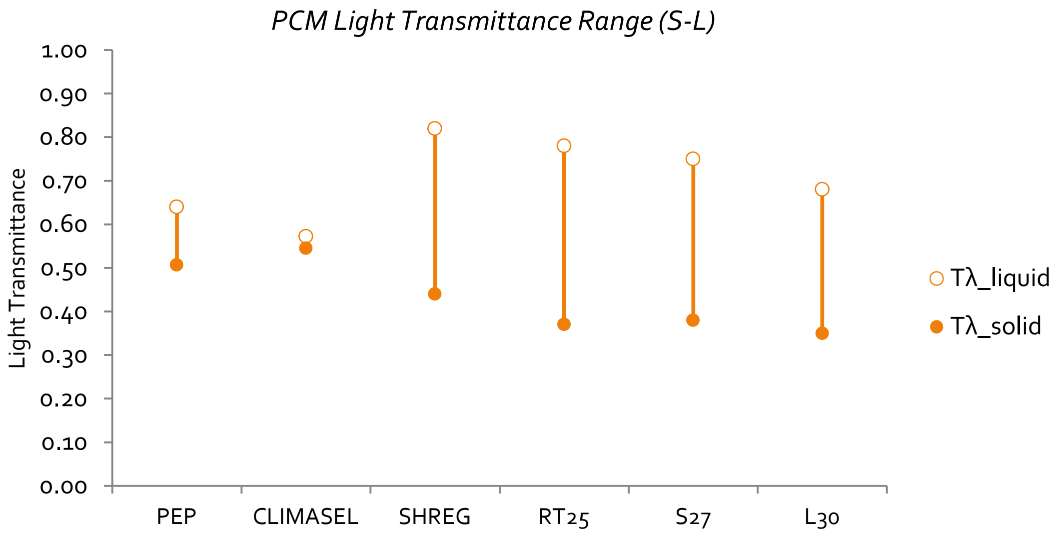

Chart 8: Light Transmittance range per PCM, thickness s=12mm.

The chart can be read from top to bottom: the light transmittance of the PCM at a liquid state (T_{λ_liquid}), top, is always higher than the light transmittance at a solid state (T_{λ_solid}) , bottom.

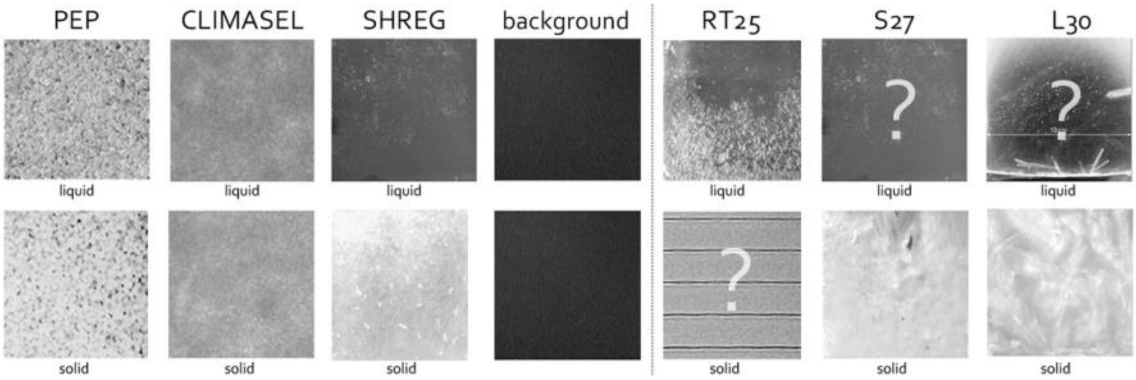

Figure 23: Comparison between the solid and liquid states of some PCMs, at a thickness of 12mm, photographed on a black background. Note: The RT25, S27 and L30 pictures (source: Weinläder (2004)), where digitally edited using the Histogram function in Adobe Photoshop. The brightness was calibrated, trying to match the Tλ values presented in the paper. It is a personal estimate and should not be regarded as correct.

The difference in T_λ between states ($\Delta T_\lambda = T_{\lambda\_liquid} - T_{\lambda\_solid,}$) is a parameter that can determine how easily PC perception can be achieved.

For example if we compare the ΔT_λ for PEP and CLIMASEL, we can expect to distinguish easier the solid from the liquid phase. the picture of a solid PEP seems brighter than the liquid, whereas the CLIMSEL seems almost the same.

Therefore, we can say that the bigger the ΔT_λ the more perceptible the PC process is.

2.3.3 Image distortion (ID) at PCMs

Due to lack of in-depth information[18] and photographic records in literature, a series of tests were conducted to evaluate ID caused by 3 PCMs. The PCMs were left to melt at flat acrylic sheet of T_λ=0.95. The thickness of each PCM layer was 3,5mm.

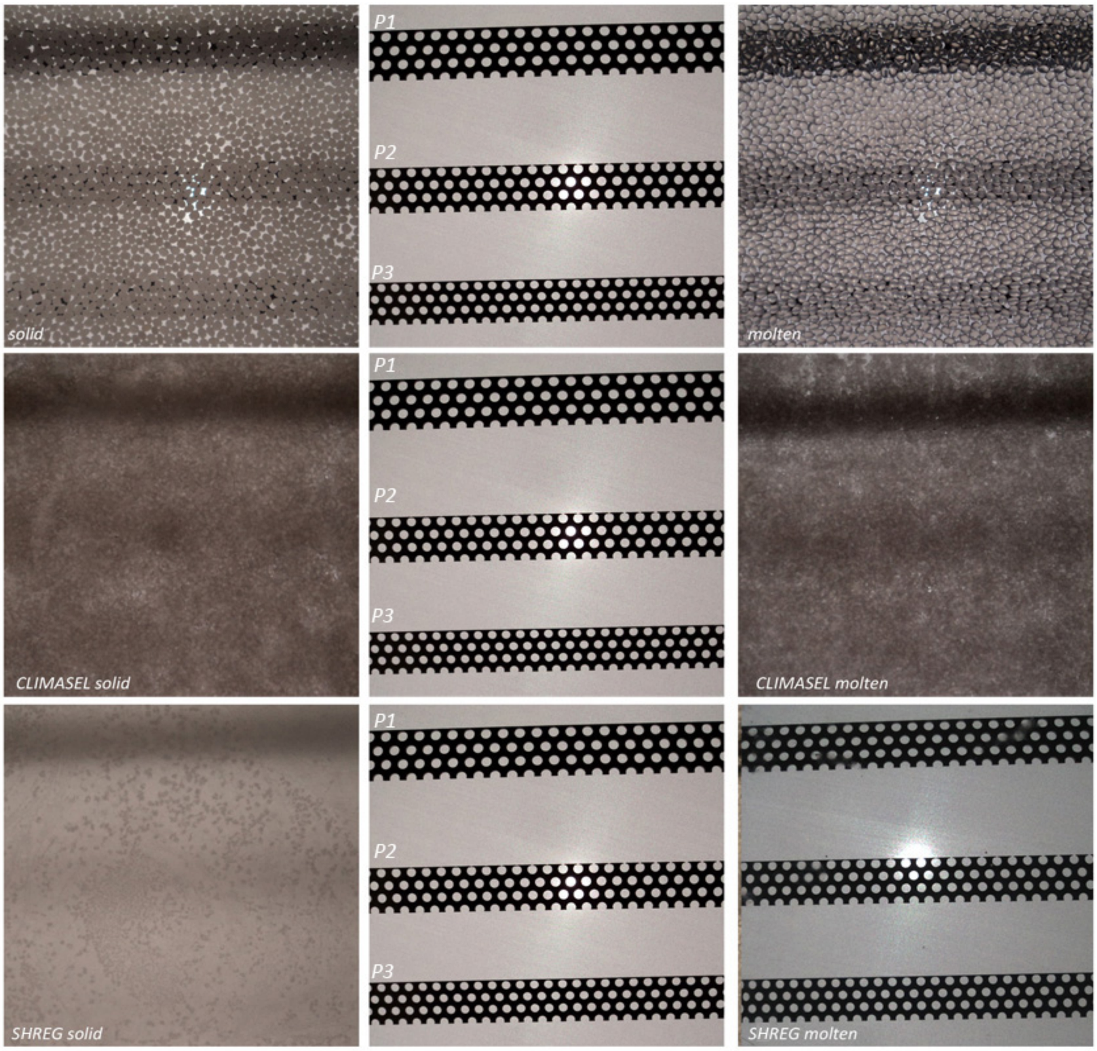

Figure 24: Image Distortion ID comparison between PEP, CLIMASEL and SHREG at a 3,5mm thickness. Left: in Solid state, Center: the comparative setup, Right: the Liquid state.

ID occurs at both physical states, but its intensity varies, depending on the PCM type. SHREG presents the highest difference in image distortion (ΔID); this is logical, since it changes to a liquid state.

PEP and CLIMASEL melt not to liquid, but to softer solids. From now on we will be referring at their phase change process as **Solid-'Solid'**.

PEP shows the second ΔID in intensity, but as we will see in a later chapter, this value could be improved.

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[18] Weinlader et.al (2005) state that '..air bubbles and—in case of the salt hydrates crystal boundaries––cause scattering and lead to a nontransparent and more or less inhomogeneous appearance of the solid PCMs '.

3 Glass Fiber Reinforced Polymers (GFRP)

Introduction

A GFRP composite material made up of fibers and a polymer matrix (also referred to as resin) is called a laminate. Fabricating a laminate is simply a matter of placing fibers within a matrix in liquid state, in the direction and form that is required to provide specific characteristics. The composite created is left to cure by heat or chemical reaction, and take its solid form. (Tooren et al., 1993)

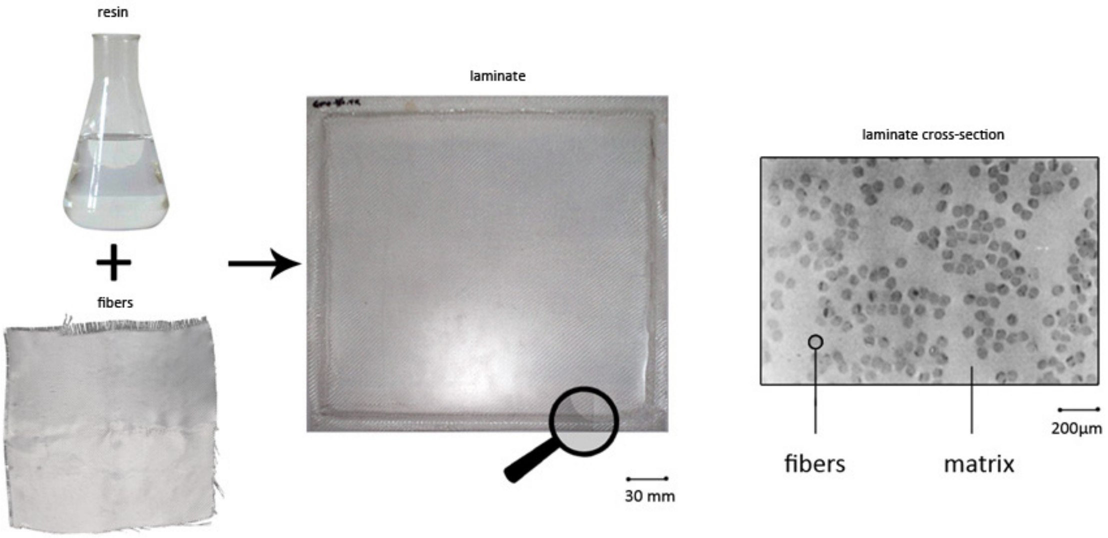


Figure 25: (left) Epoxy resin in liquid state (source: www.asia.ru) and a 160g/m^2 woven roving glass fiber mat, laminated together (at a 50/50 weight ratio) into a 0.27mm thick laminate (center). At the right, a cross section of an epoxy-fiberglass laminate (source: (Iba et al., 2002))

If the matrix is translucent in both its states, and glass fibers are used as reinforcement, the laminate is also translucent.

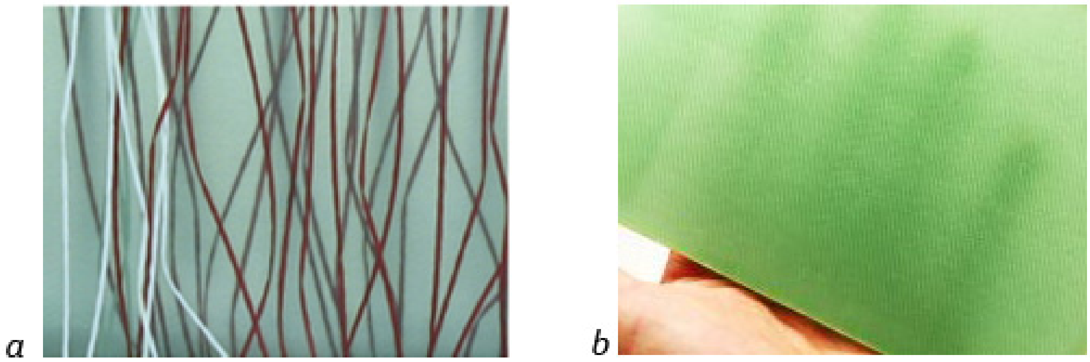


Figure 26: Raficlad, by Holland Composites, it is produced in thicknesses of 4-5mm and embeds colored threads as decorative elements, Halusite, by Hahlbrock The comparative advantage is its high fire resistance, which allows its application to wide interior surfaces (source http://www.raumprobe.de/material_3592_3384_0_1_.html)

Before evaluating the properties of the GFRP laminate, we should have a quick look at the general properties of the basic classes of matrix and glass fiber classes, most often used for the production of laminates.

1. Matrices

The two main classes of polymers used as matrices, are thermoplastics and thermosets.

Thermoplastics	soften when heated and harden when cooled. During excess heating, they eventually liquefy. These processes are reversible and may be repeated. Examples of common thermoplastics include polyethylene, polystyrene, poly(ethylene terephthalate), and poly(vinyl chloride).
Thermosets	become permanently hard during their curing, and do not soften upon heating. Only heating to excessive temperatures can cause damage to their molecular bonds that result to polymer degradation. Thermoset polymers are generally harder and stronger than thermoplastics and have better dimensional stability. Examples of common thermosets are vulcanized rubbers, epoxies, and a family of polyester resins (Callister, 2007)

In practice laminates consist almost exclusively of *thermosets* (Tooren et al., 1993).

The two most commonly used thermosets are polyester and epoxy resins.

Figure 27: Translucent sheets made of casted Polyester (left) and Epoxy (right) resin, photographed on a grey background (center)

Unsaturated Polyester resins (PUN)	are easily accessible, cheap and find use in a wide range of fields. In their liquid state, they can be stored at room temperature for a long period. Adding a curing catalyst can trigger their curing process instantaneously. During curing though, they emit harmful gasses and present volume shrinkage. They are used in automobile and structural applications.
Epoxy resins (EPO)	are widely used in filament-wound composites and are suitable for molding prepress. They are reasonably stable to chemical attacks and are excellent adherents, presenting having slow shrinkage during curing and do not emit harmful gases. These advantages, however, make the use of epoxies rather expensive. In addition, they cannot be expected beyond a temperature of 140°C. Their use in high technology areas where service temperatures are higher, as a result, is ruled out. (Pandey, 2004)

Translucent PUN and EPO are both commercially available.

2. Fibers

Over 95% of the fibers used in reinforced polymers are glass fibers, as they are inexpensive, easy to manufacture and possess high strength and stiffness compared to the plastics they reinforce. Their low density (ρ), resistance to chemicals, insulation capacity are other, although the one major disadvantage in glass is that it is prone to break when subjected to high tensile stress for a long time. (Pandey, 2004)

By definition "glass" refers to any substance formed by cooling from a liquid state to one in which the viscosity has risen to 10^{13} poises or greater.

The orientation of the fiber in the matrix is an indication of the strength of the composite. The strength is greatest along the longitudinal directional of fiber.

Glass fiber reinforcements are commercially available in 2 basic forms: chopped or in mats.

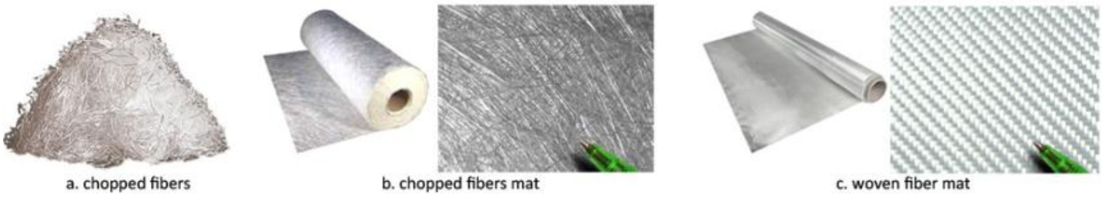
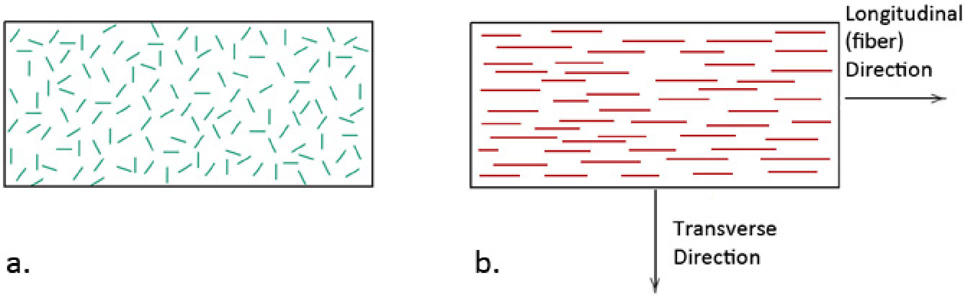


Figure 28: a. Are mostly used in free-form composites with low structural demands. b. Are used mostly in composites with medium structural demands, also to increase the thickness of the laminate. c. Are used for composites with high structural demands, since they are composed of long continuous fibers. The weaving pattern is selected according to the specific demands. (source: www.cfsnet.co.uk/)

Glass fiber reinforcement by the use of chopped fibers or chopped fiber mats (CSM), is characterized by the constant fiber-direction randomness throughout the matrix volume. Therefore, it can be said that the laminate has the same mechanical properties in all directions, and that it is mechanically isotropic.

Glass fiber reinforcement by the use of continuous unidirectional fibers woven in a mat (WR), is characterized by larger strength and stiffness of the, although only in the direction of the fibers Therefore, it can be said that the laminate is anisotropic, and it presents isotropic behavior only in the fiber direction.



Scheme 10: a. CSM laminate, Isotropic in all directions, b. WR laminate, Isotropic in the Longitudinal (fiber) direction, but anisotropic in the Transverse direction. (source: (Callister, 2007)

3.1 Properties

The matrix provides mechanical support for the fibers and assists them in carrying the loads.

Apart from the structural assistance, however, the matrix also protects the fibers from environment, provides thermal and chemical stability to the laminate, and allows its fabrication and processability (Callister, 2007).

We can then assume that in order to understand the general properties of the laminate, we should examine the matrix properties.

The basic advantages and disadvantages between the 2 thermoset matrices examined in this research are presented in the following table.

	Advantages	Disadvantages
Unsaturated Polyester (PUN)	- Low cost; also does not require special storage or shipment conditions - Good mechanical strength - Good heat resistance - Cold and hot molding	- Slightly colored in view - Flame resistant only with additives, that reduce transparency - Low viscosity and versatility - Lower strength than epoxy - Fair weatherability - High curing shrinkage - Poor chemical resistance.
Epoxy (EPO)	- Good mechanical strength-stronger than polyester - Clearer in view than polyester - More viscous and versatile than polyester - Low shrinkage during curing - Flame resistant - Good chemical resistance - No by-products formed during cure.	- High cost; also requires special storage and shipment conditions - Low service temperature - Laminate displays light brittleness. - Hot molding (usually)

Table 3: Comparison between Unsaturated Polyester (PUN) and Epoxy (EPO) resins (source:(Pandey, 2004))

A wide variety of additives is used in composites to modify materials properties and tailor the laminate performance. Although these materials are generally used in relatively low quantity by weight compared to resins and reinforcement, they perform critical functions. (Pandey, 2004)

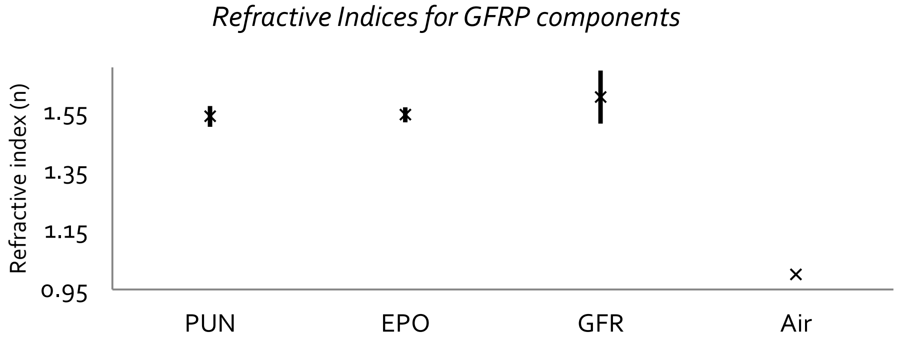
Surface quality	When a smooth surface is required, a special thermoplastic resin, which moderates resin shrinkage, can be added to thermoset resins.
Fire resistance	Flame retardant additives can improve combustion resistance. Even though polyester is flam self-extinguishing, when it burns it emits toxic smoke.
Air release	Most laminating resins, gel coats and other polyester resins might entrap air during processing and application. This can cause air voids and improper fiber wet-out. Air release additives are used to reduce such air entrapment and to enhance fiber wet-out.
Emission control	In open mold applications, styrene emission suppressants are used to lower emissions for air quality compliance.
Viscosity control	In many composite types, it is critical to have a low, workable viscosity during production. Lower viscosity in such filled systems is usually achieved by use of wetting and dispersing additives. These additives facilitate the wet-out and dispersion of fillers resulting in lower viscosity.
Thermal conductivity	Most composites have low thermal conductivity values. It is possible to obtain a degree of electrical conductivity by the addition of metal, carbon particles or conductive fibers. Electromagnetic interference shielding can be achieved by incorporating conductive materials.
Water Resistance	GFRP suffer a loss in mechanical strength when exposed to water. Both surface and internal cracking occurs. Those are caused by the large tensile forces created by hydrolysis of the polyester bonds (Ashbee et al., 1967) Both epoxy and polyester resin present problems in long exposure to aqueous environment. However, the epoxy behaves much better that polyester. Plastics are sometimes modified with antioxidants, which retard or inhibit polymer oxidation and the resulting degradation of the polymer.
Antistatic protection	Antistatic agents are added to polymers to reduce their tendency to attract electrical charge. Control of static electricity is essential in processing and handling operation of certain plastics, as well as in finished products. Static charges on plastics can produce shocks, present fire hazard and attract dust. The effect of static charge in computer/data processing applications, for example, is particularly detrimental.
Foam structure enhancement	Foaming agents are added to polymers during processing to form minute cells inside the resin. Foamed plastics exhibit lower density, decrease material costs, improves electrical and thermal insulation, increase strength to weight ratio and reduce shrinkage and part warping.
UV radiation protection	Both thermoset and thermoplastic composites use special materials that are added to prevent loss of gloss, crazing, chalking, and discoloration, changes in electrical characteristics, embrittlement and disintegration due to ultraviolet (UV) radiation. Additives, which protect composites by absorbing the UV, are called ultraviolet absorbers. Materials, which protect the polymer in some other manner, are known as ultraviolet stabilizers.

3.2 GFRP Optical Performance

Influence of glass fibers and resins

Refractive index

Iba et al. (2002) mention that to achieve high light transmission at a GFRP laminate, the refractive indices -for visible light- of the fiber and matrix must be close. If we compare the refractive indices of EPO, PUN and[19], we can see that the combinations GFR+PUN or GFR+EPO have juxtaposing areas of coinciding values.


Refractive Indices for GFRP components

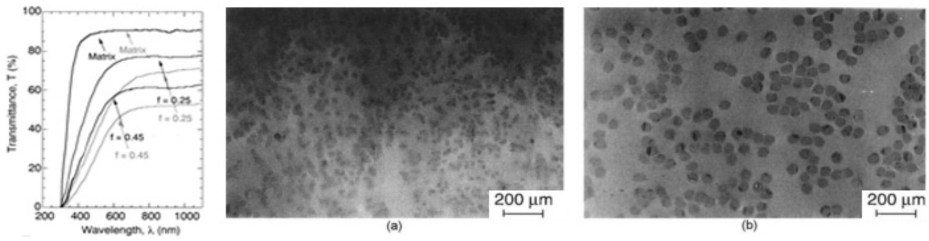
	PUN	EPO	GFR	Air
min	1.500	1.515	1.512	1.000
max	1.570	1.565	1.690	1.000

Chart 9: Refractive indices range for transparent polyester (PUN), epoxy (EPO), glass fibers (GFR) and air. PUN, EPO and GFR coincide at the range between 1.50-1.55.

The difference between the GFR and Air, also explains why glass fiber mat seem opaque to the naked eye. If we agree that a GFR sheer is a composite structure of Glass Fibers embedded in an Air matrix, the difference possesses such high differences.

Fiber quality

The resin quality, is obviously a parameter that influences transparency. However, the quality of fibers also plays an important role in the transparency values. The thicker the diameter of the glass fiber, the more transparent the fiber is. Since, however all the fibers examined in this research are coming from the same manufacturer, fiber quality is not a research or design parameter.



Scheme 11: Light transmittance for two GFRP with fibers of different diameter (b>a). The bigger the fiber diameter, the more transparent the composite is.

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[19] Values acquired from: PUN, GFR (CARPENTER, R. E. 1971. *Preparation of Glass-Reinforced Polyester Sheets*. United States patent application 3607530.) EPO (COOPER, P. R. 1982. Refractive-index measurements of paraffin, a silicone elastomer, and an epoxy resin over the 500-1500-nm spectral range. *Applied Optics*, 21.), Air (http://refractiveindex.info/?group=GASES&material=Air)

3.2.1 Light transmission at GFRPs

Due to lack of in-depth information and photographic records in literature, a series of tests were conducted to evaluate the light transmission and Image distortion ID caused by GFRP laminates.

An example of such a comparison is the EPO vs. PUN comparison. For each sample, Histogram[20] graphs from Adobe Photoshop were made to determine if any discoloration is present. Any difference in tone dispersion from the original sample, means color addition.

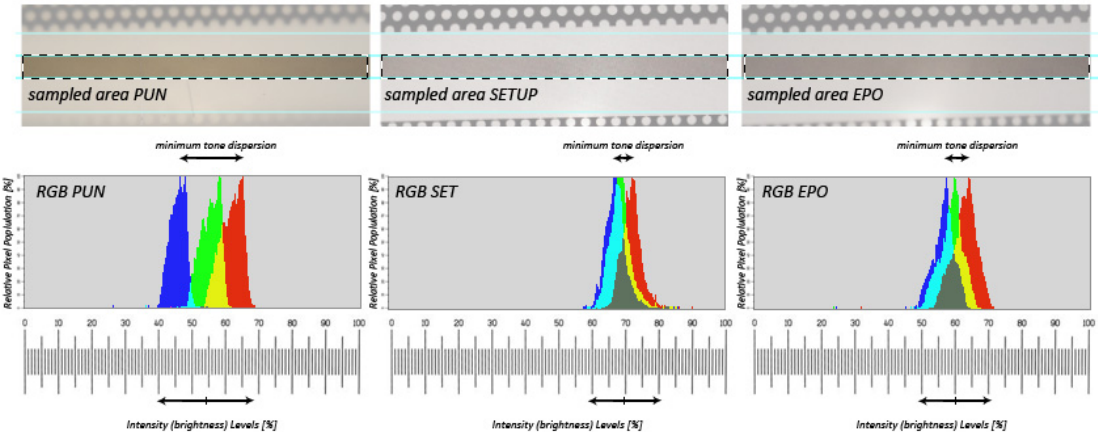

Figure 29: Histogram (Adobe Photoshop) comparison.

Transparency	The PUN sample is less transparent than the EPO at the same thicknesses.
Image Distortion	Image distortion from PUN is also much larger than EPO at long distances (>30mm), whereas at 0mm from its surface it still distorts, but not as much.

Moreover, PUN is characterized by a distinct yellowish tint, which becomes discrete at growing thicknesses. A slight discoloration is visible at the epoxy sample, which is verified by the Histograms.

Light transmittance seems to remain almost equal as the EPO thickness increases, at levels above 0.9 (max 1.0). On the other hand, PUN's transmittance seems to drop, as its thickness increases.

In other words, EPO is clearer in all of the most probable working thicknesses (1-3mm), and distorts the image behind it much lesser than PUN.

Practically, it means that if a better optical quality is demanded, then using EPO resin is a better option than using PUNs.

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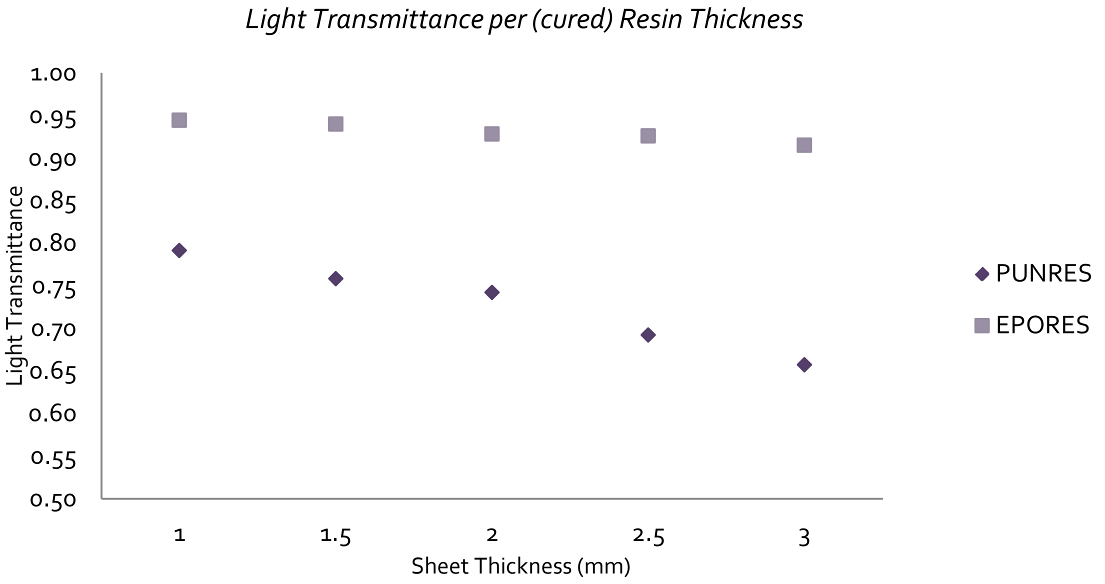
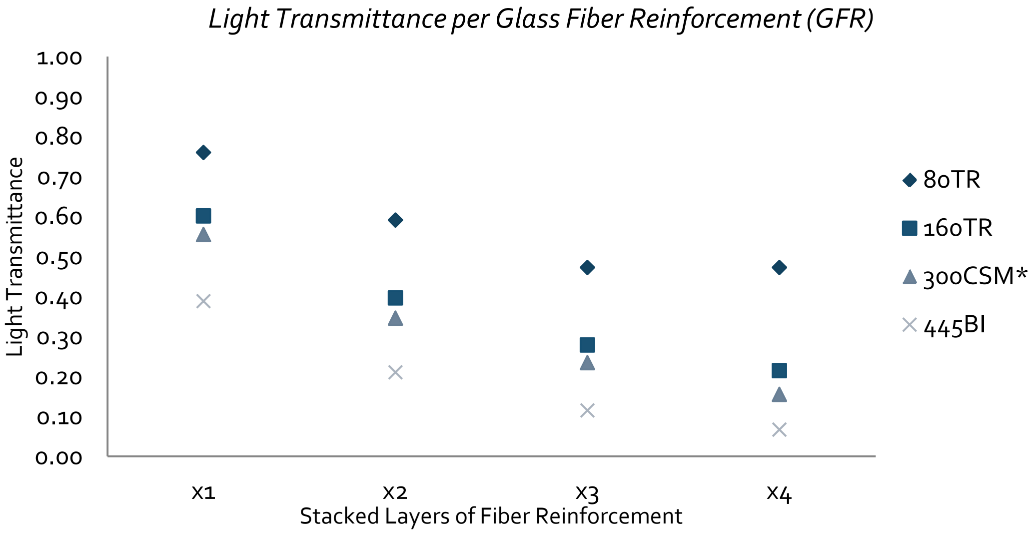
[20] A histogram illustrates how pixels in an image are distributed by graphing the number of pixels at each color intensity level. The intensity levels are set on the horizontal axis, and are scaled from 0% to 100% intensity. The brighter the image is, the bigger the intensity level. (source: http://help.adobe.com/en_US/photoshop/cs/using/WSfd1234e1c4b69f30ea53e41001031ab64-768ba.html#WSfd1234e1c4b69f30ea53e41001031ab64-768aa)



PUN	0.79	0.75	0.74	0.69	0.65
EPO	0.94	0.93	0.92	0.92	0.91

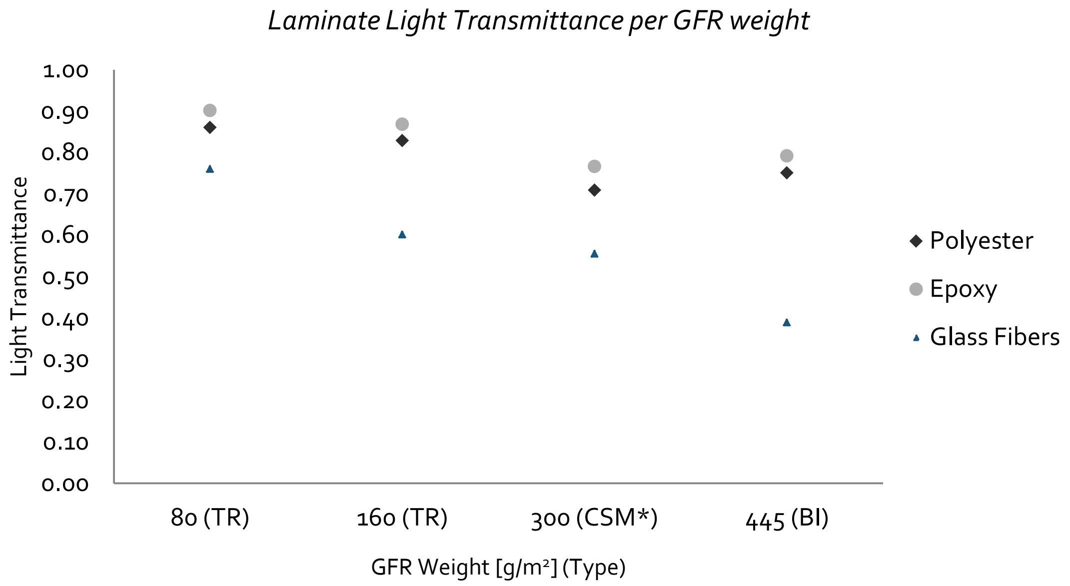
Scheme 12: Diagram comparing the measured light transmittance values of two Unreinforced thermoset sheets, EPO and PUN, at varying thicknesses.

Light transmission of a GFRP composite should decreases with the increase of the fiber quantity according to Iba et al. (2002). The transmittance values were measured separately for the fiber mats and the laminates.



80TR	0.76	0.60	0.56	0.39
160TR	0.59	0.40	0.35	0.21
300CSM	0.47	0.28	0.23	0.12
445BI	0.47	0.21	0.16	0.07

Scheme 13: Comparison between the measured light transmittance per Glass Fiber type, and times of layers (x#) per volume.



Polyester	0.860	0.828	0.709	0.751
Epoxy	0.902	0.868	0.766	0.792
Glass Fibers	0.760	0.601	0.555	0.389

Scheme 14: Measured light transmittance per basic laminate, compared with the transparency of the composing fibers.

It is obvious from the results that the light transmittance of the composites does decreases with the increase of fiber-volume fraction.

It follows the logical assumption that since the matrix is the most transparent element, any addition would decrease it.

However, it is interesting to see that the CSM (chopped strand mat) laminate presents lower values than the rest of the laminates. This is probably due by the uneven distribution of fibers that enhance the refraction and maybe the reflection within the laminate.

3.2.2 Image distortion (ID) at GFRPs

The difference in ID at different resins is much bigger in PUN than in EPO. Looking at the P1, which usually affected the most, the distortion is noticeable.

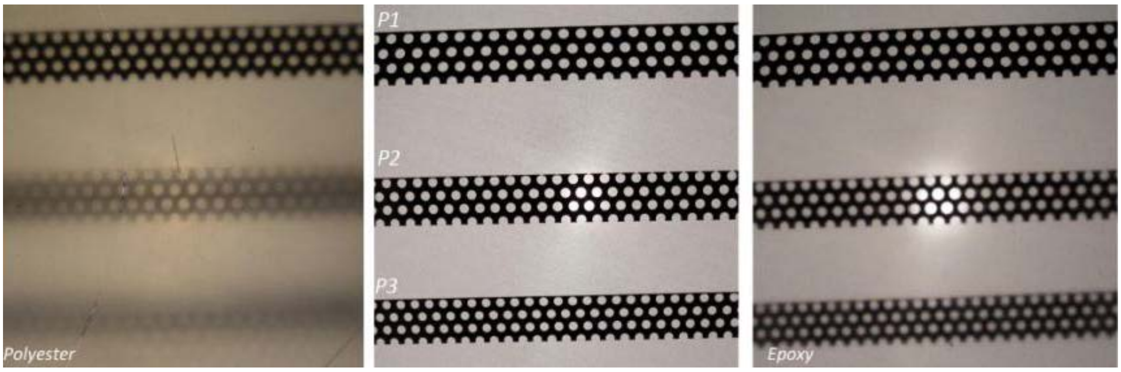


Figure 30: From left to right: 1.Unreinforced Polyester Sheet of varying thickness 4-2mm from top to bottom, 2.Comparative setup, 3. Unreinforced Epoxy Sheet of varying thickness 4-2mm from top to bottom

We should note at this point, that the resin volume fraction at those panels is 1.0, which is not representative of the laminates. A Glass fiber reinforced laminate presents volume fractions around 0.5, which is much lower.

The resin volume fraction is a parameter that controls the thickness of a laminate.

Therefore, we can say that since the ID is also a function of thickness, then a very thin PUN or EPO sheet will cause much lower ID.

An attempt to fabricate very thin EPO and PUN sheets (<1mm) was made, but the cured sheets were very brittle, due to the lack of embedded GFR, and they shattered during the de-molding process.

As we saw at previous tests, the T_λ is reduced by the increase in fiber weight/m^2 of fibers of the same type. This also seems to apply in ID: the bigger the weight/m^2, the bigger the ID.

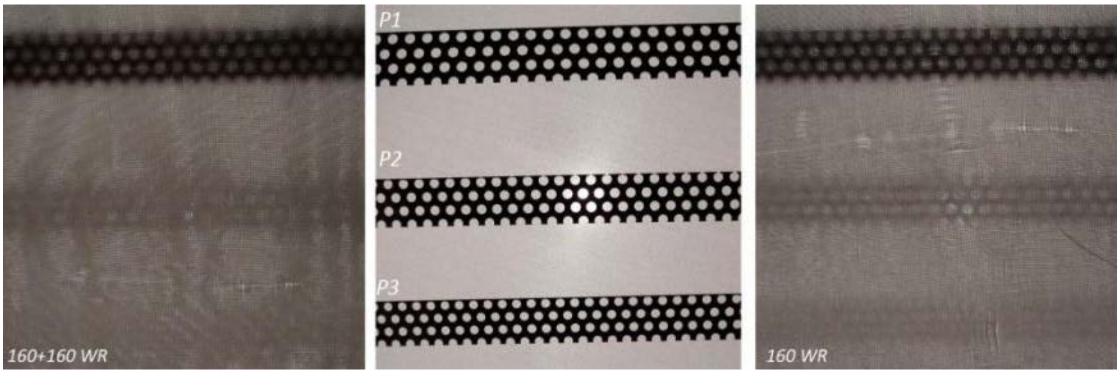


Figure 31: Comparison between a 2 (left) and a 1 (right) layer GFR sample of 160g/m^2 fiber mat. At the double layer, the P3 is almost not distinguishable. Noticeable is also the difference in brightness.

The following image shows a comparison between 2 GFR of approximately equal weight, but different types. It is obvious that between different fiber types the ID intensity also differs.

This seems to occur more due to the fiber pattern, however, than the fiber weight.

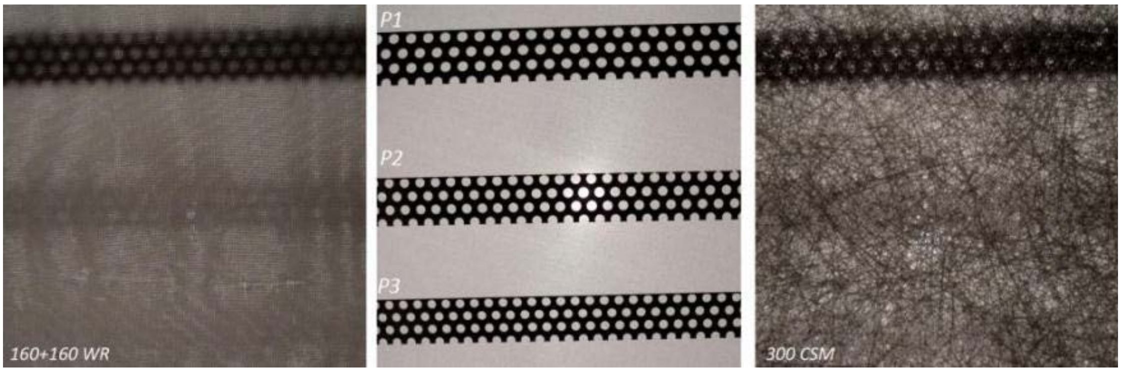


Figure 32: Comparison between a 2 layers GFR sample 160+160g/m² fibers to a 300g/m² CSM..

Based on the observation of the previous tests, it is expected that the increase of GFR weight/m² at a laminate will increase the ID.

It is also expected that the ID pattern will follow the pattern on the fibers.

The following table can be used to visually compare the effects of the resin class and fiber type has on the ID caused by a GFRP laminate.

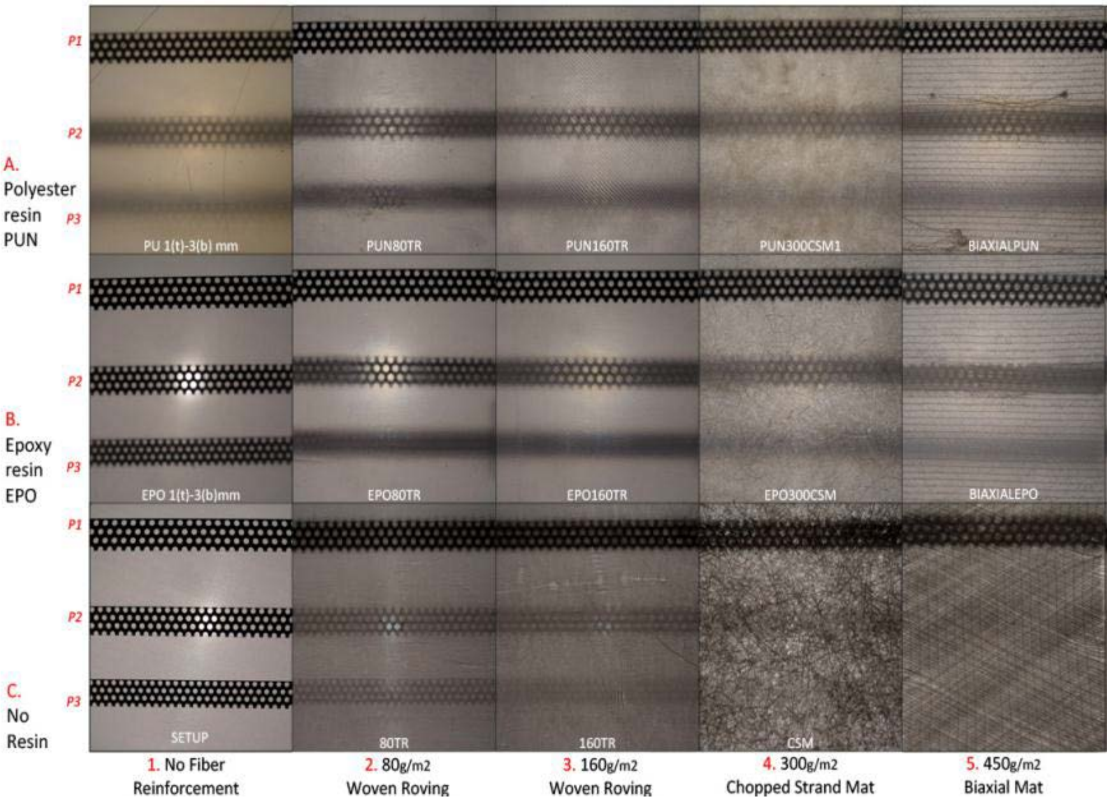
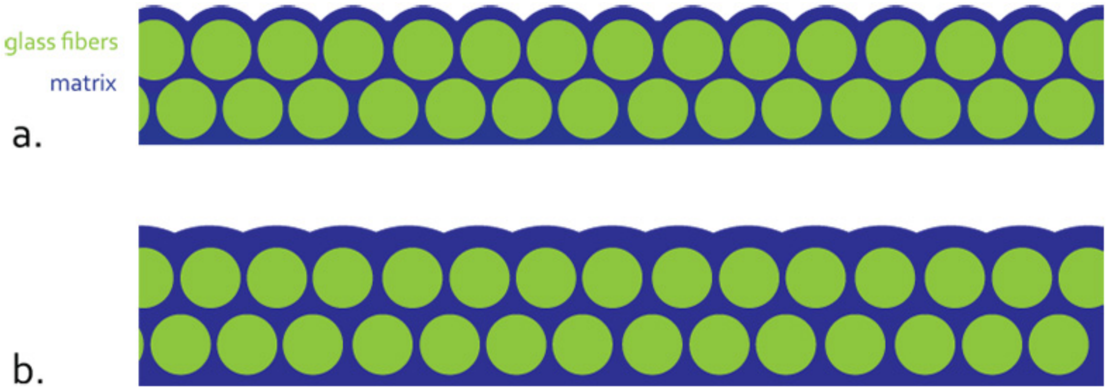


Table 4: ID comparison between EPO and PUN GFRP sheets, along with the GFRP mats.

An interesting fact is that the glass fiber reinforcement creates a pattern, which is visible at through the laminate.

This is most probably a parameter controlled by the fabrication process.

The recommended 'Fiber/Resin weight-ratio' for the fabrication of GFRP laminates using the hand-layup process is 50/50 for the WR fiber type ,and 40/60 for the CSM fiber type. The bigger the ratio is (larger fiber weight) the 'drier' the laminate is.



Scheme 15: a. A 'Dry' laminate and b. a 'Wet' laminate

The samples we created presented an average of 45/55 for the WR, and 35/65 for the CSM, so they are 'dry' laminates.

To see if the 'dryness' of a laminate influences its ID, we fabricated a 'wetter' WR and compared it to a 'dryer'. The 'dry' 80+160g/m^2 presented a f/r weight ratio=45/55, and the 'wet' 80+160g/m^2 a 25/75WR.

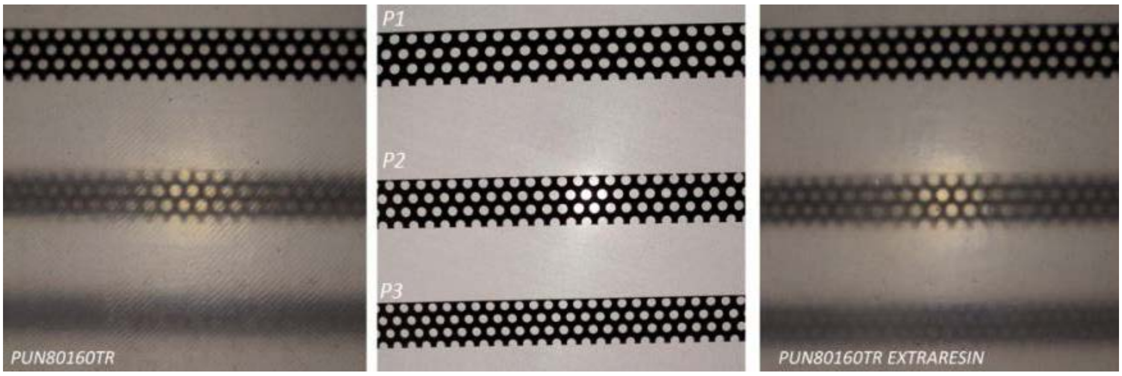


Figure 33: Comparison between a 'dry' and a 'wet' laminate.

Comparing the photographs of the sample PUN80160TR Extra Resin to the PUN80160TR, we can see that the fiber pattern at the 'wet' laminate is no longer visible.

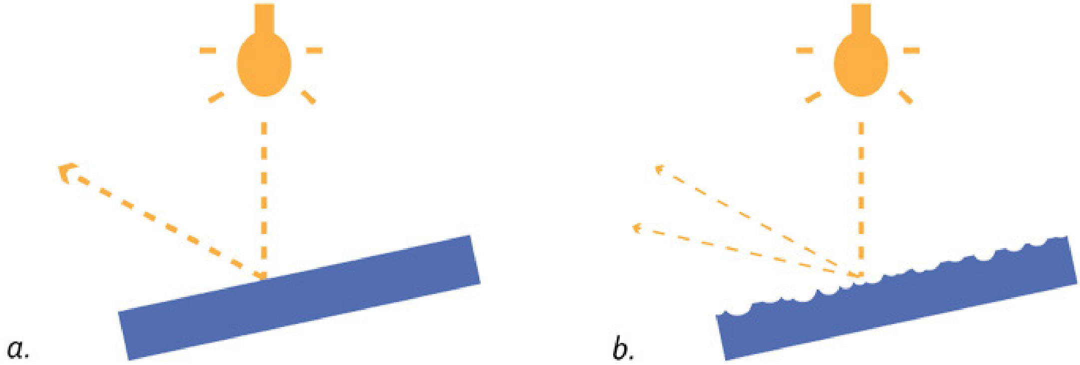
An interesting fact is that the surface of the PUN80160TR Extra Resin sample was smoother, and not as 'bumpy' as the PUN80160TR. The 'bump' on the PUN80160TR sample was created by the protruding glass fibers, as we can also see in scheme 17.

In order to evaluate the 'bumpiness of the surface', which is a parameter to define the surface quality, a third test was conducted.

3.2.3 Reflection Pattern at GFRPs

A photographic test also conducted, in order to investigate the relationship between the fiber type used for the laminate and its surface quality.

A rough surface reflects light from a light source in a diffuse way, whereas a smooth surface in a specular[21] way. The difference can be seen at the reflected light pattern, which is reflected on the surface. A rough surface presents a broader and less bright reflection, whereas a smooth surface presents a more concentrated and bright reflection.



Scheme 16: a. Specular reflection b. Diffuse reflection

As mentioned already, the process followed to create the samples was the Hand-layup. Hand lay-up is an open mold process. (Mazumdar, 2001)

In open-mold processes, the mold surface pattern is imprinted on the part of the laminate that faces the mold. A smooth mold will give a smooth finish to the laminate. This side of the laminate we will call 'smooth'.

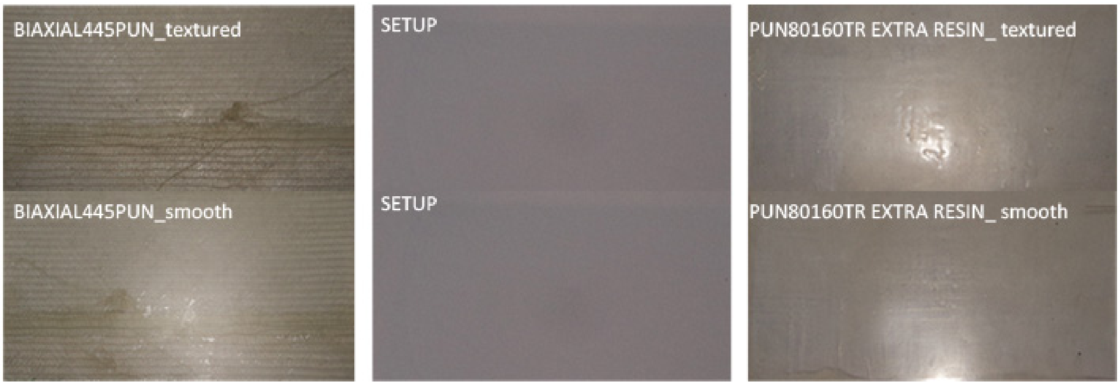


Figure 34: Comparison between the reflections at two sides of the BIAXIAL445PUN sample to the reflection at two sides of the PUN80160TRER sample. It is interesting to see that the high roughness of the BIAXIAL_textured face almost eliminated the light reflection. It is also interesting to see that the fiber pattern in the PUNEXTRARESIN_textured

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[21] Specular reflection is the mirror-like reflection of light from a surface, in which light from a single incoming direction (a ray) is reflected into a single outgoing direction.

The part of the laminate facing away from the mold, is getting a textured pattern, which follows the texture of the last layer of glass fibers. This side of the laminate we will call 'textured'.

The result of the tests for the laminates is presented in the following table.

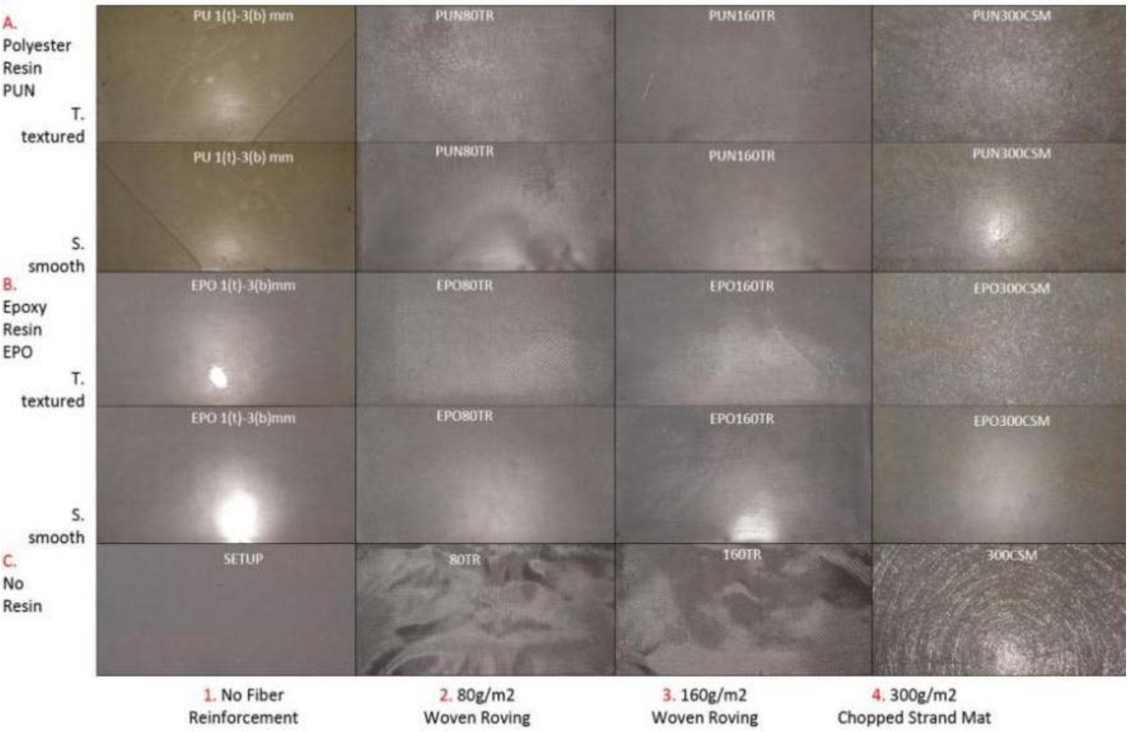

Table 5: Textured and Smooth surface quality as recorded for the fabricated samples.

From the tests it was also observed, that at the textured side, the higher the f/r ratio[22] of the laminate was, the less visible the pattern. The influence at the smooth sides was not perceptible.

In terms of esthetics, each designer should subjectively interpret these results.

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[22] -A wetter laminate'

4 PCM-FRP Panels

Introduction

Tooren et al. (1993) state that the four parameters that define the success of a final product using polymers are:

A. the suitability of material,
B. the manufacturing process,
C. geometry and,
D. size

Those parameters are interconnected and influence each other. Many problems can derive if the relationship is not correct.

Before investigating the optical performance of the panels, it is important to see which combinations between the PCM-FRP presents potential to become a product.

4.1 Material Suitability

The two most common points noted in literature regarding macro-encapsulation of PCMs are chemical compatibility and leakage.

Chemical Compatibility

As already mentioned paraffin is preferred to hydrated salts when it comes to chemical compatibility, since stays inert with most encapsulating materials.

No example has been found in literature, so far, that unites EPO or PUN laminates with hydrated salt PCMs.

Since their corrosive behavior is due to their alkaline nature and their high quantity in water, we can expect it to be corrosive . (Mehling and Cabeza, 2008)

Leakage

Leakage is a problem present to both paraffin and hydrated salts, due to their liquid nature. In most PCM applications, it is the dominant practical problem, which leads to the using concealed plastic or metal boxes, pouches or bottles as encapsulating materials.

It was a dominant problem notable also during our experimentation where, after a period of 14 days with no problems, a hydrated salt leaked out of a test panel.

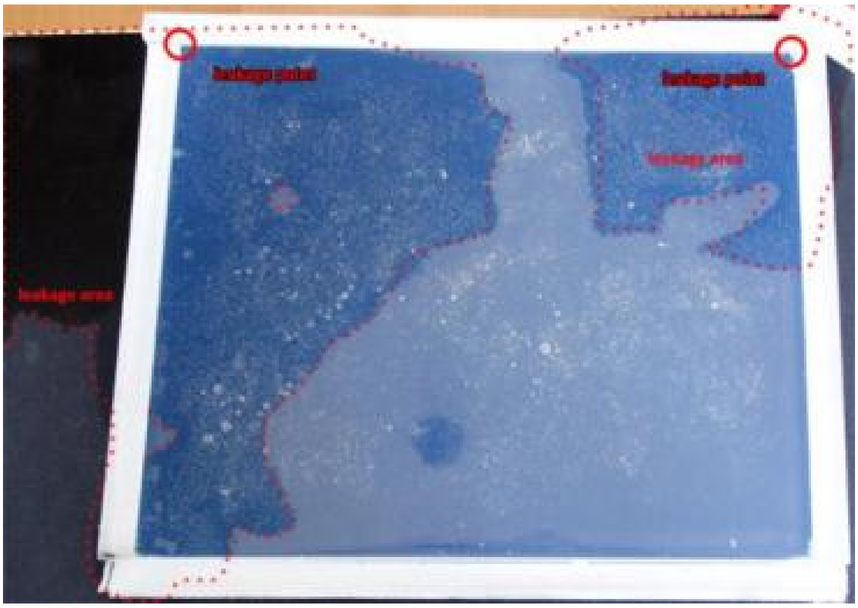


Figure 35: Hydrated Salts Leakage at a custom-made Plexiglas panel. Leakage occurred 14 days after the original filling.

Polymer encapsulated paraffin (PEP) and CLIMASEL salt hydrates have a comparative advantage on leakage, since they always stay solid (solid - solid 'phase change').

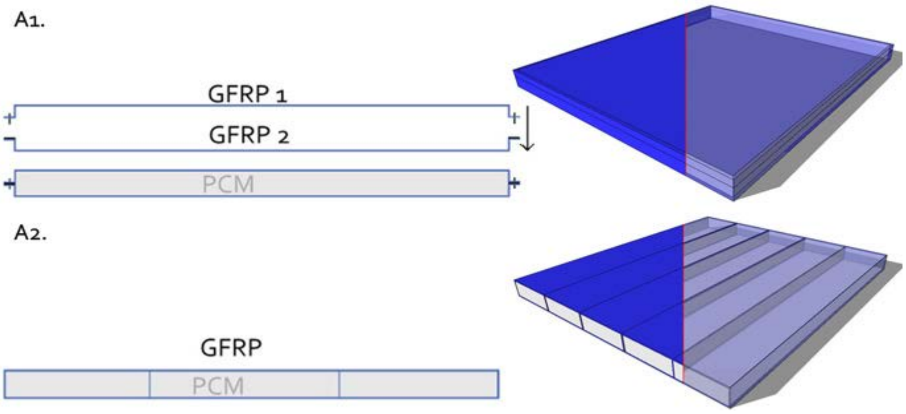
4.2 Manufacturing process

The GFRP presents the possibility to produce a panel in two distinct ways:

1) the *Box* panel.

The GFRP and the PCM are combined after the GFRP encapsulating panel is fabricated. The GFRP sheets can be produced separately, and be joined with adhesives or bolts, enabling the PCM to be filled in afterwards.

This panelization process is reversible since the GFRP and the PCM can be separated afterwards. The ease of separation depends on the adhesion between the GFRP components.

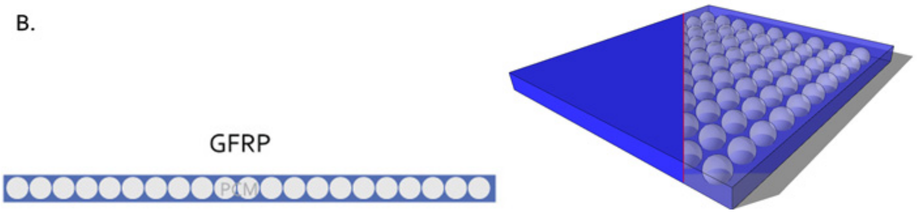


Scheme 17: Box panels. Two dished sheets joined at the sides make A1. A single Pultruded sheet makes A2.

The difference between the box panels A1 and A2, as we will see later on this chapter, is the production process they follow.

2) the *Integrated* panel.

The PCM is embedded within the GFRP matrix, during sheet fabrication. This panelization process is irreversible since the encapsulating surface and the filling cannot be easily separated afterwards.



Scheme 18: Integrated Panel. The PCM is depicted in a schematic way, as spheres

Manufacturing Processes

Using CES2011, we located the manufacturing processes used for the primary shaping for all GFRP elements, including the box and integrated panel.

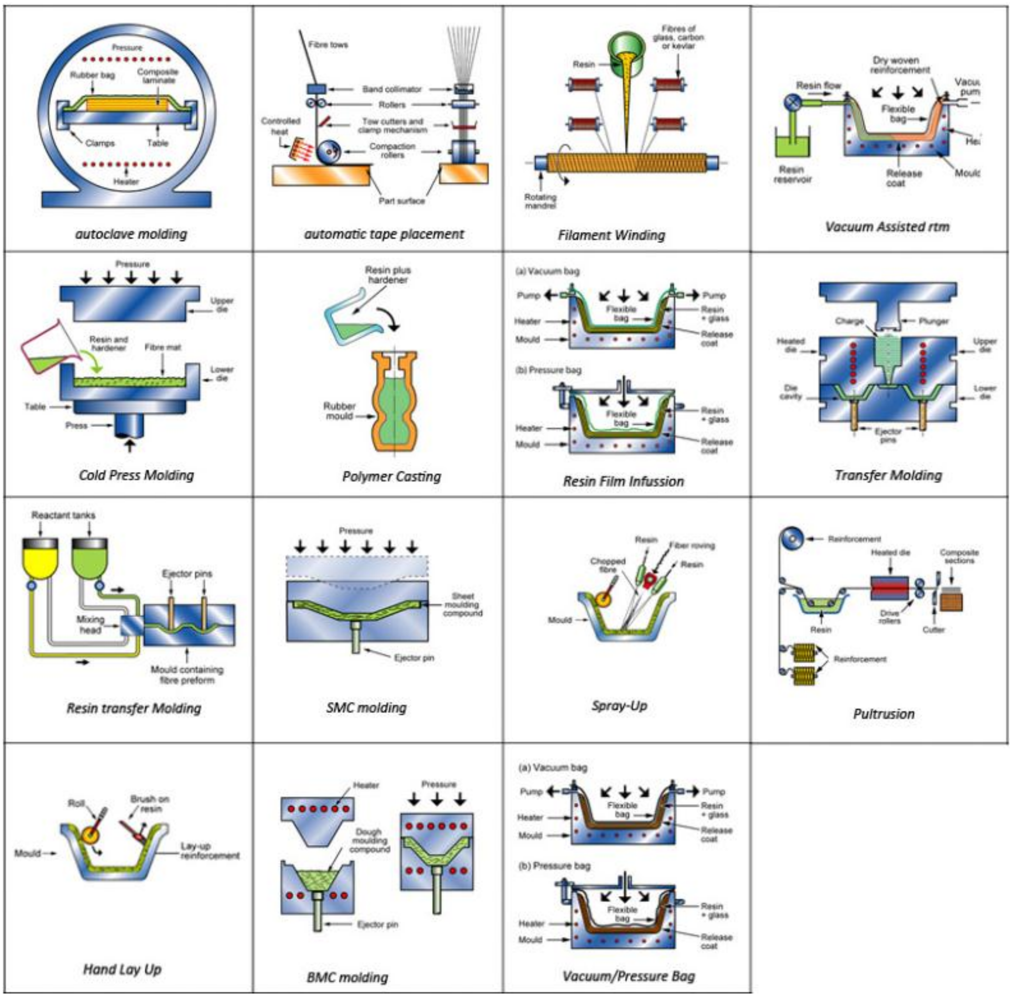


Figure 36: Manufacturing Processes used for fabricating GFRP elements (source: CES2011)

The criteria for choosing an appropriate fabrication process for a specific element, depend mostly on shape, size and cost ((Tooren et al., 1993).

- *Shape* and *Size* are parameters easy to comprehend and describe.
- *Cost* on the other hand, is not a straightforward parameter.
- Besides raw material cost, it involves other aspects such as economic batch size[23], production rate, tooling cost, capital cost and allowable tolerances.

An additional parameter, which is of outmost importance for architecture applications, is surface quality.

---

[23] The economic batch-size is a measure of the product output required before a fabrication process becomes competitive.

Surface quality

Is mathematically described by the term 'Surface Roughness' (R).
R is determined by the nature of the process and is influenced by the smoothness of the mold surfaces in casting and molding, or the depth of cut in machining. It is specified as R<100mmmm (the rough surface of a sand casting) and R<0.01mmmm (a highly polished surface).

Roughness R	*Process*	*Typical application*
R = 0.01	Lapping	Mirrors
R = 0.1	Precision grind or lap	High quality bearings
R = 0.2 – 0.5	Precision grinding	Cylinders, pistons, cams, bearings
R = 0.5 – 2	Precision machining	Gears, ordinary machine parts
R = 2 – 10	Machining	Light-loaded bearings,
R = 3 – 100	Unfinished castings	Non-bearing surfaces

Table 6: Typical Roughness R levels and their usual application. **(source: CES2011**

Post Processing

In most materials, the roughness level can usually be refined by secondary operations, such as machining, grinding, sanding and polishing. Those working principle of these processes are material-removal based: excess material is removed from the surface, until it becomes flat.

However, in the GFRP laminates we examine, these secondary operations are not easily applicable. The main reason is the delicate thicknesses that GFRP laminates. A one-layer laminate, with GFR weight = 300g/m^2 and f/r weight ratio 30/70 (wet laminate), presents a total thickness of maximum 650μm=0.65mm. Even a small reduction of thickness can increase the risk of reduced laminate performance.

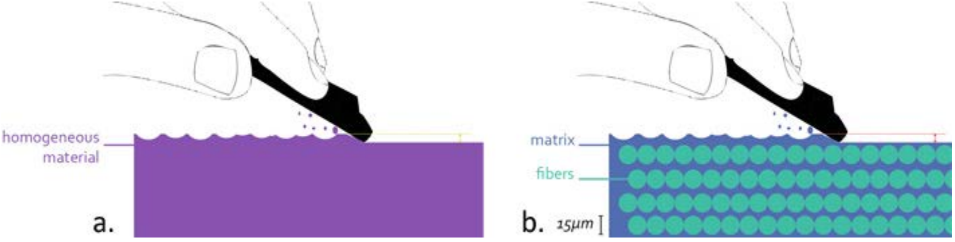


Figure 37: Without any extra coating, sanding can cause structural problems in the laminate, due to the very delicate thickness relationship between the matrix and the fibers.

A small test was conducted to see if post processing will enhance the surface quality, at a 160g/m^2 GFR Epoxy laminated PEP PCM. The surface initially, was slightly patterned due to casting mold imperfections.

Figure 38: Good surface quality (left) and not good surface quality (right). Sanding the sample to get a more homogenous surface using 3 sand papers in the following sequence: Very Fine: P280, Super Fine: P1000, Ultra-Fine: P2000

After sanding, the glass fibers started becoming visible. Even more surprisingly, the surface became less shiny, and got a more opaque look.

GFRP manufacturers propose polishing as a means to get a shiny surface, using epoxy coatings. Polishing with epoxy also for extra surface scratch resistance.

Figure 39: Polishing an acrylic headlight (source: ww.youtube.com/user/meguiarsasia?feature=watch)

However, it requires extra person-hours, , fact which makes it more costly so not appropriate for mass production. Moreover, the most complex the shape becomes, the more difficult and time consuming it is to finish

Therefore, it is recommended that after the primary fabrication process, no post process to be applied.

Practically, this means that the fabrication process selected, should produce panels with a low R.

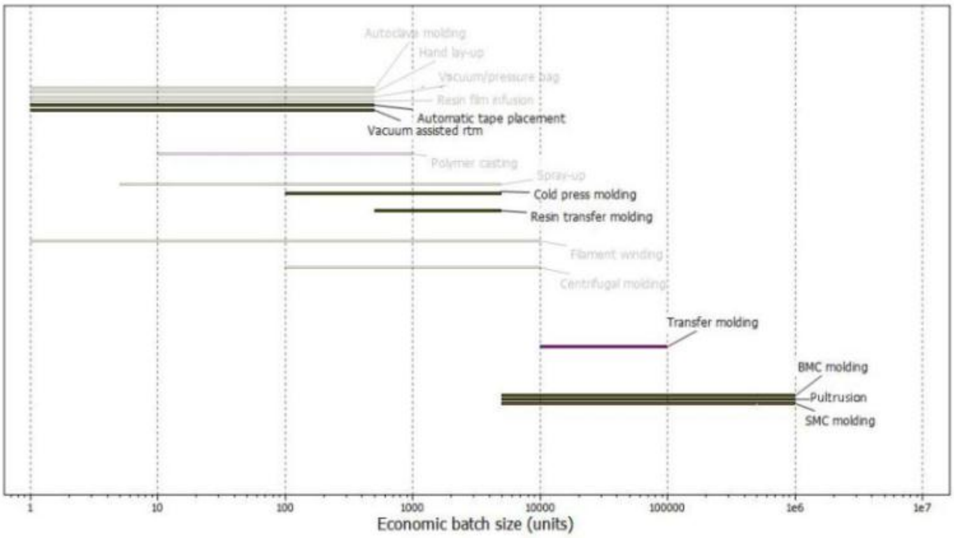
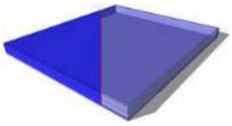
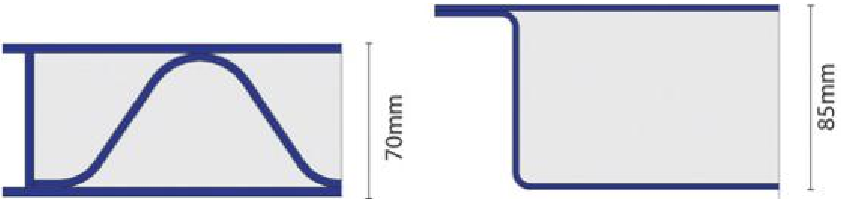


Chart 10: Fabrication Processes for GFRP composites suggested for a good surface quality R=0.3, and their economic batch.

Panel A1



Most of the processes mentioned already are suitable for production of the panel type A1.



Scheme 19: Sections of commercial panels made from planar and dished GFRP sheets, joined with adhesives, by (left) Scobalit and (right) Fiberline. (source: (DETAIL, 2010)

Panel A samples for this research were fabricated using the e hand lay-up process.

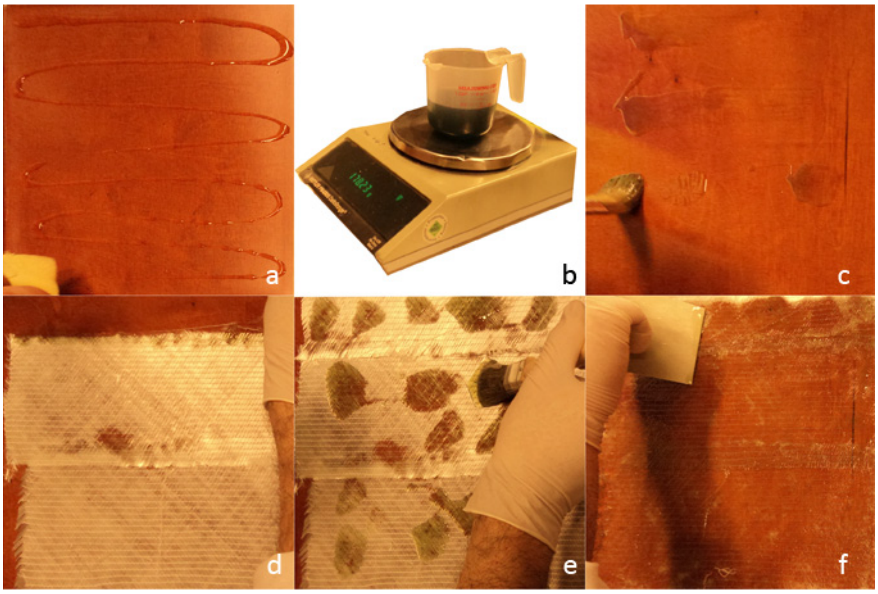
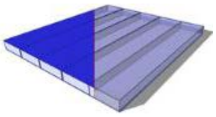


Figure 40: Hand Lay-up fabrication process: a. Laying of the PVA release agent. B. measuring the resin weight, mixing with the catalyst, c. layering the first layer of resin, d. placing the fibers, e. adding the rest of the resin, f. removing trapped air with a plastic spatula. The laminate is left to dry for 48 hrs in room temperature.

However, fabrication of Panel A1, is a 2-phase process. At first, the individual sheets are created, and at second, they are connected together.

The practical difficulty that appears due to the 2-phase fabrication, is the on the airtightness and water tightness at the connections; Leakage of Hydrated Salts and Paraffin PCMs at their liquid state.

Panel A2

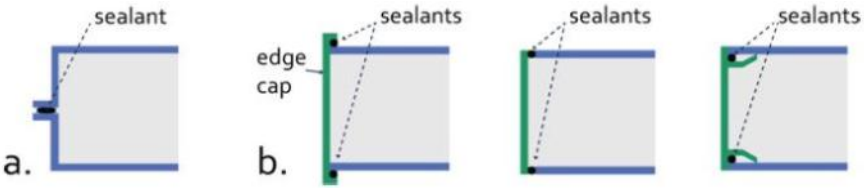


Pultrusion is the most suitable process for production of the panel type A2.

Panel 2 is morphologically the same as panel A1. The advantageous difference is that it is a 1-phase process. Little or no post connecting is required. Leakage is less of a risk, sing the panel is airtight and watertight within its core.

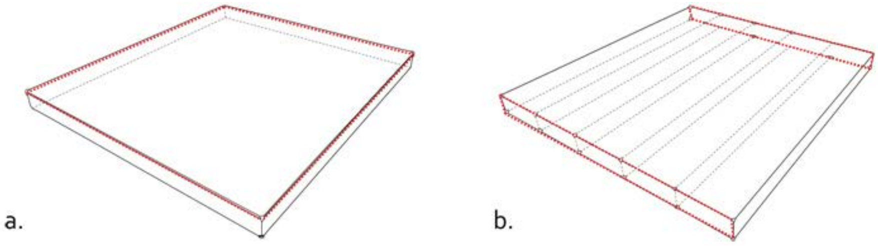
Figure 41: Pultruded GFRP panels from (left) Scobalit –translucent- (source: (DETAIL, 2010) and (right) Fiberline (source: www.reinforcedplastics.com/view/5828/german-bridge-combines-composite-and-steel/)

To minimize leakage risk, the panel should minimum number of possible leakage points. Looking at a cross section, we see that A1 has the need for one sealant point, whereas A2 has the need for two.



Scheme 20. Sealing Points for panel A1 (a.) and panel A2 (b)

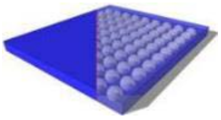
When we look at the entire setup, we see that A1 has need for a sealing line running throughout is periphery. P2 has need for sealing only at its edges. However, two lines of sealing are required, one at each edge.



Scheme 21: Sealing Lines for Panel A1, and Panel A2

Panel A2 has the sealing problem isolated at its two edges. Therefore, compared to panel A1, is a better option.

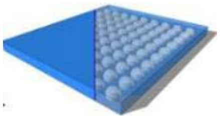
Panel B



An experimental study on the fabrication of a GFR Epoxy and PEP took place in order to pinpoint any practical problems that might derive from this combination.

The fabrication was done for two samples, one flat, and one curved, by the 'hand lay-up' method.

Panel B1



The first sample (PEPEP) was unreinforced[24] and cast on a flat polished-surface wooden mold. The EPO resin was mixed with the catalyst at the recommended ratio[25]. PEP was spread in one layer, until the resin covered its surface. The sample was left to cure for 48 hrs at room temperature and was then removed from the mold.

Figure 42: The PEP at its solid state was stored in an EPS insulated box, until casted.

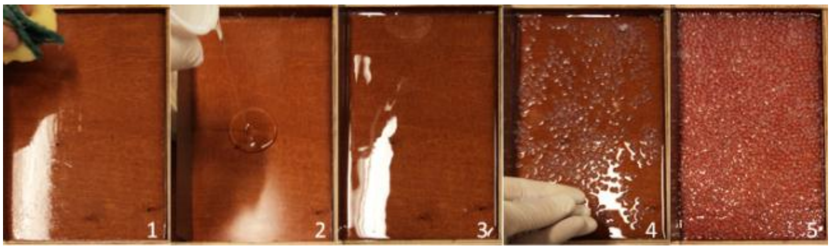


Figure 43: Manufacturing process 1. The PVA release agent is applied to the mold and left to dry for 20 minutes. 2. The mixed EPO+catalyst resin is cast at a first layer3.4.PEP is spread. 5. The final EPO layer is laid, to close any gaps at the surface.

From the process, several observations were made.

Integrating a PCM into an FRP matrix at a Panel B setup[26], can be possible if the PCM is at its solid state during the fabrication process.
In practice, this means that the PCM temperature should stay below its $T_{pc.}$ If the temperatures during fabrication rise above the $T_{pc,}$ the PCM melts.

Exothermic curing

This is a difficult parameter to control since the temperatures at many manufacturing processes regarding GFRP production can reach high levels:

---

[24] Reinforcement should not affect the chemical material compatibility

[25] Recommended by the provider (2 Epoxy-1Catalyst)

[26] Assuming that the materials are compatible, or that the compatibility can be enhanced.

Polyester and epoxy GRP laminates cure with the addition of catalysts (Pandey, 2004). The curing process is exothermic, meaning that it releases energy from the system in the form of heat.

Polyester is curing in much greater exothermic temperatures than epoxy.

This phenomenon was visible during the fabrication of a Panel B sample, in which PEP was molten immediately after it was cast in an Epoxy resin during its cure.

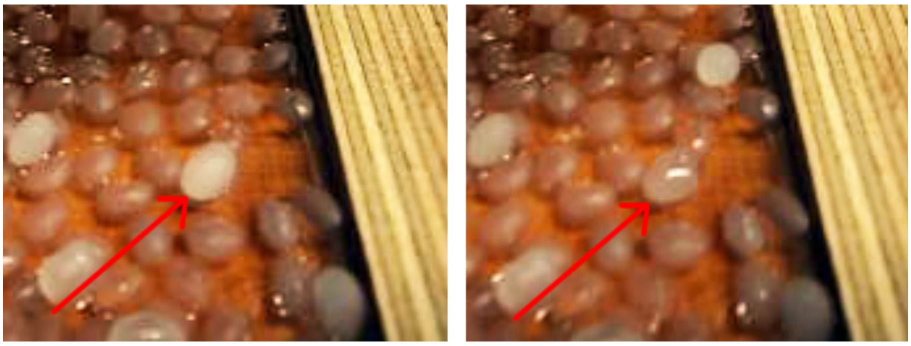


Figure 44: The exothermic curing of GFR Epoxy matrix melts the solidified PEP PCM, in only 2 sec. This means that the $T_{curing}>T_{pc}$.

It is obvious that solid->liquid PCMs are not appropriate for this process, if the melting temperature is around ambient room temperatures. Solid->solid PCMs, such as PEP and CLIMASEL are recommended.

Heat during production

Apart from the catalyst addition, GFRP laminates cure faster in higher ambient temperatures.

Fabrication lines that need rapid GFRP production, tend to use fabrication processes that involve elevated temperatures. In that way, the GFRP products acquire the same mechanical characteristics, quicker.

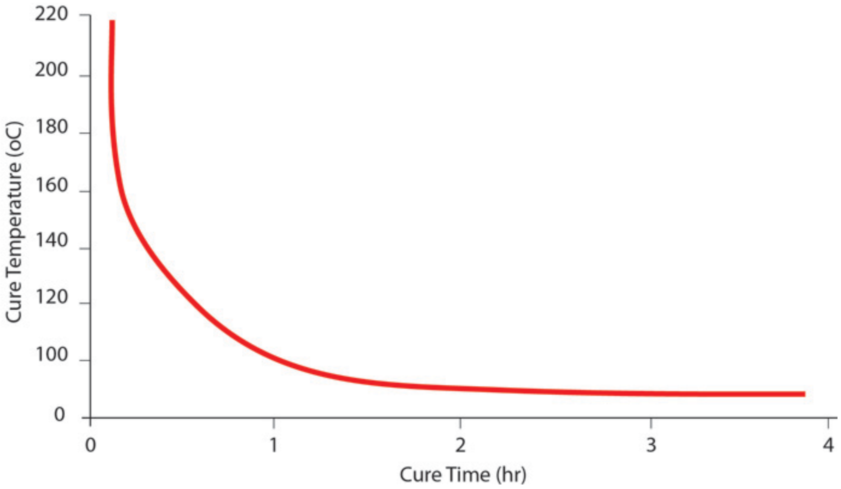


Chart 11: Ambient curing temperature VS time relationship for an epoxy laminate (source: Ltd. (2005))

For the fabrication of the panel B, we can filter the processes mentioned above adding the parameter of low curing temperature (around room level). The following chart shows the results.

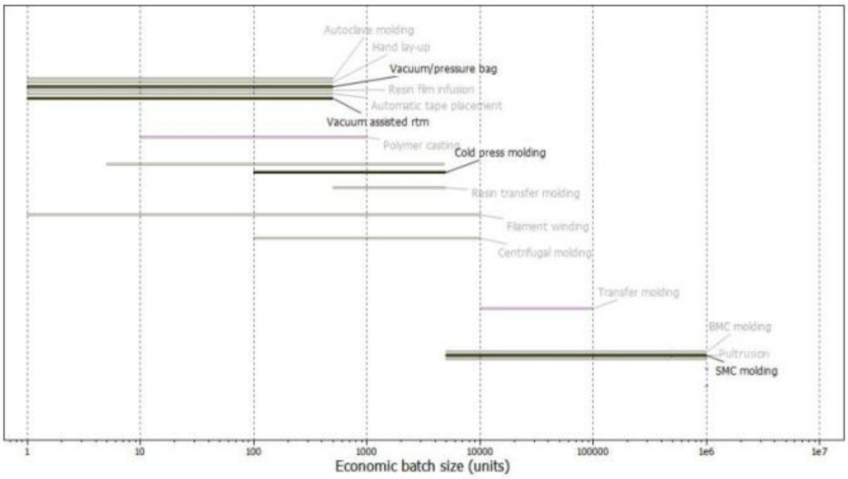


Chart 12: Processes with low machining temperature

The demand for low process temperatures, also excludes the use of thermoplastics[27] for integrated Panel B types.

The sample presented bumpy surfaces at both sides, less at the surface facing the mold, and more at the surface at the exposed side. The texture of the surface was taken from the protruding PEP .

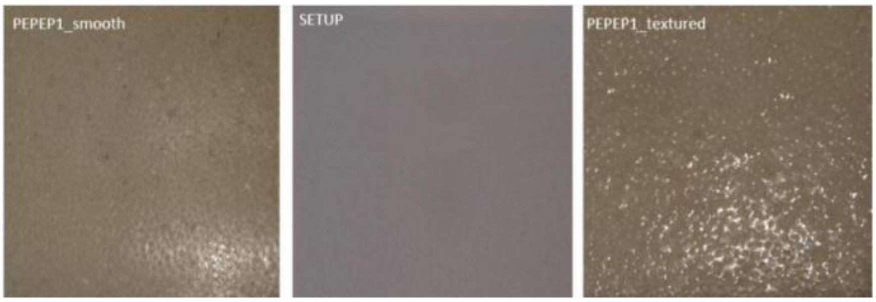


Figure 45: Comparison between the reflections at two sides of the BIAXIAL445PUN sample to the reflection at two sides of the PUN80160TRER sample.

The bigger protrusion at the open mold can be explained if we review the fabrication process.

After setting the first layer of EPO, the PEP capsules were spread. The resin was left to cure for 5 minutes, before setting the second layer of EPO. Surprisingly, after the second layer was set, the PEP PCM, started 'floating' in the epoxy resin.

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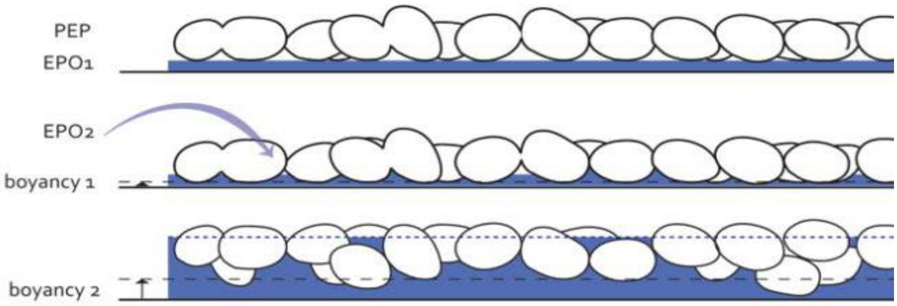
[27] Forming or casting a thermoplastic requires high processing temperatures.



Scheme 22: The floatation of the PEP capsules in the liquid EPO resin.

The buoyancy of the PEP capsules can be explained if we compare the densities of the components: EPO resin (+ 33% hardener) presents a density ρ_{EPO}= 2000kg/m^3, whereas ρ_{PEP}=865kg/m^3.

Since PEP is lighter than EPO, and EPO is still at its liquid form, it is natural that PEP floats.

Figure 46: A cutout section of the PEPEP sample, with the PEP capsules removed. Thickness 3.20 mm

Extra EPO resin was cast in the mold at a part of the PEPEP sample, in order to cover the exposed PEP capsules. The result was more satisfying. However, the total PCM/resin ratio increased from 49/51 to 55/45.

Figure 47: A side view of the final PEPEP sample. Thickness 3,52 mm

By using the vacuum infusion process, instead of the hand lay-up, the result should theoretically be better. The thickness of the panel should become smaller by the PEP compression caused by the vacuum. Moreover, the amount of resin should be reduced, since the capsules will be prevented to float by the vacuum again.

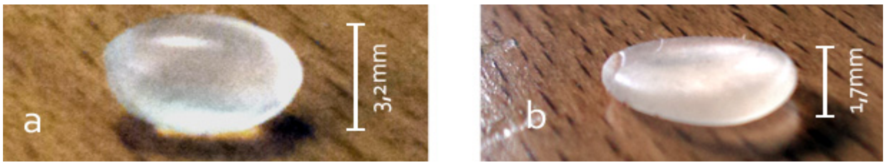
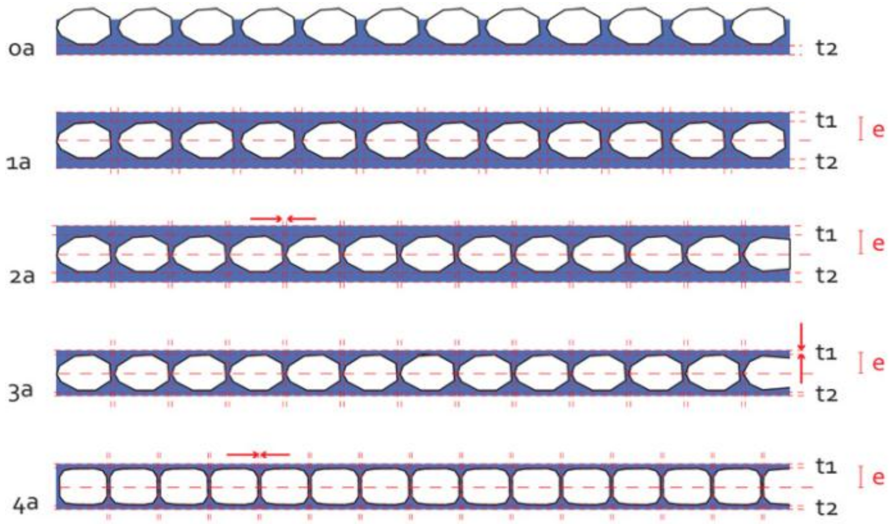


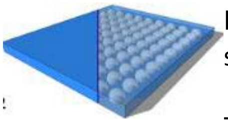
Figure 48: A PEP capsule at its original state, with h= 3,2mm a. and squeezed with h=1,7mm

The composite will not only be more economical to produce, but will also behave better thermally (thinner resin, means easier heat transfer) and optically (thinner resin, means higher transmittance and lower distortion).



Scheme 23: Optimization process (from 0a-4a). 0a. Composite made by laying PEP on an epoxy layer. 1a. Composite made by laying a second epoxy layer after the first has sufficiently cured. 2a. Minimizing the gaps between the PEP capsules will increase their number/area, thus the heat capacity of the panel. 3a. Minimizing the top and bottom epoxy thickness layer (also by using reinforcements) will decrease the use of material. 4a. Compressing the capsules using a vacuum will increase the PCM density and decrease the use of material epoxy.

Panel B2



The floatation phenomenon observed during the fabrication of the PEPEP panel, as well as the lack of possibility to manufacture a test sample in vacuum, led to the fabrication of a second B type panel.

The question was if the addition of glass fiber reinforcement could solve the problem of the exposed PEP capsules. Moreover,

Figure 49: The sample PEPEP2 had two 160gr/m^2 WR GFR mats at its both sides.

As expected, the texture was smoother at the mold side and got the fiber pattern at the open mound side.

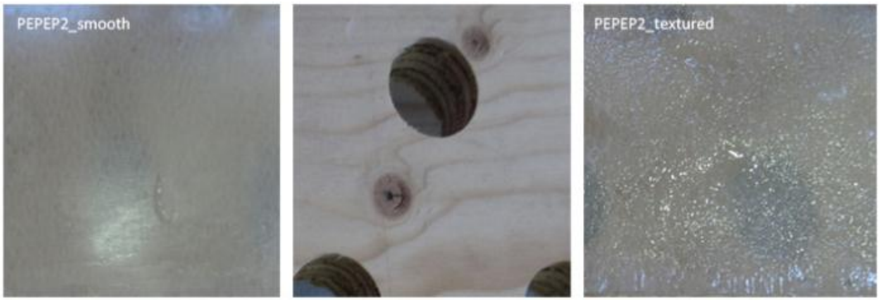
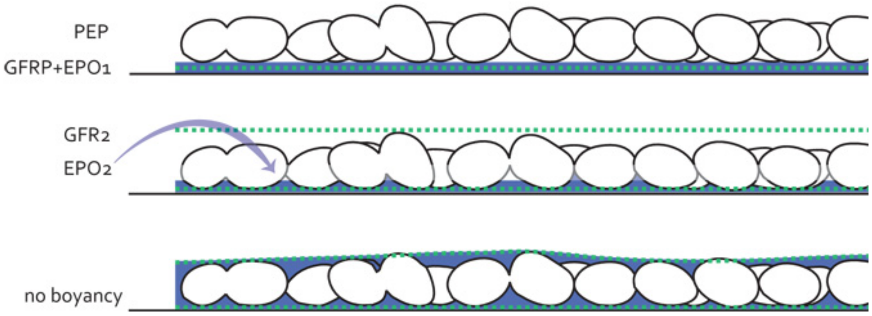


Figure 50: Comparison between smooth and textured side of a PEPEP2 sample. In the middle, the setup.

No PEP capsule protruded at the smooth side, and the textured side, presented a 'wavy' section, due to the non-uniform placement of the PEP capsules on the bottom surface.

Floatation was not a problem this time, since the weight of the GFR - especially after saturated with resin- kept the components compressed.



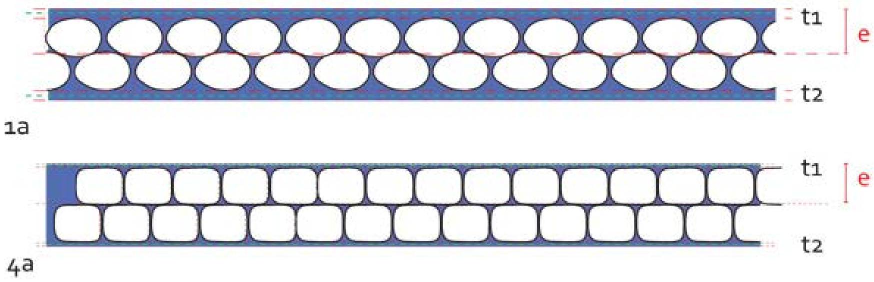
Scheme 24: The top and bottom fiber mats restrain the buoyancy effect and protect the PEP capsules.

The total PCM/resin ratio was 49/51, similar to the first PEPEP sample, but this time without any problems.

Figure 51: A side view of the PEPEP2 sample. Thickness 8,20 mm

Similar to the PEPEP panel, PEPEP2 can be optimized with the selection of a more appropriate fabrication process.

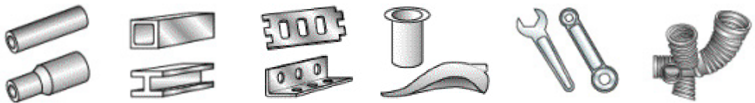
Producing it in a vacuum, should minimize all thicknesses, assist in a more compact distribution of the PEPEP capsules and in general create a more slender panel.



Scheme 25: Optimization using a vacuum, for a slender panel, similar to process described at PEPEP panel

4.3 Geometry

Geometry is related to the manufacturing process.



Process and geometry	Circular Prismatic	Non-Circular Prismatic	Flat sheet	Dished Sheet	Solid-3d	Hollow 3d
Autoclave molding			x	x		x
Hand Lay up				x		x
Spray Up				x		x
Vacuum/pressure Bag			x	x		x
Continuous laminating		x	x			
BMC molding			x		x	
Cold Press Molding			x		x	
SMC molding			x		x	
Spray up			x			
Centrifugal Molding	x					
Filament winding	x	x				x
Polymer casting	x	x			x	x
Pultrusion	x	x	x			
Resin transfer molding	x	x			x	x
Transfer molding	x	x			x	

Table 7: Geometry in relation to the manufacturing processed for GFRP. In green, the processes that give a satisfying surface quality, in red those that do not.

A1 Panel Curved

Creating a type A1 curved panel is difficult. Since it is a 2-component panel, it requires two different molds, and very low tolerances.

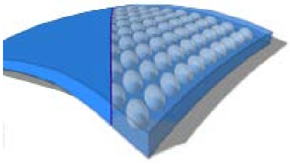
A2 Panel Curved

Creating a type A2 curved panel is also difficult. The pultrusion process only allows the production of flat elements. Bending them afterwards is possible, but only in big curvatures and only in one direction. The possible curvature increases with the increase of the panel thickness.

B Panel Curved

Creating a type B curved panel, also in two curvatures, seems to be an easier option. Similar to a chainmail, where metal rings are linked together in a pattern to form a mesh, the PCM capsules (PEP) are linked together with the help of the resin.

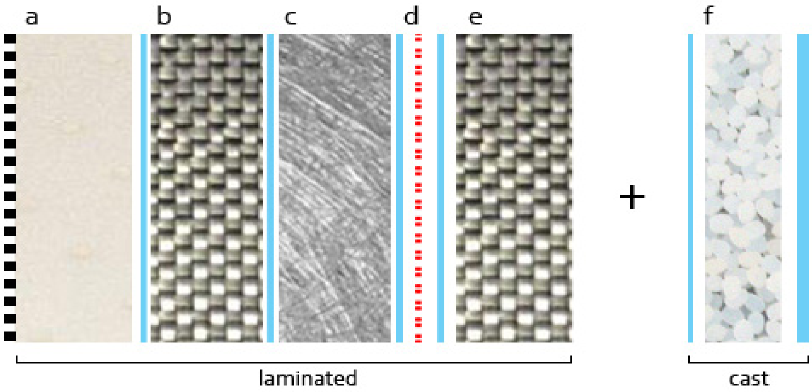
Curved Panel B



In order to verify this assumption, a PEPEP3 sample was made in a curved shape.

The sample was a sadwich type GFRP, instead of a sheet laminate (PEPEP1 and PEPEP2). By doing so we could also verify the possibility of a having a laminate attached to a foam core.

For material economy, we only laminated one side of the core. The core used was PET foam.



Scheme 26: The sandwich laminate layering[28]: a. bent PET foam b. Woven Roving mat 160g/m2, c.CSM 300g/m2, d. print paper cutouts, e. Woven Roving mat 160g/m2, f.PEP PCM. The blue lines depict the EPO resin layers. (images source: (sourcewww.cfsnet.co.uk))

3 layers of GFR were laminated on the bent PET foam using the hand-lay-up method. Before the last fiber layer was placed, colored paper cuts were inserted, to verify the transparency of the laminate.

The PEP capsules were cast, but not laminated with a brush. The liquid resin could not withhold the capsules in place, and they were dislocated as soon as the brush ran over them.

Figure 52: Manufacturing process 1. The Glass Fiber layers were laminated with EPO resin on the bent PET foam, 2. Paper cutouts were inserted before the last fiber layer, 3. The PEP capsules were spread, 4. EPO resin was cast

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[28] The sandwich layering was proposed by Holland Composites manufacturers, after personal communication with their production manager.

Unfortunately, the cast resin did not stay in place and flowed out of the sample. This occurred mainly to its low viscosity (η) and slow curing time.

- The lower the viscosity, the faster the resin flow.
- The faster the curing time, the faster the viscosity of the resin will rise. The less viscous the resin is, the easier it is to stay in place as cast.

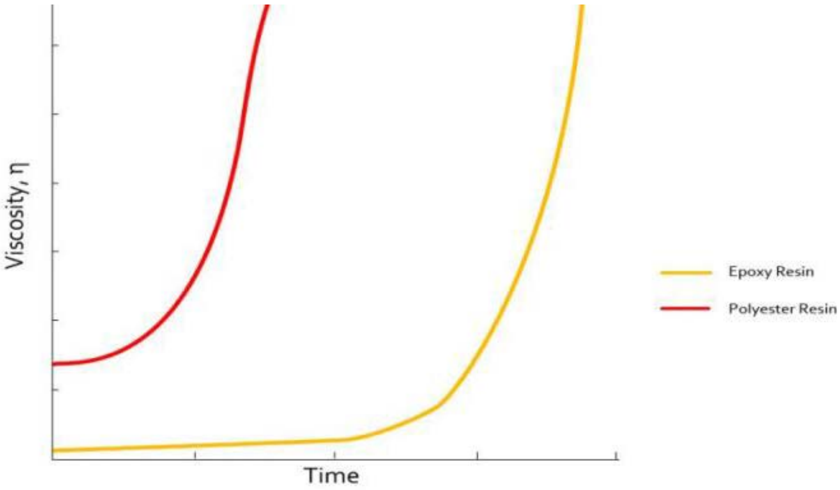
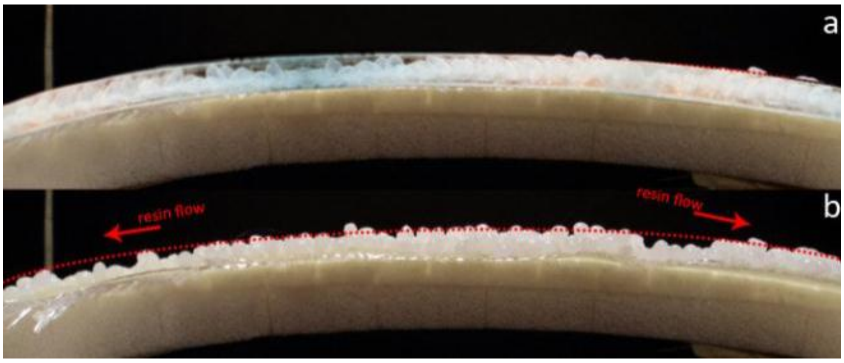


Chart 13: Viscosity of an EPO and a PUN resin, curing in room temperature (25°C) (source:(Van Assche et al., 2001), (Monti et al., 2012))

This would probably be less of a problem if a PUN resin was used since not only its viscosity is higher, but it also inreases faster.

Thefinal result differed a lot of what was expected, since the majority of the resin flowed away from its surface.



Scheme 27: PEPEP3 sample: a. expected laminate. b. resulting laminate, where the resin slid over the curved surface, due to its curvature.

Manufacturing the prototypes with the vacuum infusion process, will most probably eliminate this problem.

The resin will not be able to flow out of the mold, kept in place from the vacuum.

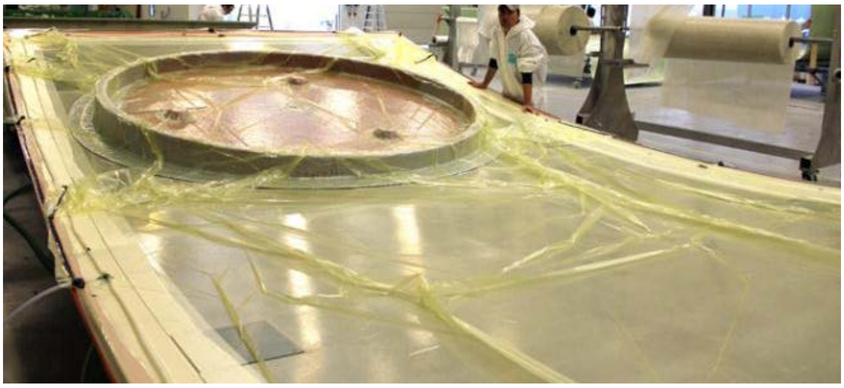
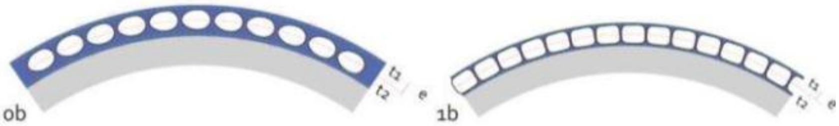
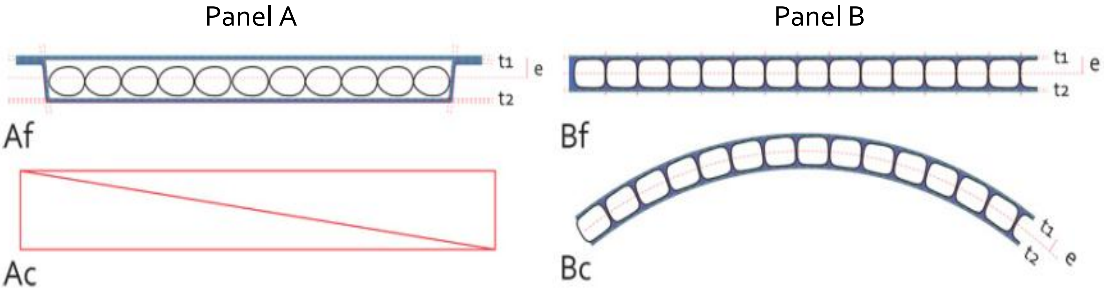


Figure 53: A vacuumed GFRP sandwich curved panel. Image taken at the Holland Composites factory, in Lelystad, Netherlands, 2011.

Moreover, similar to the sample panels examined earlier, the PEP layer's thickness can be optimized to a thinner one.



Scheme 28: Optimization using a vacuum, for a slender panel, similar to process described at PEPEP panel



Scheme 29: Geometry potentials for panel A (left) and B (right). f stands for flat, c stands for curved

Panel A is a good option only for flat geometry. Its box-nature allows the encapsulation of all types of PCM, if chemical compatibility can be enhanced. Leakage is the basic practical problem.

Panel B is a good option for both flat and curved geometries. However, it can only integrate PCMs that stay solid during the fabrication process, or those that do no change physical state (solid-solid).

4.5 Size

Introduction

Size has to do more with the application of the product, than the manufacturing process.

The size depends on the demands of each application, which usually differentiate between structural and non-structural.

As we mentioned in the introduction, the GFRP panels used for structural elements are mostly sandwich panels with a core.

It is also a fact that the single sheet laminates are rarely used. They are most often attached to each other through thinner sheets called 'spacers', which are in reality, another type of core.

The core can be, according to Tooren et al. (1993):

1. A massive, homogeneous material,
2. A foamed material,
3. A honeycomb, or
4. A corrugated sheet

Therefore, we can classify the panels we are discussing in this report, as sandwich panels.

Stiffness and strength are basic properties that describe the structural performance of any element, and of sandwich panels.

Stiffness [k]	is a measure of the resistance offered by an elastic body to deformation. Stiffness is a structure property.

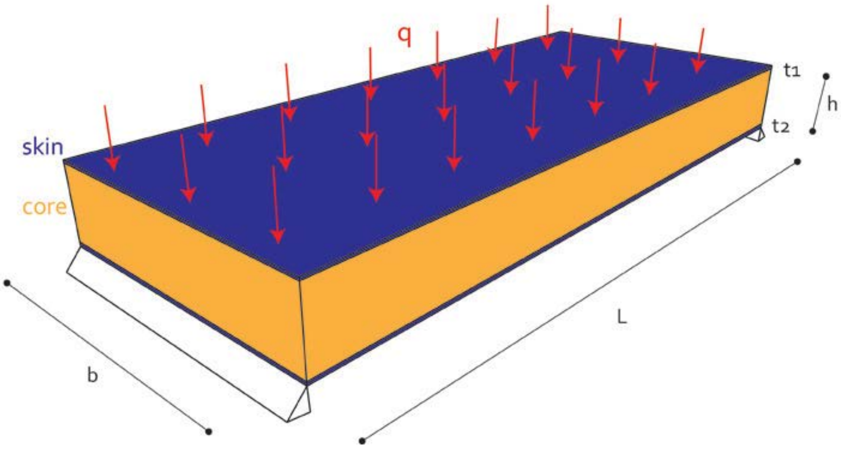
Figure 54: A cookie is Stiff but not Strong

Strength [σ]	is measure of the maximum load that can be placed on a material before it permanently deforms or breaks. Strength is a material property.

Figure 55: A rope is Strong but not Stiff

The stiffness and strength can give us an idea estimation on the size of the GFRP panel.

The sandwich panels are composed of two thin sheets of a strong and stiff material, separated by a thick core of low-density material possessing less stiffness and strength.



Bending Stiffness

For a sandwich panel the bending stiffness (k) can be expressed by the formula:

$$k = E_{core} \cdot J_{core} + 2 * E_{skin} \cdot J_{skin}$$

Substitution of the moments of inertia J_{core} and J_{skin} results in

$$k = E_{core} \cdot \frac{1}{12} \cdot b \cdot t_{core}^3 + 2 * E_{skin} \cdot [\frac{1}{12} \cdot b \cdot t_{skin}^3 + b \cdot t_{skin} \cdot \left(\frac{1}{2} \cdot h\right)^2]$$

where: E= Modulus of Elasticity [MPa], b= width of panel [m], t_{core}, t_{skin}= thickness of core and skin respectively [m], h= distance between the center of the two skins [m]

Modulus of elasticity

The Modulus of Elasticity (E) also gives a first impression of the strength of the material. A higher E denotes a stronger material.

For an isotropic GFRP lamina (skin) we can calculate E using the Rule of Mixtures. The rule of mixtures states that each element affects the overall proportionally to its fabric volume content (Theulen and Peijs, 1991):

$$E_{skin} = E_{matrix} \cdot v_{fr.matrix} + E_{fiber} \cdot v_{fr.fiber}$$

where: E_{skin}, E_{matrix}, E_{fiber} = Moduli of Elasticity [MPa], for the lamina, matrix and fiber respectively, $v_{fr.matrix}$, $v_{fr.fiber}$ =fabric volume contents for the matrix and fibers respectively.

Shear Modulus

The Shear Modulus describes the resistance to shear forces and can be calculated as:

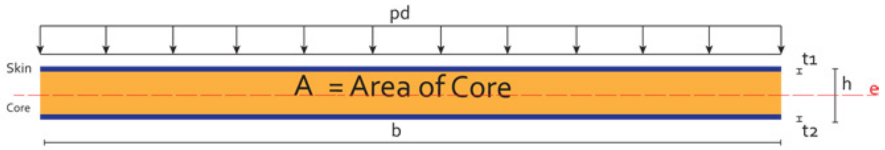
$$G = \frac{E}{2 \cdot (1 + v)}$$

where: G= Shear modulus [MPa] for an isotropic material, and v=Poisson's ratio for an isotropic material

Shear Stiffness Mostly shear forces affect the core of a sandwich panel. The shear stiffness (V) of the core is described by the ratio:

$$V = G \cdot A$$

where: A= is the area [m^2] of the core, where the shear forces are applied



Therefore, G is an important property, and along with the quantity of the material controls the core properties.

For two materials with the same thickness h, and the same desired V:

- higher G required smaller A (for example an aluminum honeycomb core)
- lower G requires a larger A (for a PU foam core)

Deflection If we know all the material properties and the dimensions of the sandwich panel, we can then calculate the deflection (w) at the center of a sandwich panel,= resting at its two sides from the formula:

$$w = \frac{5 \cdot q \cdot L^4}{384 \cdot k} + \frac{q \cdot L^2}{8 \cdot (b \cdot h) \cdot G}$$

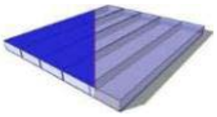
For this research we will assume a max deflection at the center to be 1/360 of the panel length:

$$w_{max} = \frac{1}{360} \cdot L$$

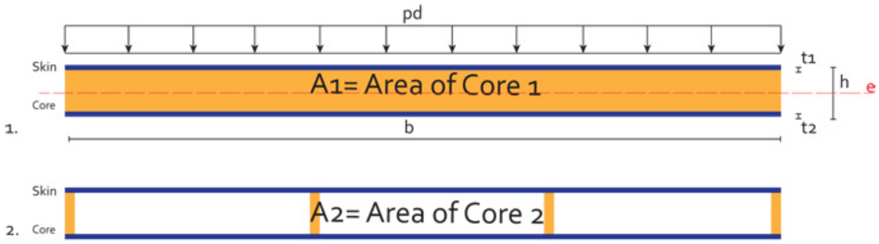
This deflection is sometimes considered to be too small (Theulen and Peijs, 1991).

However, as we already saw, a large deflection can cause change in the shape of the panel, which non-uniform shape can cause non-homogeneous melting.

Panel A2



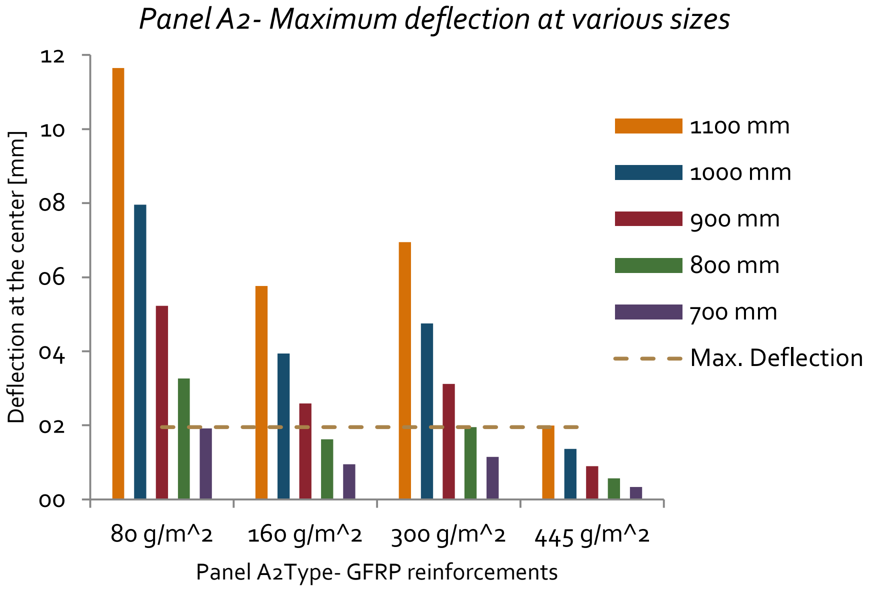
We will test a panel A_2 of b=1000mm with a core where A_2=2%·A1, and a G equals to that of an EPO resin, under its own load.



The quantity of PCM used is similar to the commercial Energain panel, by Du Pont.

Fiber Weight	Total Thickness h mm	Area Weight pd kg/m^2
80 g/m^2	7.70	4.12
160 g/m^2	7.90	4.28
300 g/m^2	8.52	4.71
445 g/m^2	8.62	4.85
Energain	5.20	4.50

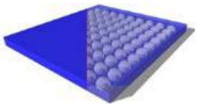
We see that the deflection is smaller when stronger reinforcements are used. The L that allows the most transparent laminate to be used is 700mm.



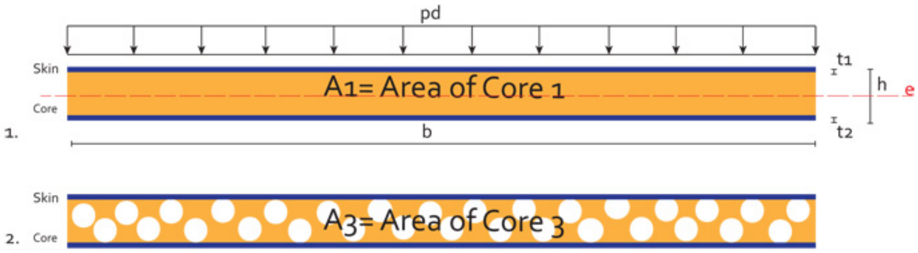
Width *[mm]*		Length *[mm]*	80*[g/m^2]*	160*[g/m^2]*	300*[g/m^2]*	445*[g/m^2]*
			Deflection (max. 2.0 [mm])			
1000	x	**1100**	11.7	5.8	6.9	**2.0**
1000	x	**1000**	8.0	3.9	4.7	**1.4**
1000	x	**900**	5.2	2.6	3.1	**0.9**
1000	x	**800**	3.3	**1.6**	**2.0**	**0.6**
1000	x	**700**	**1.9**	**1.0**	**1.1**	**0.3**

Chart 14: Estimation of Maximum Length (span) for a 1000 [mm] wide PCM, A type panel with one layer of GFR. The maximum deflection was estimated as w_{max}=L/360=2.0 [mm]. See appendix.

Panel B



The core of panel B is more similar to foam than a massive core.



Therefore, predicting its behavior is more difficult, since the shear forces are distributed unevenly throughout the core.

In order to get an understanding of the structural behavior of this panel, we prepared two samples that also presented the same amount of PCM as the commercial Energain panel.

The test was a 4-point bending test (the numerical values are presented in the Appendix).

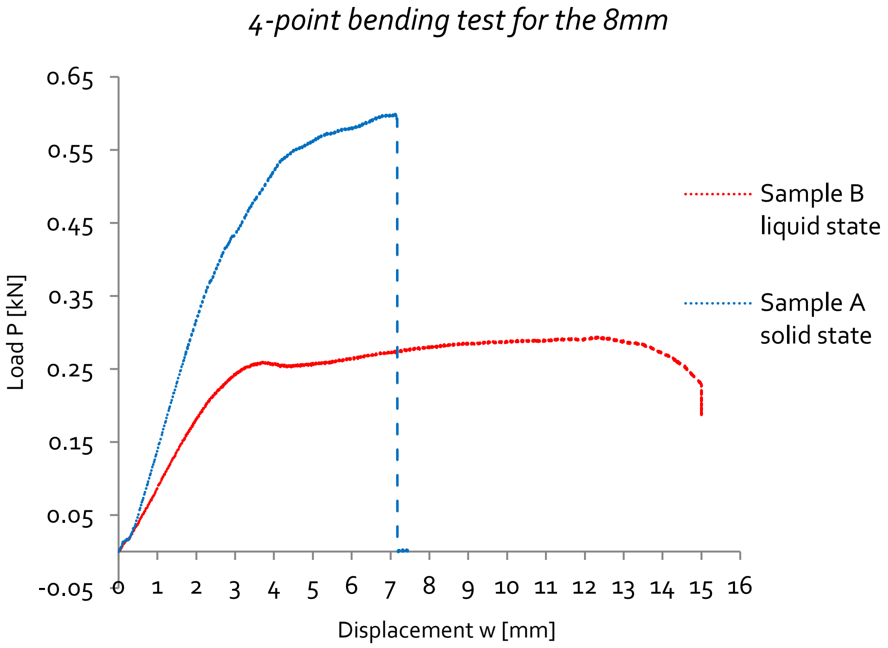
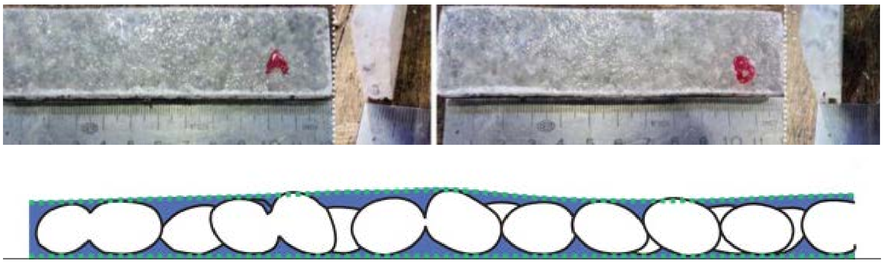


Chart 15: Comparison of strength between the solid and liquid sample.

We can calculate the Modulus of Elasticity from the tests using the formula:

$$E_{PEP} = \frac{L^3}{32 \cdot b \cdot (\frac{t}{2})^3} \cdot \frac{dP}{dw}$$

Sample A	Sample B
PCM at its solid state	*PCM at its liquid state*
E_{PEP_solid}=4294 [MPa]	E_{PEP_molten}=2442 [Mpa]



Dimensions (bxLxh)			120.0 x 30.0 x 8.2 [mm]
Top/Bottom Laminates (Epoxy)		……	1 layer W/R mat 160 [g/m^2] (50/50 fiber/resin mass ratio)
Filling (Epoxy)	(51% mass)	🟦	3.7 [kg/m^2]
PCM	(49% mass)	○	3.6 [kg/m^2]

Figure 56. The samples prepared for the structural test: 120x 30x8.2 [mm] each, the schematic section and the quantities used.

Figure 57: Pictures at the fracture (sample a) and maximum displacement of the 4-point-bending machine (sample b), at left and right respectively.

Even though, one bending test is not sufficient to get a clear picture it is enough to make some useful preliminary observations.

In its solid state, the sample shows higher strength than at its liquid state.

In its liquid state, the strength was almost half.

At the liquid state, the sample presented a ductile behavior.

Usually thermosets have brittle fracture at low temperatures and ductile fracture at high temperatures [29]. However, the softer PCM seems to affect the ductility, apart from the strength.

The most important fact is that the physical state of the PCM affects the structural performance of the composite.

This is also different to more foam materials where usually the foam is a composite of the main material and air. Air has $G_{air}=0$, so it does not assist in the shear resistance. So, as a conclusion we can say that the PEPEP belongs to a sandwich category between a foam and a massive core.

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[29] Source: www.virginia.edu/bohr/mse209/chapter16

4.6 PCM-GFRP Optical Performance

Introduction

The optical performance of the PCM-GFRP combination should follow the principles of the individual components.

Light transmission of the composite is a property affected by the light transmission properties of the individual composing materials. It stays the same for a GFRP laminate, but changes during the phase change process for a PCM

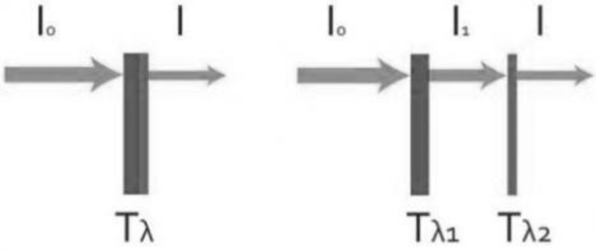
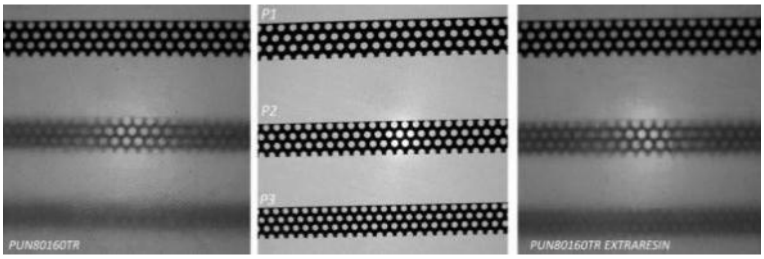


Image Distortion of the composite is a property affected by the individual materials. A GFRP laminate causes more distortion, the 'dryer' it is, and less distortion the 'wetter' is it.



A PCM causes image distortion in different ways that depend on the state, orientation of the melting process, quantity and type of PCM.

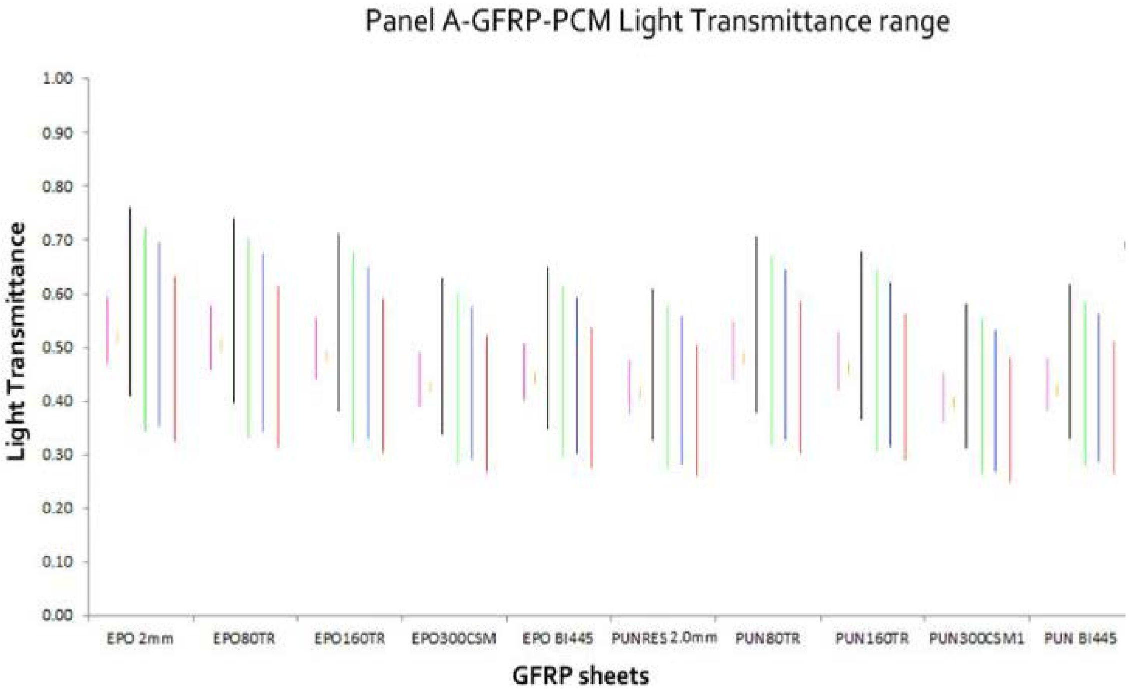
The principles are interlinked and influence each other.

The added principle that can act as an additive value is time. Time is connected to the phase change process and is influenced by the parameters as described in chapter 3.2. The phase change process is connected to the difference in light transmission and image distortion.

By predicting the combination of these parameters, we can predict the optical dynamism potential of a PCM-GFRP combination in architecture.

4.6.1 Light Transmission at PCM-GFRP panels

Since we know the T_{λ} properties of each component, we can easily calculate the Tλ for a GFRP-PCM panel A1, for most possible combinations:



		EPO					PUN				
		2.0 mm	80 TR	160 TR	300 CSM	BI 445	2.0 mm	80 TR	160 TR	300 CSM	BI 445
	-	0.93	0.90	0.87	0.77	0.79	0.74	0.860	0.828	0.709	0.751
PEP	m	0.59	0.58	0.56	0.49	0.51	0.47	0.55	0.53	0.45	0.48
	s	0.47	0.46	0.44	0.39	0.40	0.38	0.44	0.42	0.36	0.38
CLIMA SEL	m	0.53	0.52	0.50	0.44	0.45	0.42	0.49	0.47	0.41	0.43
	s	0.51	0.49	0.47	0.42	0.43	0.40	0.47	0.45	0.39	0.41
SHREG	m	0.76	0.74	0.71	0.63	0.65	0.61	0.71	0.68	0.58	0.62
	s	0.41	0.40	0.38	0.34	0.35	0.33	0.38	0.36	0.31	0.33
RT25	m	0.72	0.70	0.68	0.60	0.62	0.58	0.67	0.65	0.55	0.59
	s	0.34	0.33	0.32	0.28	0.29	0.27	0.32	0.31	0.26	0.28
S27	m	0.70	0.68	0.65	0.57	0.59	0.56	0.65	0.62	0.53	0.56
	s	0.35	0.34	0.33	0.29	0.30	0.28	0.33	0.31	0.27	0.29
L30	m	0.63	0.61	0.59	0.52	0.54	0.50	0.58	0.56	0.48	0.51
	s	0.32	0.32	0.30	0.27	0.28	0.26	0.30	0.29	0.25	0.26

Scheme 30: Light Transmittance range per PCM-GFRP A type panel

From the graph we can see that GFRP panels using PCMs at pure state (paraffin and hydrated salts) present a higher potential for becoming visually dynamic, than the rest.

An example of a Panel A1 GFRP-PCM combination for a 12mm PEP PCM, can be seen here. The PEP has been encapsulated within 8 different laminates.

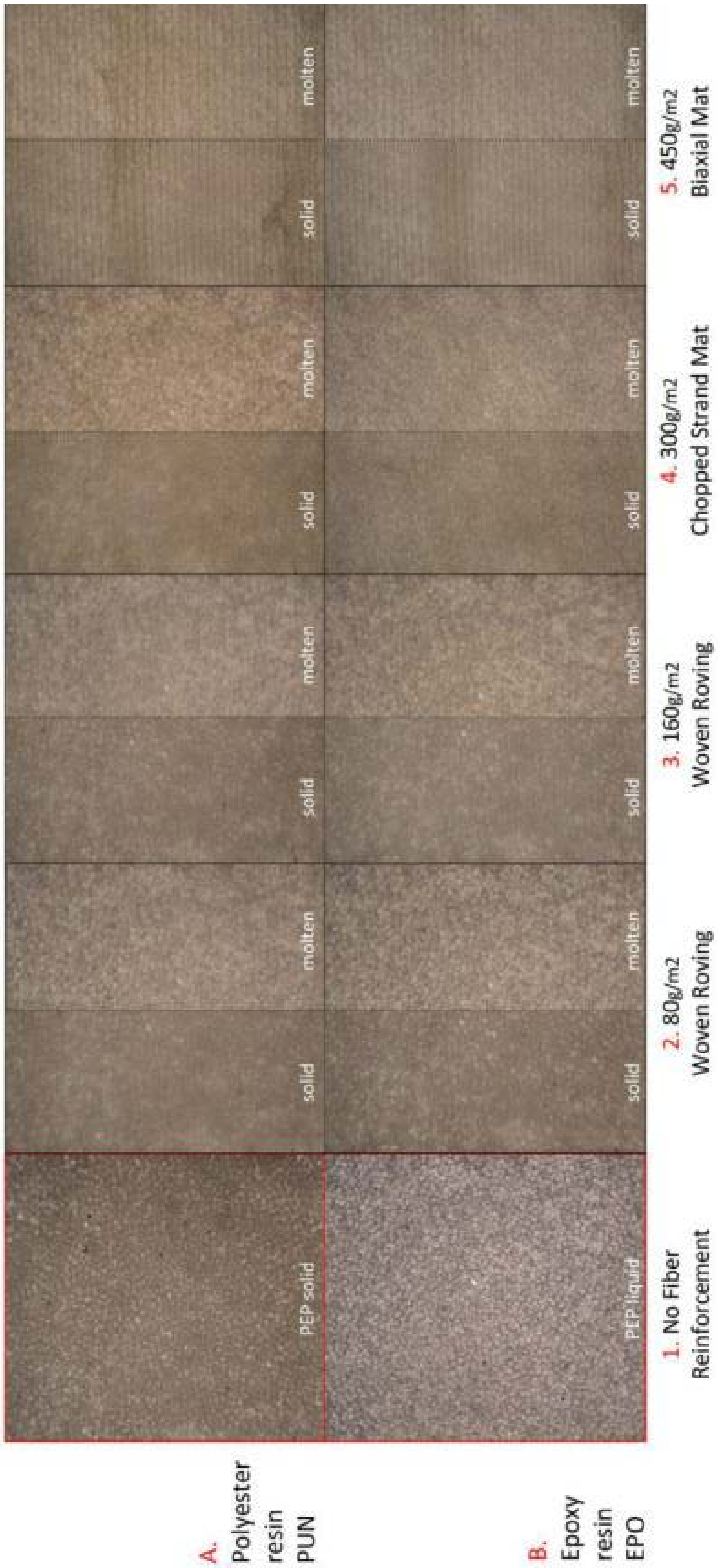
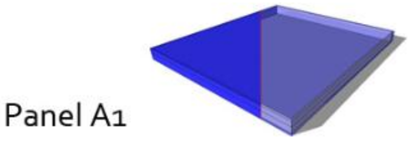


Figure 58: Transparency in variations of Panel A1 using PEP as PCM

4.6.2 Image Distortion at PCM-GFRP panels



The previous setup was also used for an image distortion test.

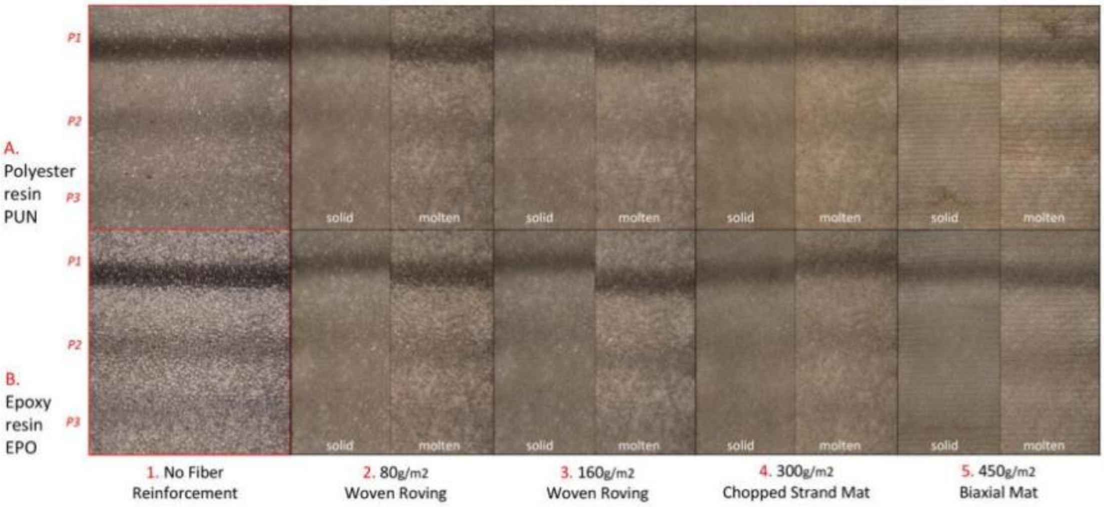


Figure 59: Image distortion in variations of Panel A1 using PEP as PCM

Comparing it to the 3.5mm PEP samples we tested in a previous chapter, we can see that the image distortion effect is in general terms the same: the pattern appears more blurry the farther it is from the panel, and in the solid state.

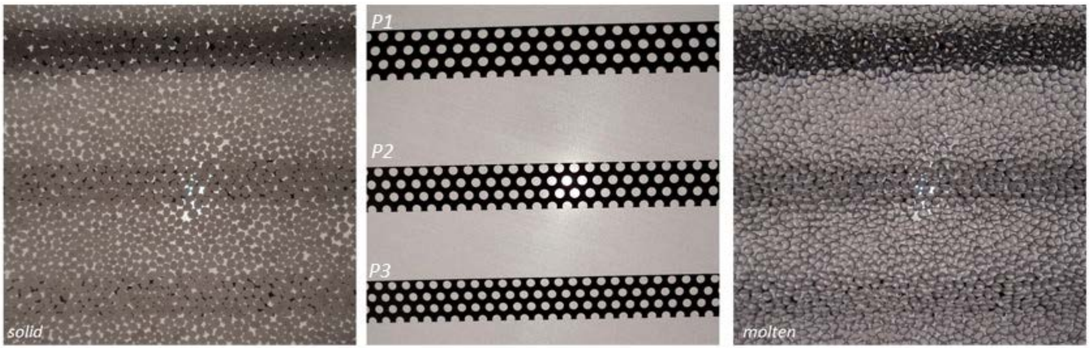
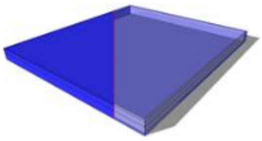


Figure 60: Image Distortion ID comparison between the solid states of a 3,5mm layer of PEP PCM.

However, in order to have a clear picture on the optical performance between the two panel types, a comparison should be made.

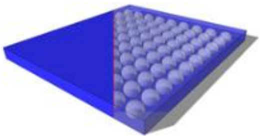
Therefore, we will compare the image distortion cause by the two panels using the same GFRP and same PCM.

Panel A1



VS

Panel B



A type A panel, with Unfilled EPO resin (EPOCL) is compared to a type B panel with EPO resin (PEPEP). Both encapsulate the PEP PCM. The completely solid and liquid states are compared to the initial setup.

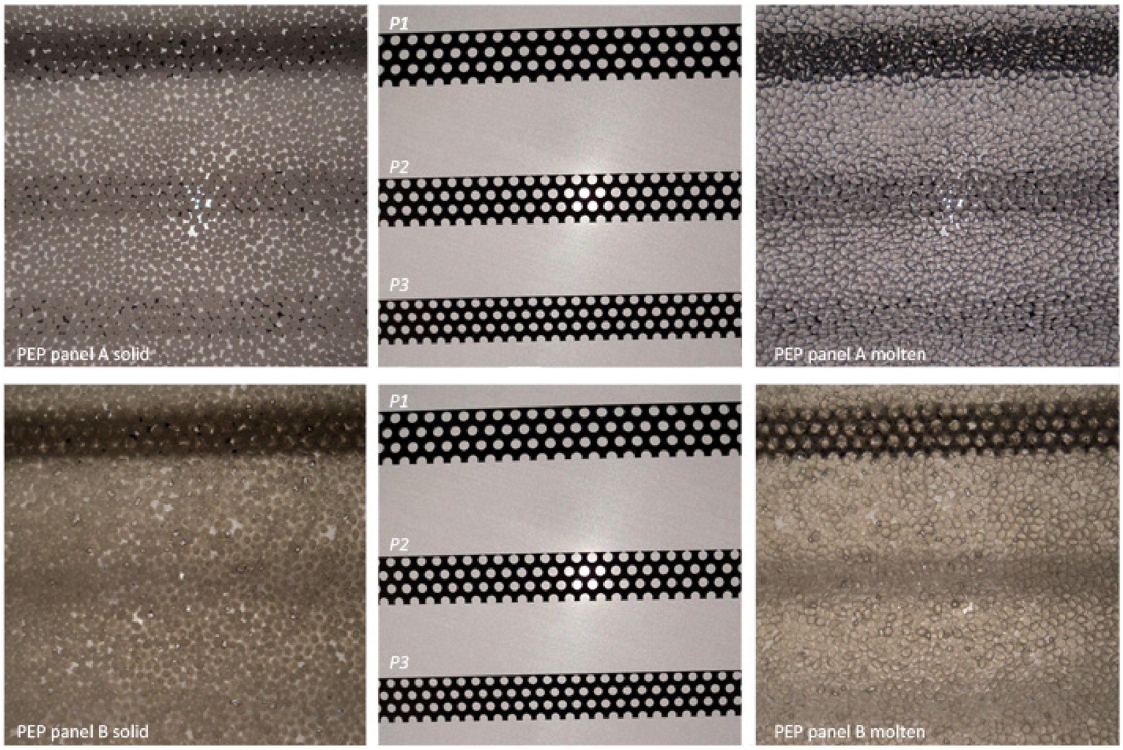


Figure 61: Panel A 3,5mm. EPOCL-From left to right: 1.Solid phase of one layer of Energain- dispersion 83.02%, 2.comparative setup, 3.Molten phase of one layer of Energain-dispersion 83.02%,. Panel B 3,5mm. PEPEP- From left to right: 1. Solid phase of the epoxy composite dispersion 85.88%, 2.comparative setup, 3.Molten phase of the epoxy composite dispersion 85.88%

The yellow tint of the PEPEP is given by the hardener used in the epoxy (ratio 33%). The interesting fact is that even though the PCM dispersion rate is similar, PEPEP shows less distortion in the molten phase, that ECLPEP but less distortion in the molten phase.

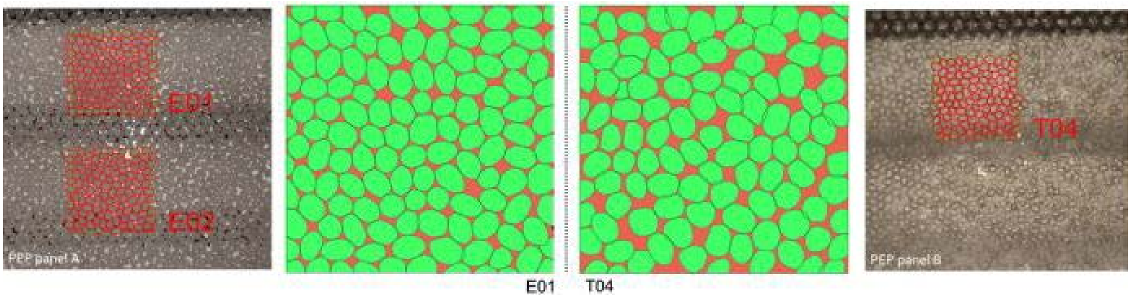


Figure 62: The left one (EPOCL) presents a PCM dispersion of 83.02% of its total surface area. The right one (PEPEP) presents a dispersion of 85.88% of its total surface area

Refractive Indices

An explanation could be given, if we look at the refractive indices (n) of the composing materials.

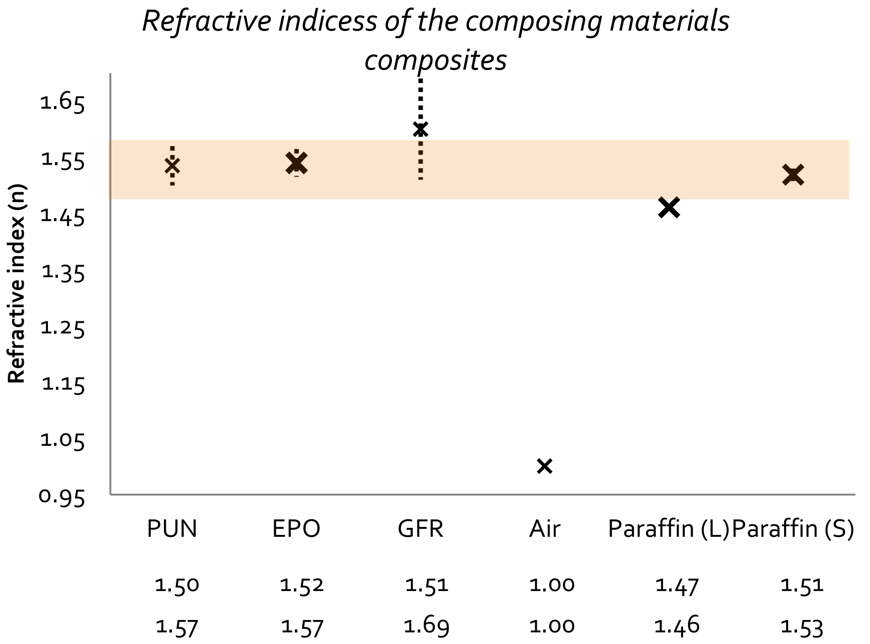


Chart 16: Refractive indices range for transparent polyester (PUN), epoxy (EPO), glass fibers (GFR), air, and Paraffin at both the solid and liquid state. (source: (Freund et al., 1982) page 105)

The refractive index of Epoxy (EPO) and Paraffin are similar.

Therefore, according to the theory, the closer the refractive indices are, the less distorting the material is.

Inhomogeneous image distortion

We should not forget to mention that an important disadvantage of panel A, is the high possibility for a non-homogeneous melting process..

Two small tests that were conducted using Hydrated salts, verified the problems that can derive from either the PCM or the container.

- Phase separation occurred within the material at a vertical cylinder setup
- Uneven melting occurred due to tilt of the container surface during melting.

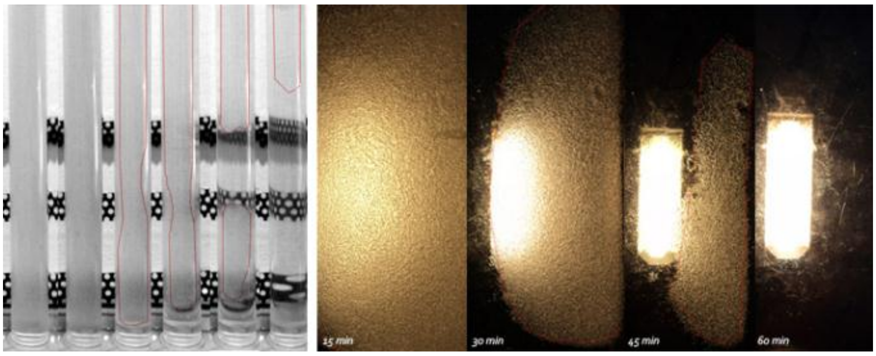


Figure 63: Phase separation in SHREG causes inhomogeneous melting. Uneven melting of a Hydrated Salt due to uneven leveling of the encapsulating panel

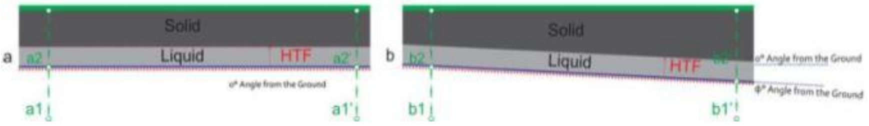
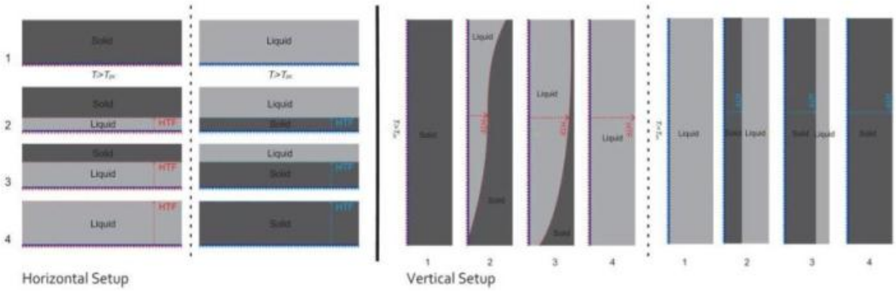
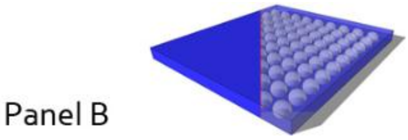


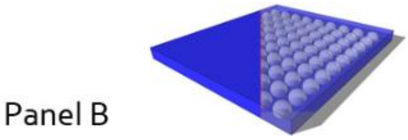
Figure 64: Uneven melting will cause uneven light transmittance values along the non-leveled axis.



Scheme 31: Melting (a) and Solidifying (b) process of a PCM in horizontal setup, heated/cooled from below and side.



VS



Last, we can compare the two B type PEPEP panels (PEPEP1 and PEPEP2 we created at chapter 5.2), which have the same resins but different thicknesses.

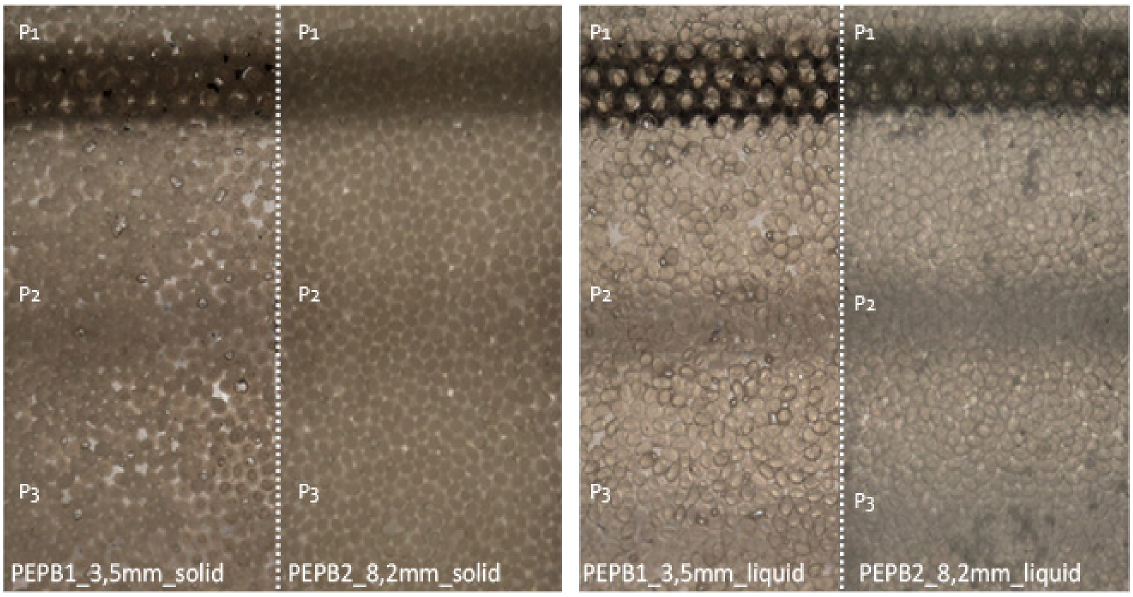


Figure 65: Comparison between two type B panel, with varying thicknesses, for both solid and liquid state. PEPEP1=PEPB1 (left) PEPEP2-PEPB2, right

Surprisingly, we can observe that at the liquid state of the PEPEP2 panel, the outline of the pattern P1 is almost clearly visible.

The interesting fact is the at its solid phase, the pattern is completely undistinguishable.

Therefore, we can say a panel type B using PEP as it PCM, presents potential for dynamism. The potential derives from the difference in Image Distortion (ΔID) and not from the difference in Transmittance.

4.6.3 Dynamism at PCM-GFRP panels

As mentioned in the introduction, dynamism is a property taken by the PCM.

We have excluded CLIMASEL, as it is dynamic neither in light transmittance (T_λ), nor in image distortion (ID).

The remaining PCMs are:

i. the SHREG, which is a pure Hydrated Salt and
ii. the PEP, which is Paraffin microencapsulated in a polymer.

SHREG has high ΔT_λ and high ΔID values.

PEP has a high ΔID values.

According to the discussion so far, we expect not only the perception of its solid and liquid phase to be discreet, but also the in-between phase.

In order to see if our expectations can be verified, a test was conducted for the two PCMs:

The temperature within our insulated climate box (blue line) was measured throughout the melting process of :

- a type A panel with a 1,5 mm clear PLEXIGLAS box as a container containing a layer of 4mm SHREG PCM (PLEXIGLASS was used instead of an epoxy resin, because it was easier to fabricate and control the leakage. However, the thermal properties and transparency are similar), and

- a type B panel with EPO resin encapsulating a layer of 3.5mm PEP PCM,

while photographs of the panels were taken every 2.5 minutes.

The temperature of the room was recorded from the thermostat reading. The panels were lit from above from a 300W light bulb at a distance of 1200mm.

Both the panels were first left to cool at the fridge at approximately 3 degrees, before inserted in the box. This is the reason why in both tests, the ambient temperature in the panel drops in the beginning.

Even though the tests are preliminary, we can see the effect of the PCM heat absorption in both cases. Of course, since the quantity and the latent heat storage capacity are bigger in the SHREG box, the effect is clearer. This is also the reason why the test using the SHREG PCM lasted for 200min contrary to the test using PEP that lasted only 55min.

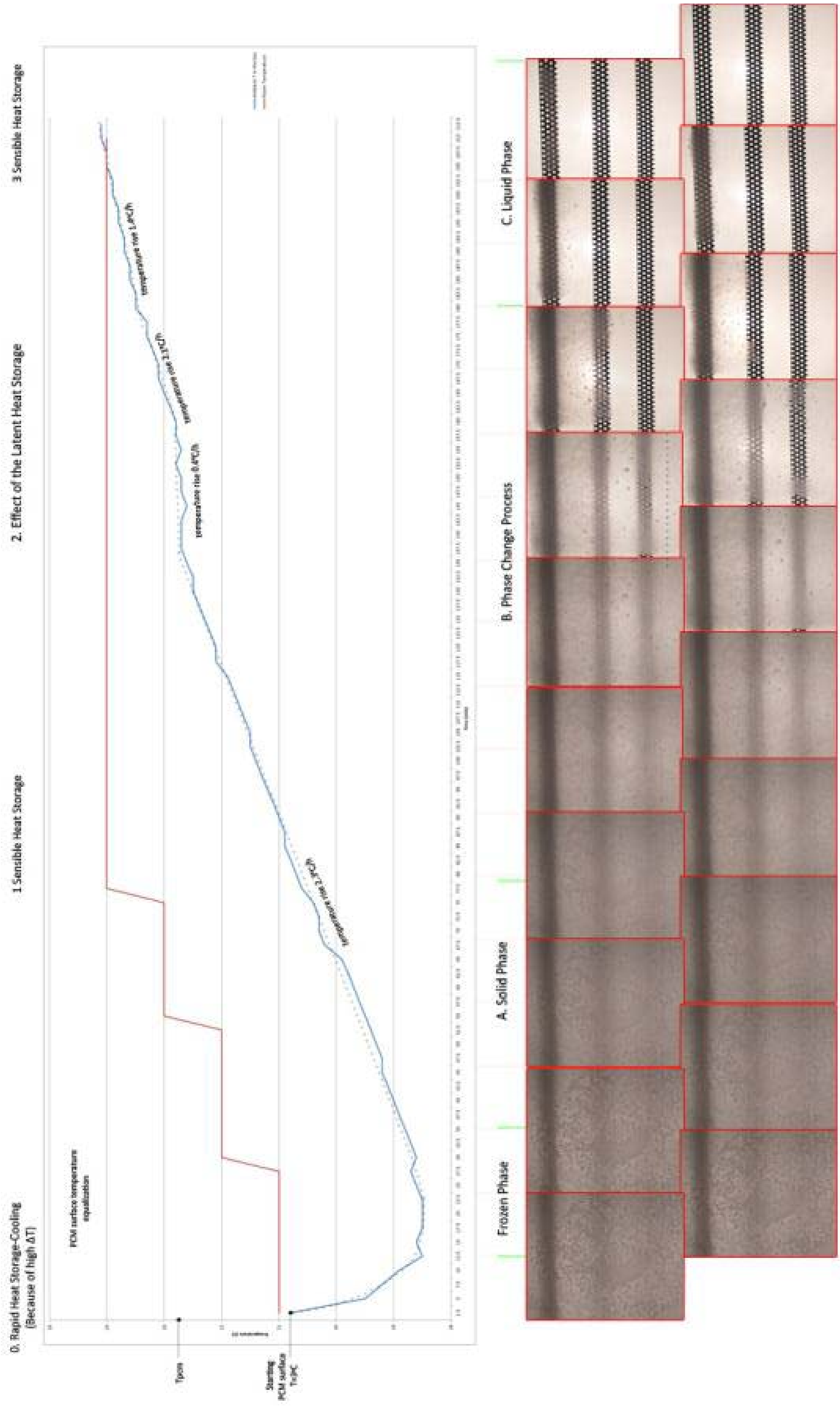


Figure 66: Test panel A. Melting Pattern of a SHREG PCM, with the corresponding pictures per time.

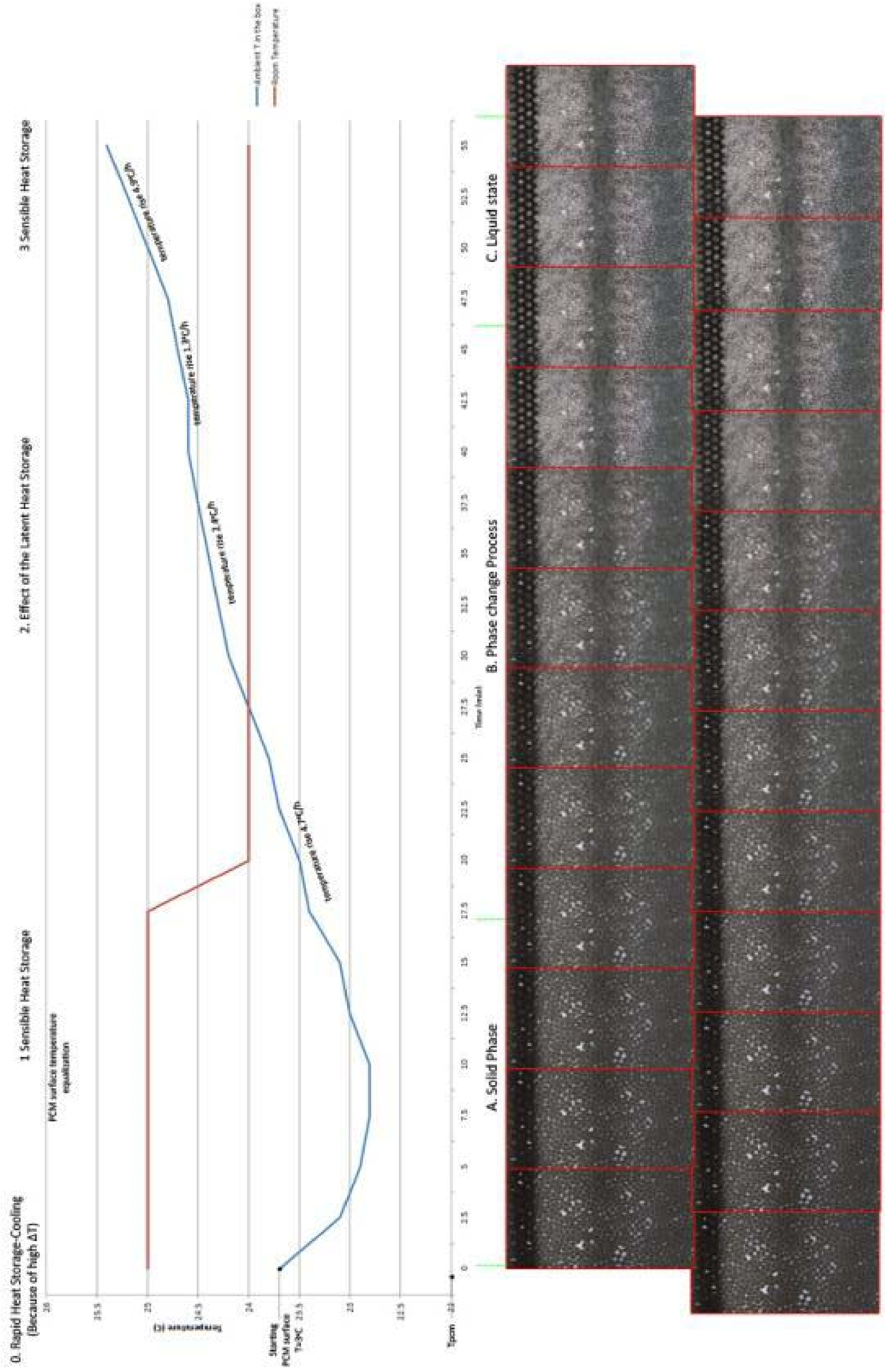


Figure 67: Test panel B. Melting Pattern of PEP PCM, with the corresponding pictures per time

5 Conclusions

The combination between GFRP and PCM is possible.

Combining PCMs and GFRP into a translucent element is possible, as the experiments showed.

Compatibility between GFRP-PCM though, includes more parameters that chemical compatibility. Based on the choice of PCM class and the demands of each application (fire safety, smell reduction etc.) certain adjustments should be made at the GFRP encapsulation laminate.

Translucency of the combination

Translucency's intensity and behavior can be adjusted at a combined panel by the composing materials' quantity and quality. It is affected by the individual material translucency levels, as well as the composition of the final panel.

For example, reducing the amount or the weight of the Glass fiber reinforcement, could increase the translucency levels of the panel.

Average translucency value

Looking at the experiment results, we see that the average translucency at a PCM-GFRP panel ranges around a value of 50% (in visible light).

Moreover, the Image Distortion at big distances from the panel is intense in all combinations, making the panels suitable for applications where privacy is a demand.

Hydrated Salts present more potential in dynamism than PEP

Solid-Liquid Hydrated Salts presented better results in all Optical Performance experiments. Considering also their higher volumetric heat capacity and the cost, we should agree that they present greater potential for architectural applications than the other PCM classes.

A GFRP-Hydrated Salt panel can change from 40% up to 80% in transparency between states, as witnessed during the experiments. The perceivable difference will be much larger though, due to the big change in Image Distortion it causes.

The tools and materials available during this research were not adequate to explore the full potential of the Hydrated Salt PCM. More complex fabrication techniques[30] and special additives (see chapter 3.1) should be used to create safer and leakage-proof GFRP encapsulating panels.

Homogeneity and Leakage

Keeping Hydrated Salts homogeneous and not leaking is a challenge that should be dealt in both the design and fabrication process.

PEP allows more freedom in exploration

Polymer Encapsulated Paraffin, on the other hand, constantly stayed in solid phase, was easier to use, and allowed hands-on experimentation. Inevitably, more focus was given to this material despite its lower thermal and optical performance.

This fact, denotes that in PEP presents more potential in do-it-yourself applications. It can be more interesting material for exploration by

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[30] Than hand-layup

It is important to mention that its, optical performance seems to be increasing if it is embedded at an integrated Panel B type. The two materials' refractive indices coincide resulting in a successful optical cooperation.

Moreover PEP dynamism potential seems to be increasing when its thickness is increasing. By increasing the thickness, $T\lambda_{liquid}$ remains almost constant and the $T\lambda_{solid}$ decreases, resulting in a bigger $\Delta T\lambda$.

PCM quantity

The bigger the thickness or the latent heat capacity of a PCM, the less dynamic it probably is, since the slower it takes it to melt[31]. The thickness is a parameter connected to the thermal performance. Thicker panel, means more energy is absorbed or released, so better thermal performance.

Epoxy is a better resin choice

The optical performance of the composite depends on the matrix (resin). Epoxy laminates are comparatively more transparent, less refractive and stronger than polyester ones.

During fabrication it quickly became obvious that Epoxy is easier to handle and assists PEP in hands-on experimenting.

Polyester laminates in larger thicknesses were dominated by intense odors, a parameter which should be taken into account when designing elements for interior spaces.

Woven Glass Fiber is a better reinforcement option

The transmittance of the panel depends on the fiber reinforcement type. The more 'organized' the reinforcement is, the more predictable its optical behavior is. Woven fabrics refract light homogeneously along an axis on their surface whereas CSMs refract light randomly along an axis on their surface.

The transmittance of the panel depends on the amount of fibers used, where heavier reinforcement means less transparency.

GFRP laminates perform

As already mentioned the melting and solidifying process of a PCM is affected very little by the type of the encapsulating container, if its thickness is too small.

The performance of the panel depends on the manufacturing process.

Machine-controlled processes diminish the chance of creating non-homogeneous laminates. A common problem observed during experimentation was the appearance of air 'pockets' within the laminate which decrease the transparency levels.

Not all GFRP production processes can be used with PCMs, therefore not all shapes combinations are possible .

Surface quality should be taken into account from a primary process level, since post-processing the laminate cannot be easily post-processed. Not all geometries can be produced with the same surface quality.

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[31] At constant heat transfer conditions.

Leakage is a dominant problem when Pure PCMs are used.

Performance of the combination

So far, the basic properties, advantages and disadvantages of both constituent materials, in aspects like transparency, thermal performance (per thickness), strength, cost etc. have been examined.

Synthesizing the information collected, we can conclude at a qualitative estimation on the expected performance for different GFRP-PCM combinations. This way, we can have an overview of the composite behavior.

For simplicity, we can consider the comparison to occur between sandwich-type panels; two GFPR sheets enclosing a PCM layer.

The qualitative comparison is shown in the following table:

GFRP+PCM combination	Hydrated Salts		Paraffin		PEP		CLIMASEL	
	+		+		+		+	
Expected Performance	PUN	EPO	PUN	EPO	PUN	EPO	PUN	EPO
ΔTλ	🟧	🟩	🟧	🟩	🟧	🟩	🟥	🟥
ΔID	🟩	🟩	-	-	🟧	🟧	🟥	🟥
Dynamism	🟧	🟩	🟧	🟩	🟧	🟧	🟥	🟥
Homogeneity	🟧	🟧	🟥	🟥	🟩	🟩	🟩	🟩
Heat Capacity	🟩	🟩	🟧	🟧	🟥	🟥	🟩	🟩
Compatibilit	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥
Leakage	🟥	🟥	🟥	🟥	🟩	🟩	🟧	🟧
Flammability	🟧	🟩	🟥	🟧	🟧	🟩	🟧	🟩
Surf. Quality	🟧	🟩	🟧	🟩	🟧	🟩	🟧	🟩
Versatilit	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥
Strength	🟧	🟩	🟧	🟩	🟧	🟩	🟧	🟩
Life Span	🟥	🟥	🟧	🟧	🟩	🟩	🟥	🟥
Price	🟧	🟩	🟩	🟧	🟧	🟥	🟩	🟩

G: Good Performance *M: Medium Performance* *L: Low Performance*

Table 8: Expected performance of a sandwich-type panel of average PCM thickness (5-10mm) and average GFRP sheet thickness (0.2-1.00mm).

A combination that shows better potential at each sector is marked in Green, a combination that shows potential but presents problems is marked in Orange, and a combination that shows little potential because it presents unsolvable problems is marked in Red.

6 Applications

Introduction

PCMs can replicate the effect of thermal mass at lightweight structures or structures that require additional thermal mass. Once the room temperature increases due to internal heating sources or solar gains, PCMs in panels will absorb and store the heat, which will be released when temperature drops in the evening and night hours.

Figure 68: The Delta Cool Board (by Doerken.de) is a commercially available PCM panel used in ceiling cooling applications.

A PCM absorbs and releases big amounts of heat, while still being lightweight. Being lightweight is the feature that makes it advantageous to concrete or other heavyweight building materials. It can be used as a complementary or even the main measure to control temperature inside a building. It can be used in heating and cooling applications, for both passive and active systems.

The combination of translucent Glass Fiber Reinforced Polymers and PCMs, could upgrade applications using the standard systems, with additional values:

Translucency: The PCM system could allow penetration of light, where other thermal mass systems cannot, while simultaneously function as a temperature regulating system.

Visual Dynamism: The object will optically change throughout the day, at the same time highlighting its functionality.

Formability: The system could present flexibility in forming if specific PCMs are used (PEP or CLIMASEL)

The applications discussed in the following chapter propose PCM-GFRP systems as:

- A Part of the Envelope
  1. as additional panels.
  2. integrated at the building structure
- B Independent elements
  - 1. Related to the Facade
    - i. as a lightweight Solar Wall
    - ii. as a Sunspace partition
  - 2. Not related to the Facade
    - i. as an interior separating wall
    - ii. as furniture

From the analysis, we concluded that the most promising PCMs for a visually dynamic system are Hydrated Salts and PEP. CLIMASEL on the other hand is equally translucent at states. This characteristic, which at first glance seems to be a disadvantage, could actually become a design parameter for a suitable application.

In order to have a picture of the GFRP-PCM panels' overall appearance, 3 small prototypes were manufactured and photographed under natural light conditions.

Panel A1:

Hydrated Salt SHREG

T_{pc}=22°C

Phase Change: Solid-Liquid

d=12mm

with 80g/m^2 GFRP thickness

(the sample was photographed on a black background)

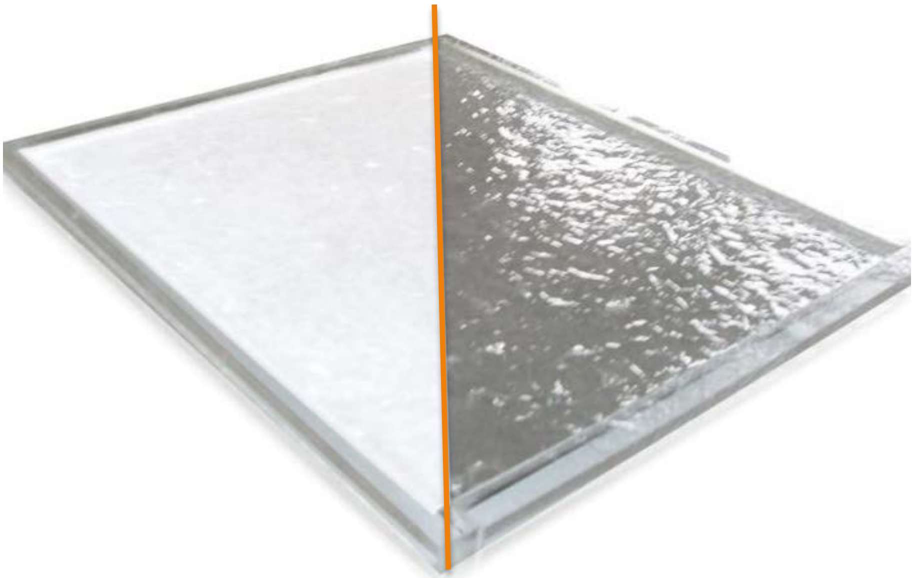


Figure 69: Solid (left) and Liquid (right) state of a 12mm PCM-GFRP panel using hydrated salts as PCM. Tλ-solid= 0.40, Tλ-liquid=0.74.

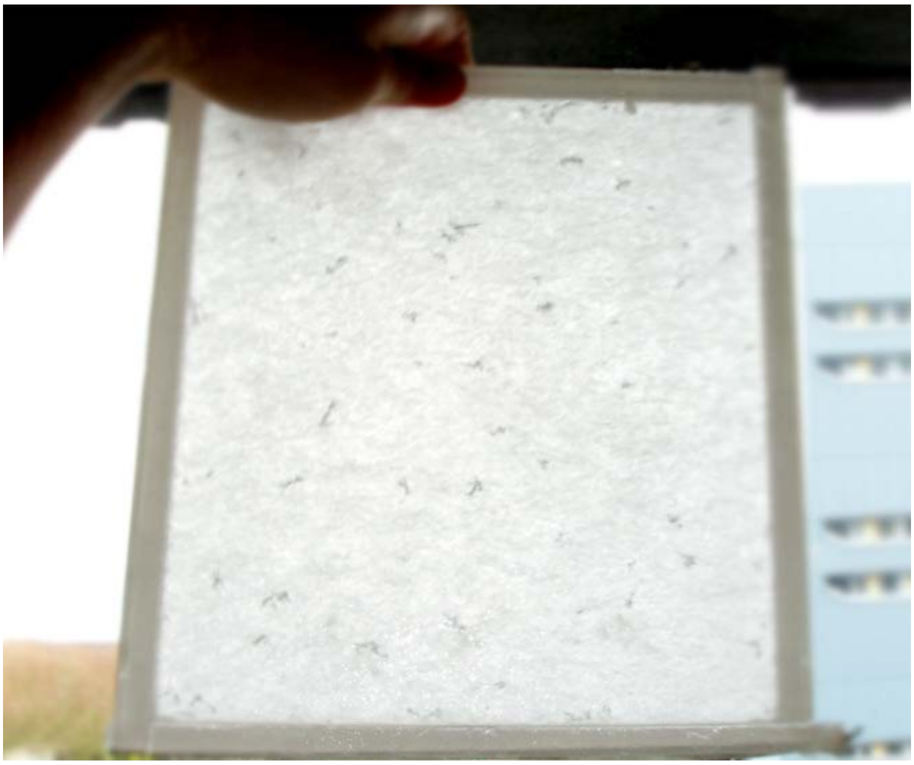


Figure 70: The 12mm PCM-GFRP panel at its Solid state against a window, with a diffuse sky.

Panel A2:

Hydrated Salt CLIMASEL

$T_{pc}=21^{\circ}C$

Phase Change: Solid-'Solid'

d=5mm

with 80g/m^2 GFRP thickness

(the sample was photographed on a black background)

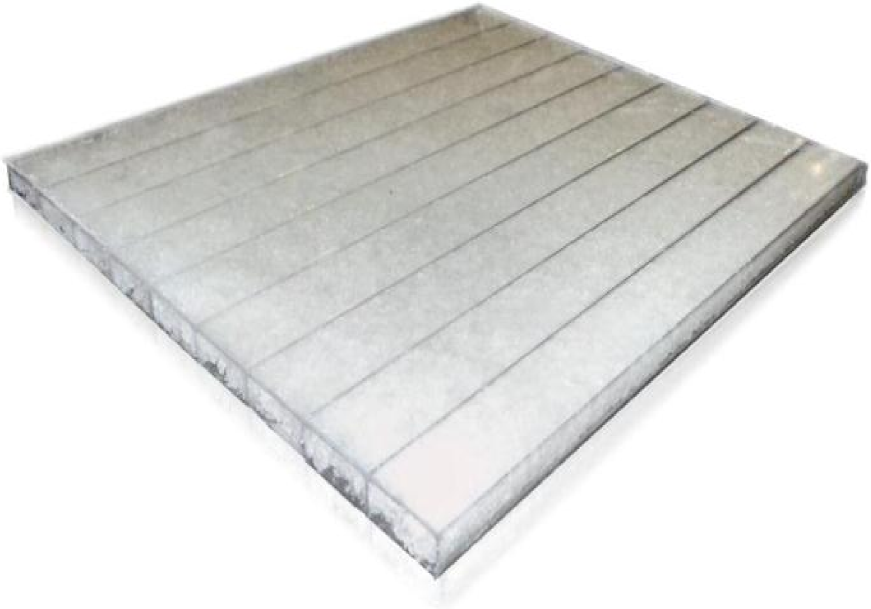


Figure 72: The CLIMASEL PCMs' Tλ stays almost constant at both phases. Tλ-solid, liquid~0.53.

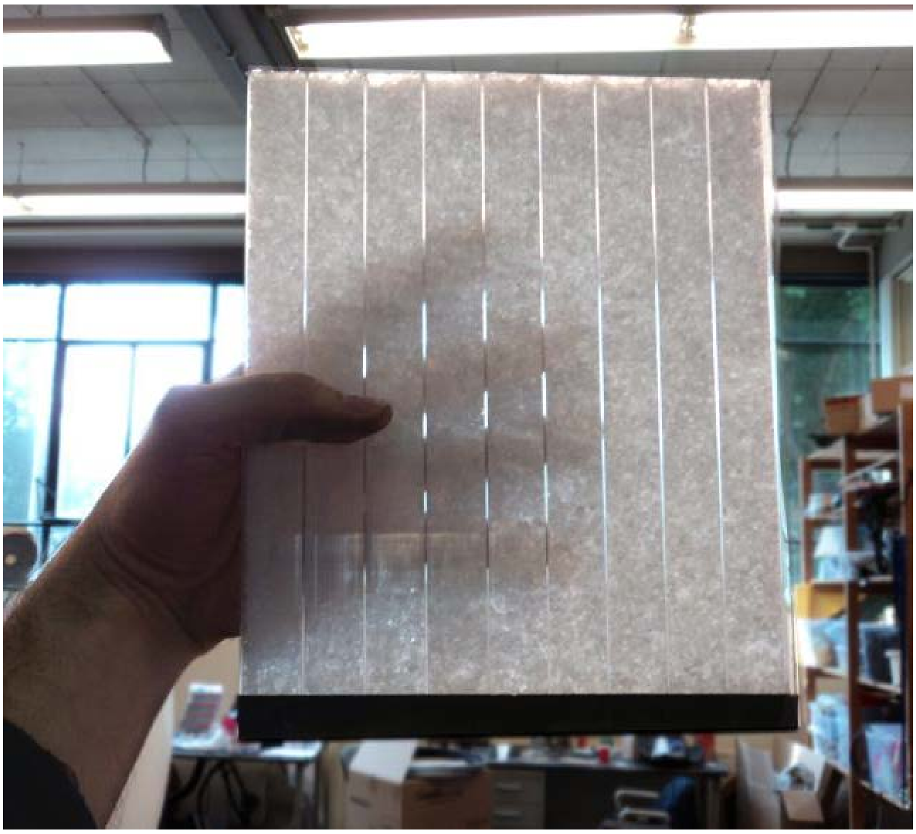


Figure 73: The 5mm CLIMASEL PCMs' Tλ panel at its Solid state at an interior lit environment with diffuse light entering also from a window.

Panel B:

Paraffin Encapsulated In Polymer

PEP

T_{pc}=21.7°C

Phase Change: Solid-'Solid'

d=8.3 mm

with 160g/m^2 GFRP thickness

(the sample was photographed on a black background

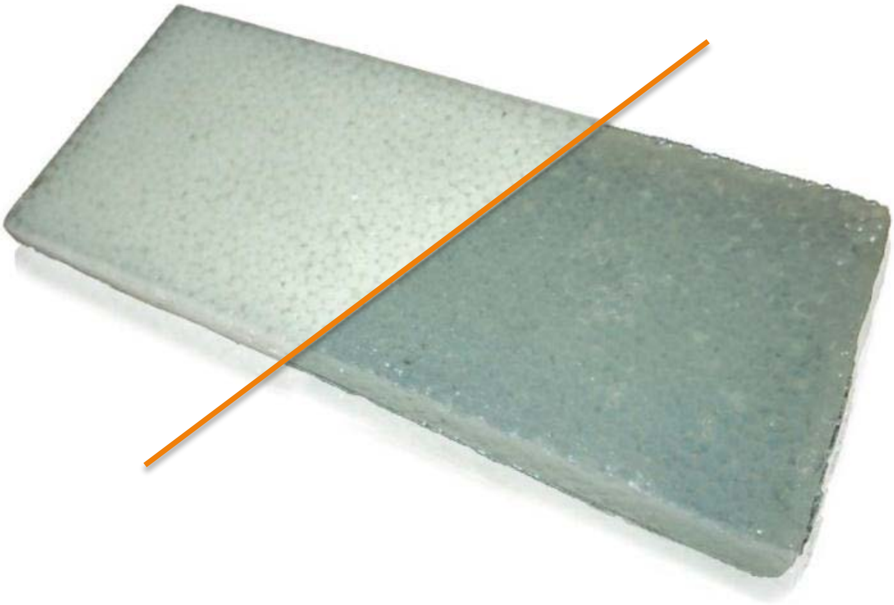


Figure 74: Solid (left) and Liquid (right) state of an 8.3mm PEPEP panel using PEP as PCM, and Epoxy as resin. Tλ-solid= 0.57, Tλ-liquid=0.70.

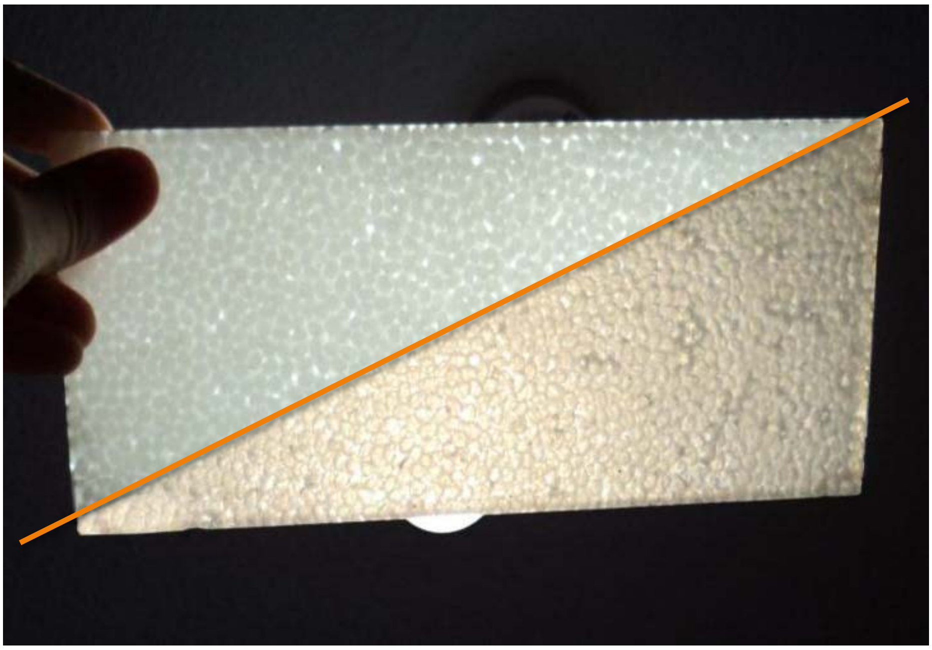


Figure 75: The 8.3mm PEPEP PCMs panel at its Solid and liquid state in front of a 40W incandescent light bulb.

6.1 Application Potentials

A. PCM-GFRP as part of the Envelope

Passive or Active Cooling/Heating ceilings, walls and floors, become more and more a common application for PCM systems.

Principles

The design principles vary between an active or passive system, and mainly depend on the heat transfer mechanisms. Heat-flows to and from the building interior surfaces occur through convection and radiation, and can be calculated as:

$$q_{res} = a_{res} \cdot (T_1 - T_2)$$

where: q_{cv} [W/m^2]= the heat flow density, α_{res} [W/m²·K]= the heat transfer coefficient, T1 – T2 [K]= the difference in temperature (ΔT) between for example the surface of the construction and the air flowing past

α_{res} is the summation of the convective α_{cv} and radiative α_{rd} heat transfer coefficient. The radiative heat transfer coefficient is usually $\alpha_{rd} \approx 5.4$ [W/m^2·K] and stays constant.

The convective heat transfer, on the other hand, is not always constant: A warm low surface creates an upward airflow, and the α_{cv} along its surface is higher. In contrast, a cool high surface creates a downward airflow making the α_{cv} along its surface also higher.

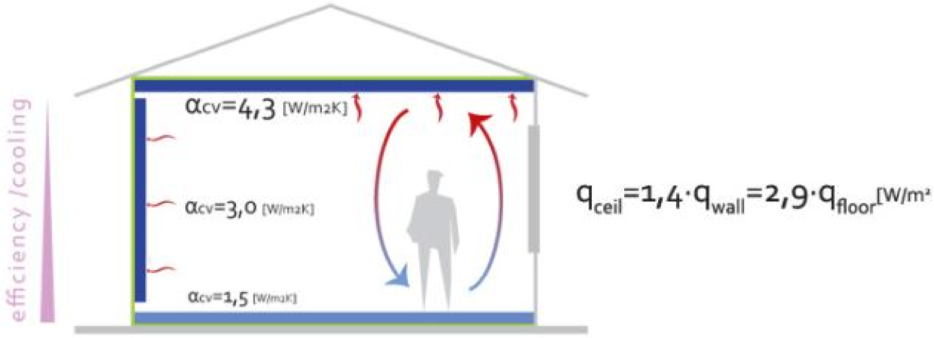


Figure 76: Average Inside convection values for cooling, derived from CIBSE 1993 (source:(Delaforce et al., 1993)

The values that are often used in practice are the following:

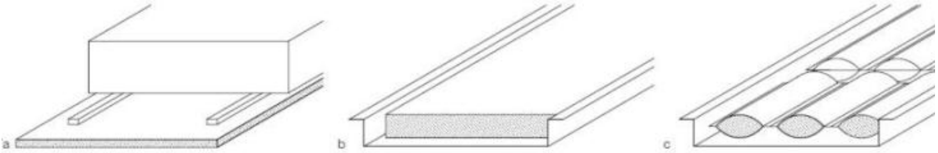
	Heating	Cooling
Ceiling	α_{tot} = 6 [W/m^2 ·K]	α_{tot} = 10 [W/m^2 ·K]
Floor	α_{tot} = 10 [W/m^2 ·K]	α_{tot} = 6 [W/m^2 ·K]

In practice, this means that a floor is more suitable for heating, a ceiling more suitable for cooling.

The thickness and the performance of the PCM panels, depend on the strategy of the application (passive or active) and the type of PCM used.

Passive Strategies and System dimensioning

Passive PCM ceilings depend on 'free cooling' (usually cross ventilation) to discharge at night. A passive cooling ceiling is a good application when diurnal external ΔT is big. The bigger the ΔT between the day and night, the faster the PCM ceiling can discharge, and the most efficient it can be.



Scheme 32: Cooling PCM ceilings in passive systems: a. Gypsum plasterboard with microencapsulated paraffin, b. Sheets as matrix for salt-hydrate/paraffin mixtures, c. Aluminium pouches with salt-hydrate filling *(source: DETAIL 2005/6)*

The proposed thicknesses for the PEP and SHREG PCMs, for passive cooling ceilings, were calculated using the liquid boundary model:

	Average Thickness [mm]	Area Heat Capacity [W*h/m^2]	Area Weight [kg/m^2]	Max. Cooling Power Estimation [W/m^2]	Average Cooling Power [W/m^2]	Min. P.C. time [h]
SHREG	**2.1**	198.3	4.8	35.0	25 - 30	5
P.E.P.	**8.3**	168.2	8.4	27.4	20 - 25	5
Concrete	100.0	200.0	240.0	25.0	-	-

Table 9: For a passive cooling ceiling, assisted with night ventilation, at a room ΔT=4°C from the comfort temperature, and an α_{res}=10. The values for concrete were taken from www.concretecentre.com The values for the average cooling power were compared to data from www.autarkis.nl-PCM klimaatplafond.

Cooling loads vary from 50 W/m² for buildings in cool climates with small internal gains, to 200 W/m² or more for commercial buildings in hot climates with high internal gains[32]. According to the climate and available ceiling area, a passive PCM-GFRP system can save up to 50% in energy consumption.

Active Strategies and System dimensioning

Active PCM ceilings and walls use artificial means (mechanical ventilation or forced water convection) to discharge the absorbed heat at night, if necessary. Usually they have higher cooling capacity, and therefore the panels are thicker.

The proposed thicknesses for the PEP and SHREG PCMs for active cooling ceilings, were calculated using the liquid boundary model:

	Average Thickness [mm]	Area Heat Capacity [W*h/m^2]	Area Weight [kg/m^2]	Max. Cooling Power Estimation [W/m^2]	Average Cooling Power [W/m^2]	Min. P.C. time [h]
SHREG	**5.5**	299.0	20.2	117.6	48 - 61	4
P.E.P.	**17.0**	285.9	9.7	60.3	44 - 58	4
Con. Core Activation	**100.0**	300.0	480.0	93.5	40 - 45	-

Table 10: For an active cooling ceiling, at a liquid cooling ΔT=6°C, and a α_{liquid}=15. The values for concrete were taken from www.concretecentre.com. The values for the average cooling power were compared to data from www.autarkis.nl PCM klimaatplafond.

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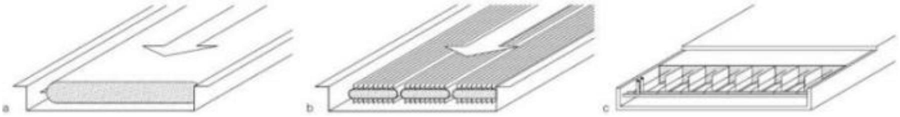
[32] source:www.iklimnet.com/expert_hvac/cooling_load

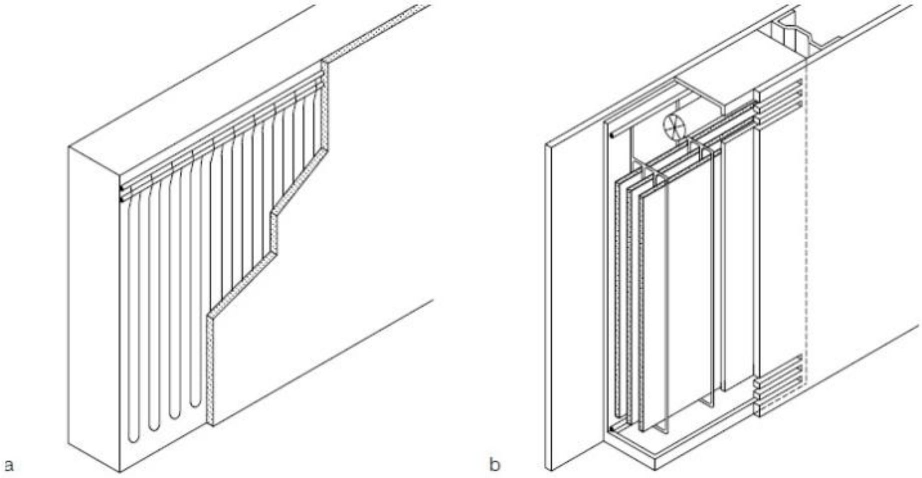
It is obvious that the PEP performs poorly compared to the Hydrated Salts, and that is due to its low conductivity. Therefore, strategies with conductive fins inserted to increase heat transfer within the material are very often used.



Scheme 33: Cooling PCM ceilings in active systems: 8a Aluminium containers with salt-hydrate filling; mini-fan for discharge of heat, b. Aluminium panels with salt-hydrate filling; mini-fan for discharge of heat, c. Aluminium panel: inlaid capillary-tube mat; filled with paraffin-gypsum mixture *(source: DETAIL 2005/6)*

Walls

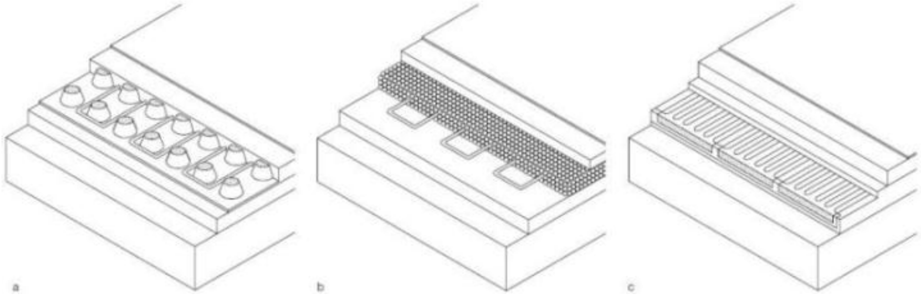
Walls use PCM in active systems more often than passive.



Scheme 34: Active wall systems with water cooling: a. PCM gypsum plaster on mat with capillary tubes, b. Wall ventilation plant, mounted on or built into partition as a modular system; w = 120 mm, h = 2.10–ca. 4 m. Aluminium panels with salt hydrate/ paraffin mixture, and copper tubes for recharging; mini-fan for air intake *(source: DETAIL 2005/6)*

Floors

Floors use PCM in (heating) active systems more often than passive.
Typical values for building heating load range from 20 - 120 W/m².



Scheme 35: Floors in active systems: a Water tubes between bossed capsules with salt-hydrate filling for discharge of heat, b. Water runs between paraffin-granule filling for discharge of heat, c. Panels for charging with electricity; h = 25 mm *(source: DETAIL 2005/6)*

A floor is most susceptible to decay, due to its use, and it usually covered with carpets, tables etc. These facts make it make it an inappropriate receiver for a translucent system; therefore, it will not be examined in this report.

A.1. PCM-GFRP used as additional panels.

Proposed PCM class for better performance:
Hydrated Salts

Proposed panel type:
Panel A1, A2

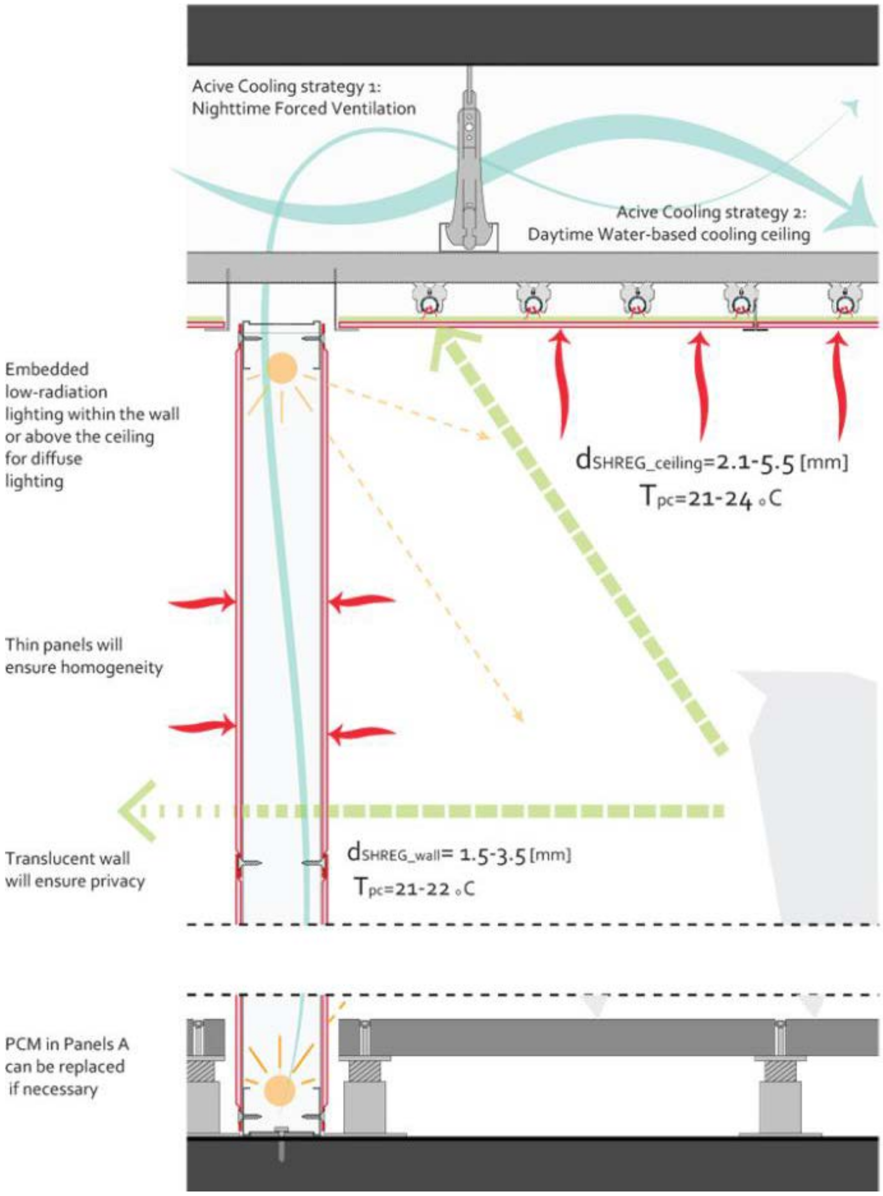
Proposed PCMs for maximum visual dynamism:
SHREG

Proposed PCMs for constant translucency levels (for walls/used for privacy):
CLIMASEL

The panels could be used in new constructions or refurbishments. It would be preferable to be used in spaces whose uses allow active cooling strategies (usually during nighttime), in order to maximize their performance (like offices, schools etc.) and therefore be cost-efficient.

They should be protected from direct exposure to the sun, since their functionality depends mostly in internally generated loads (for cooling).

As mentioned previously, Translucency and Visual Dynamism are competitive additive values that a translucent PCM system can present to an opaque one. Lighting fixtures can be added behind a GFRP-PCM panel to assist in its dynamism perception, or even function as diffuse lighting element.



Scheme 36: Proposed application of a dynamically translucent GFRP-PCM Panel A1, at a cooling ceiling and an interior wall of an office (in this example for Cooling applications. The optical range is presented in green line; the density of the dashed line denotes better visibility.

However, if constant optical changing is unwanted, for privacy maintenance in interior separating walls for example, then CLIMASEL PCM can be used. CLIMASEL, as we saw through the experiments presents an almost constant transparency between 45-50% ($\Delta T\lambda$=0,45-0.55), and very high Image Distortion values.

A representation of the application at a south facing office for an Epoxy panel A, with a CLIMASEL PCM:

For the morning hours:

Figure 77: Epoxy panel A with CLIMASEL PCM at an office, at ceiling and walls, during day.

For the evening hours:

Figure 78: Epoxy panel A with CLIMASEL PCM at an office, at ceiling and walls, during the night.

A.2. PCM-GFRP Integrated at the building structure

As we saw at the introduction, GFRP is more and more used in lightweight shell construction, for transportable houses, freeform architecture etc. Attaching a panel B PEPEP laminate at GFRP sandwich, is an application that exploits further the inherent ability of a Polyester or Epoxy resin to embed or to be attached to other materials.

Proposed panel type:
Panel B

Proposed PCM:
PEP

Proposed strategy for maximum visual dynamism:
Add Patterned fiber mat as a last laminate layer

Proposed strategy for control:
Embedded Lux meter can initiate mechanical cooling

Figure 79: A 75mm GFR polyester panel, with a 20mm cement fiberboard layer attached at its interior surface.

The PEP could be casted during the fabrication process and create an integrated panel. As we saw during the experiments, the perceiving the phase change process at a PEPEP panel is achieved mainly through an the change in Image distortion between the PCM states.

Therefore, it is recommended that a patterned fabric (surface tissue) be set underneath the PEPEP layer, as illustrated in the following figure.

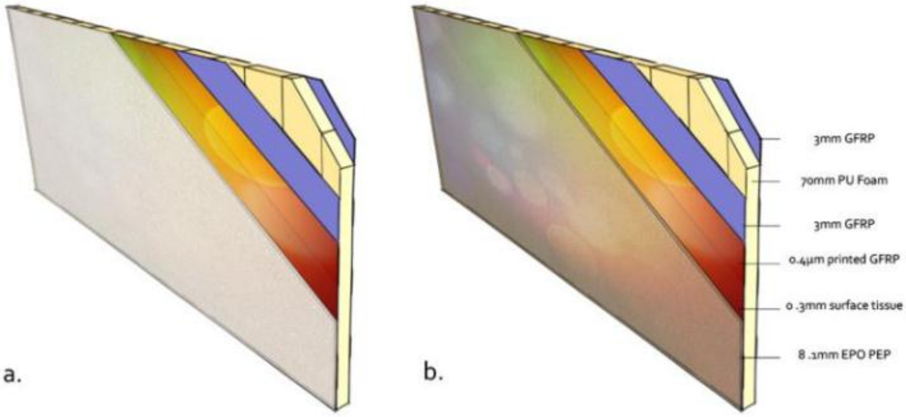


Figure 80: Integrating PEP within a sandwich GFRP laminate. a. at its solid and b. at its liquid state.

The integrated PCM layer might seem inflexible compared to a separate panel. However, it is advantageous in applications where complex geometries are required, since it will follow the shape of the structure.

A representation of the application at the interior of a museum, fabricated in curved GFRP, for a PEPEP panel is presented here:

For the morning hours:

Figure 81: PEPEP panel B with at a museum, integrated at its shell, during morning hours. The pattern selected is a 'fishbone'. Due to higher heat flow at ceiling it will start becoming transparent sooner than the walls.

For the evening hours:

Figure 82: PEPEP panel B with at a museum, integrated at its shell, during evening hours. The pattern selected is a 'fishbone'.

In this application lies the possibility to integrate lighting fixtures within the laminate. The lighting fixtures should emit little to none heat (like LED lights), in order to affect the thermal behavior of the PCM as little as possible.

An small prototype was made to see how such a setup would look like, at both the molten and solid phase, with the light on and off.

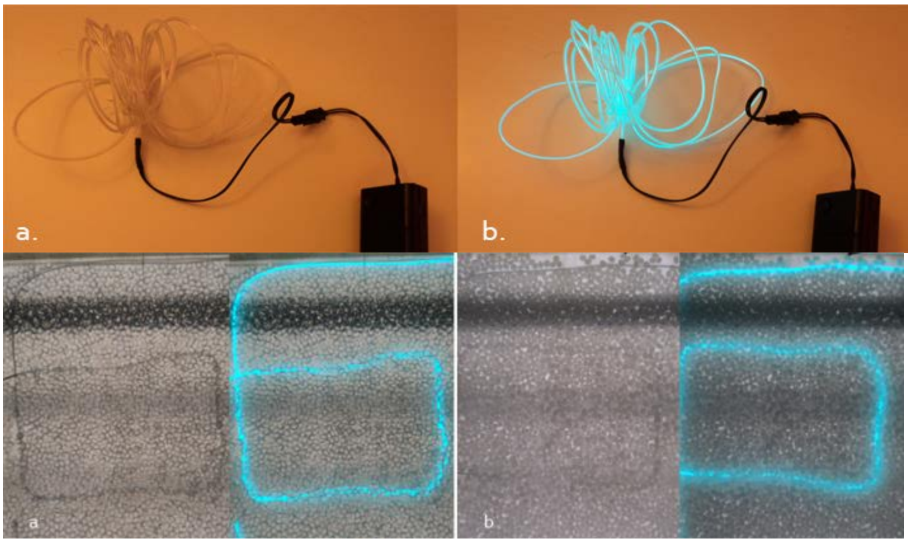
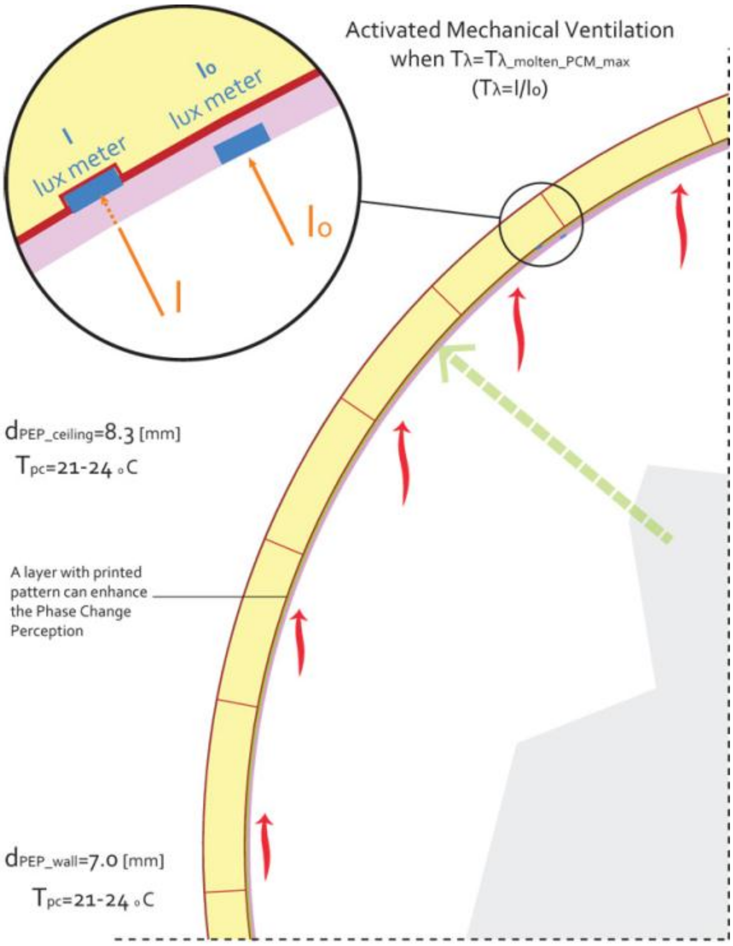


Figure 83: Integrating NEON lights embedded in a flexible transparent tube, within a PEP PCM at its molten (b) and solid (b) phase.

Using the dynamic value T_λ to automate the PCM cooling process

An alternative that could exploit the dynamic translucency of the PEPEP, would be the integration of LUX meters on and behind its layer. They ratio (Tλ, see chapter 2) would be periodically recorded; when it increased at the maximum (Tλ_molten=.59), the forced ventilation would automatically be activated, to initiate the PCM cooling process.



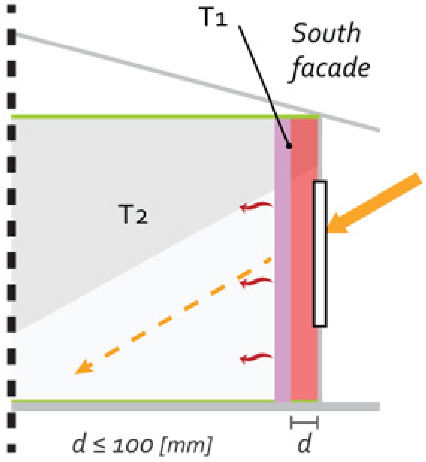
Scheme 37: Proposed application of a dynamically translucent PEPEP panel B at a GFRP structure

B. PCM-GFRPs as Independent elements

Overview of the applications

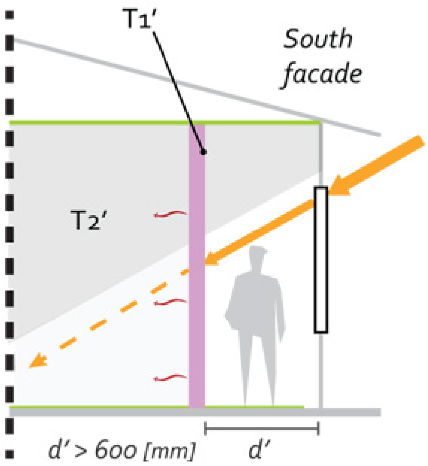
1. PCM-GFRP elements Related to the Façade

i. Translucent Solar (Trombe) Wall



A Solar wall is a sun-facing wall separated from the outdoors by glass and an air space at a very close distance. It absorbs solar energy and releases it selectively towards the interior at night. When a massive material is used, the wall can also be called 'Trombe wall'.

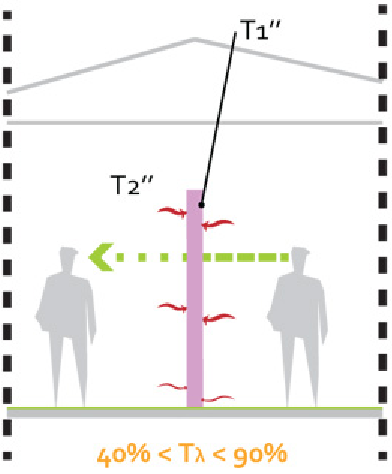
ii. Solar Storage Walls



Solar Storage walls are south facing walls that can be used to collect and store heat at the egde of a room. The heat can be released back, when the ambient room temperature drops. The difference with a solar or trombe wall, is that a thermal storage occurs mainly by direct solar radiation

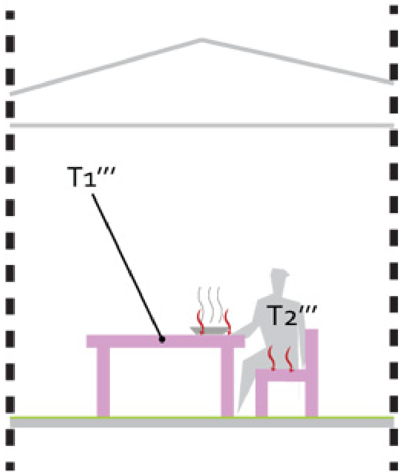
2. PCM-GFRP elements Not related to the Façade

i. Interior freestanding privacy wall



An interior partition wall can accumulate or release heat, similar to the application A1. However, contrary to that wall, it can be freestanding and adjustable.

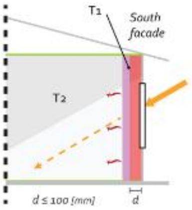
ii. Furniture



Furniture occupies the largest area in an inhabited room. If PCMs are introduced into their bodies, then they could assist in thermal storage strategies, even though not as efficiently as ceiling/wall floor elements. The additive value would also be the changing transparency.

B.1. PCM-GFRP elements Related to the Façade

B.1.i. Translucent Solar (Trombe) Wall



Proposed PCM class for better performance:
Hydrated Salts

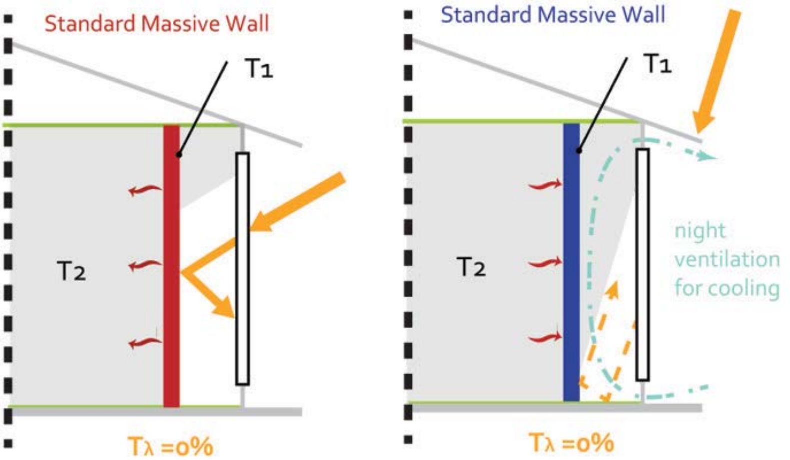
Proposed panel type:
Panel A1, A2

Proposed PCMs for maximum visual dynamism:
SHREG

Proposed PCMs for constant translucency levels (for walls/used for privacy):
CLIMASEL

Such a wall (Trombe) usually has vents at the top and bottom of the interior wall, to allow heated air to flow via convection into the building interior. The vents have one-way flaps which prevent convection at night, thereby making heat flow strongly directional. The top and bottom of the exterior window also have exhaust openings to the outside air, to enable night-time ventilation, which is necessary for passive cooling strategies.

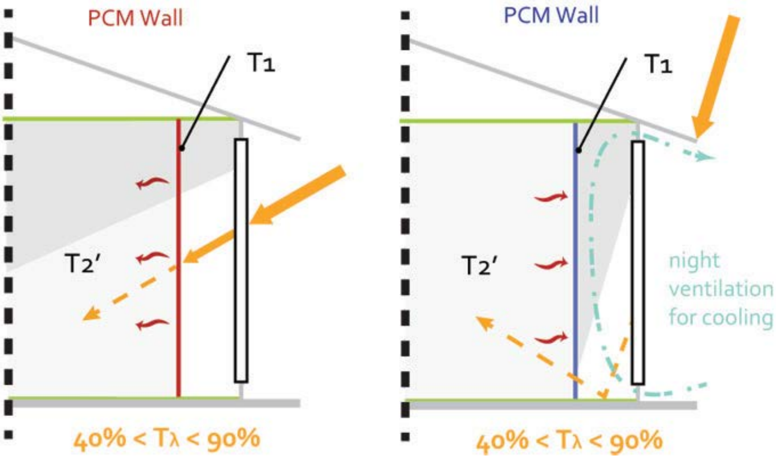
Trombe walls are used mostly for heating strategies.



Scheme 38: A usual opaque massive Trombe Wall. A proposed thickness for concrete is 300mm (Brown and DeKay, 2001)

Usual Trombe Walls possess two basic characteristics, that from some can be considered as disadvantages: they are heavy (so they are not usually preferred in taller buildings where reduction of weight is important), and they are opaque.

A translucent alternative could be achieved using PCMs as the heat storage medium. It would be lightweight and also allow visible light through. If Hydrated Salts are used, the transmitted light would range from 40% to 90%.



Scheme 39: A translucent PCM Solar Wall, which should behave the same, but be lightweight and allow visible light to enter the house.

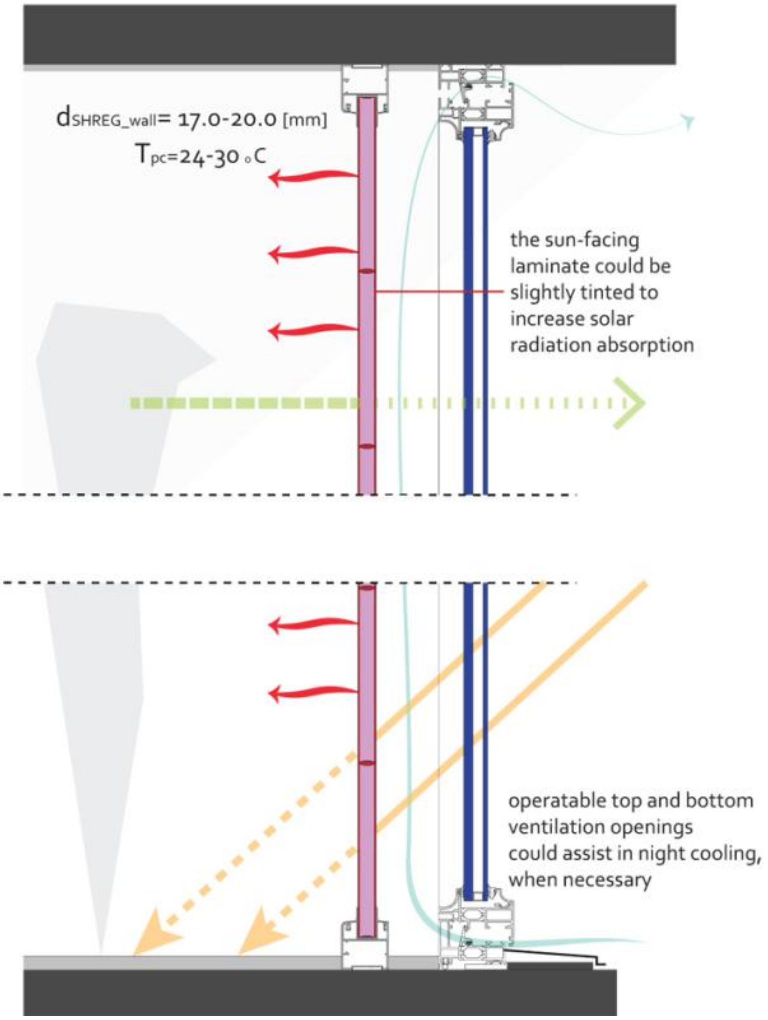
A comparison of weight and heat capacity between a concrete Trombe and PCM solar walls, for a period of 10hrs. It is important for a PCM layer to fully melt, in order to absorb as much energy as possible.

	Average Thickness [mm]	Area Heat Capacity [W*h/m^2]	Area Weight [kg/m^2]	Melting Time [h]
Concrete Trombe	300	2250	720	-
Hydrated Salts	20	1166	29.4	10
PEP	40	672	61.4	10

Table 11: Rough estimation of the performance of three solar walls, for a $\Delta T=15^{\circ}C$, a melting PCM time=10hrs, with a 7.5 W/m^{2}K heat transfer coefficient within the solar cavity.

A rough calculation shows that thicker PCM layers than those stated in the previous table, will not allow a full melting of PCM, therefore reduce the heat flow, into the building. Moreover, iinadequate thermal storage capacity can cause overheating.

This fact however requires further and deeper investigation.

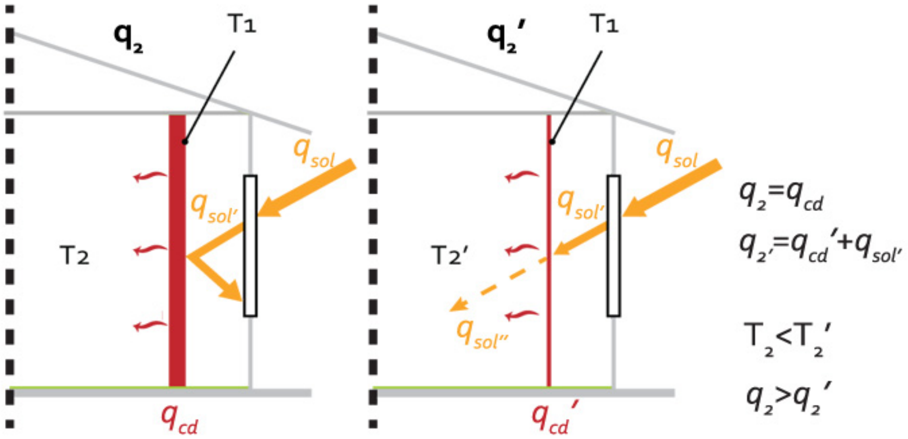


the sun-facing laminate could be slightly tinted to increase solar radiation absorption

operatable top and bottom ventilation openings could assist in night cooling, when necessary

Scheme 40: Proposed application of a dynamically translucent Hydrated Salts Panel A2 PCM for a lightweight solar wall

Overheating can also be caused if not only visible, but also infrared solar irradiation could be transmitted through the PCM layer. Usual Trombe walls are opaque and eliminate this possibility.



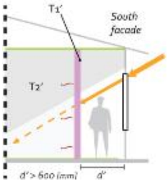
Scheme 41: Infrared radiation is absorbed (and partly reflected) from the Trombe wall [left]. whereas it can be transmitted from the PCM solar wall.

Despite those challenges, such walls using hydrated salts have been commercially developed, and are thoroughly described by Mehling and Cabeza (2008). The most famous example is Glass X, that uses Hydrated Salts with T_{pc}=26-28°C, and has a heat capacity of 1185 W*h/m².

Figure 84: Exterior View of a Trombe Wall (source: http://www.lxrdesign.biz/DETAILS.htm

Figure 85: Interior View- Example of a translucent Glass X solar wall (source: www.glassx.ch)

B.2.ii. Solar Storage Walls



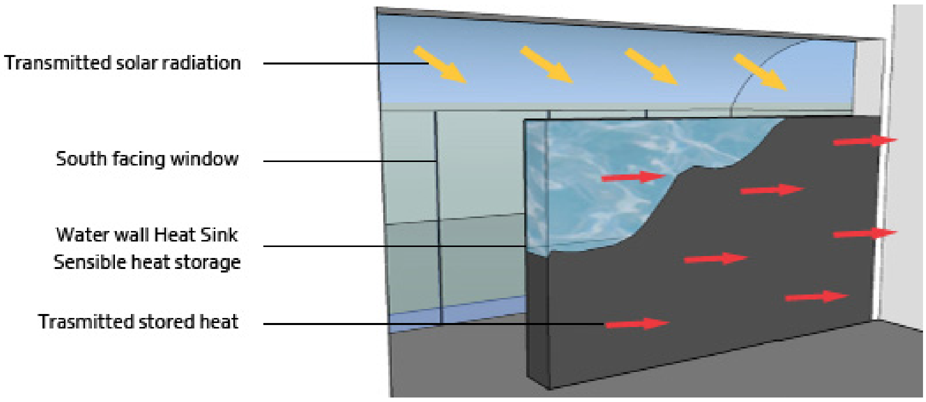
Proposed PCM class for better performance: Hydrated Salts

Proposed panel type: Panel A1, A2

Proposed PCMs for maximum visual dynamism: SHREG

Proposed PCMs for constant translucency levels (for walls/used for privacy): CLIMASEL

A Solar Storage wall absorbs heat primarily from the façade, and secondarily from the interior loads. The advantage to a Solar wall is that it allows the use of the space between itself and the façade (d>600mm). The disadvantage is that it is less efficient.



Scheme 42: A water container acting like a solar storage wall (source: greendesigncollective.com/green/nine))

Solar Storage walls are also used in sunspaces.

A comparison of weight and heat capacity between water and 2 PCM solar storage walls, for a period of 10hrs is presented here. It is important for a PCM layer to fully melt, in order to absorb as much energy as possible.

	Average Thickness [mm]	Area Heat Capacity [W*h/m^2]	Area Weight [kg/m^2]	Minimum Phase change time [h]
Water	120.0	1250	110.4	-
Hydrated Salts	14.5	845.8	20.3	10
PEP	29.0	487.7	25.1	10

Table 12: Rough estimation of the performance of three solar storage walls, for a ΔT=10°C, a melting PCM time=10hrs, with a 7.5 W/m^{2}K heat transfer coefficient at its surface.

The example is similar to the B.2.i. Solar Wall application, therefore the same challenges apply to it and should be considered for deeper examination.

A representation of a heat sink wall, based on a real example is presented here:

Figure 86: A house using a massive slate wall as a heat sink (source: www.paulraffstudio.coms)

In this example, the massive slate heat sink wall also assists structurally at the bearing of a staircase.

It would not be impossible for the PCM wall to exploit the structural potential of a GFRP laminate (probably in a corrugated form, to increase the moment of inertia, and the buckling resistance) and assist structurally the bearing of the staircase.

For the morning hours:

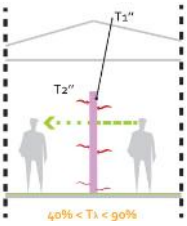
Figure 87: A PEP-GFRP wall can replace a massive slate wall as a heat sink, while at the same time allow for penetration of natural light. PCM at its solid state

For the evening hours:

Figure 88 Figure 89: A PEP-GFRP wall can replace a massive slate wall as a heat sink, while at the same time allow for visual connection to the exterior. PCM at its liquid state.

B.2. PCM-GFRP elements Not related to the Façade

B.2.i. PCM-GFRP paneling as an Interior privacy wall



Proposed PCM class for better performance:
PEP

Proposed panel type:
Panel B

Proposed PCMs for maximum visual dynamism:
PEP

Proposed PCMs for constant translucency levels (for walls/used for privacy):
CLIMASEL

Through the experiments we observed that the image distortion increases as the distance from the PCM-GFRP panel is increasing. In solid-'solid' PCMs we tested, the image distortion remained high at both states.

Figure 90: By using a panel B type of PEP-GFRP, the flexibility of creating complex geometry is added.

Moreover, PEPEP could exploit its ability to be fabricated in any shape. For example, similar the separating walls of Erwin Hauer (fig. 92), a standardized module could be created which through its repetition could be developed in an interior wall element.

Figure 91: Casted gypsum-cement partition wall, designed by Erwin Hauer, at ElieTahari's Manhattan fashion studios, NY (source:www.erwinhauer.com)

The following design shows the design of such a module, using PEP in epoxy resin.

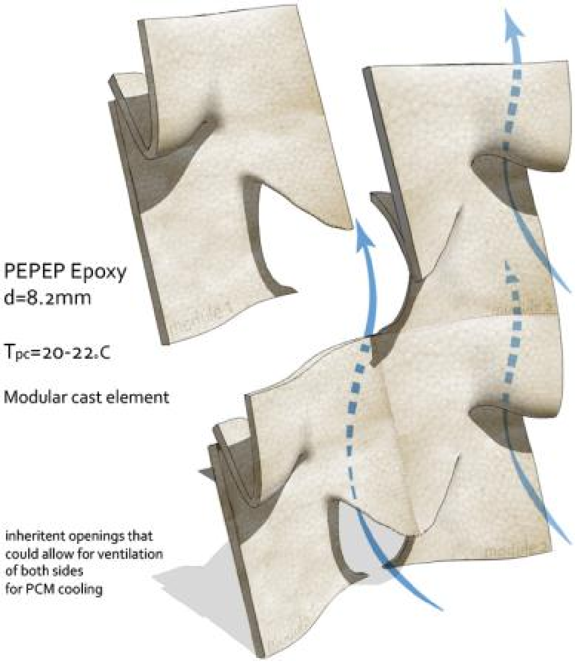


Figure 92: A 200x200 mm module that could be repeated into the formation of a system.

Due to its complex shape, chopped fibers it is recommended to be used as reinforcements.

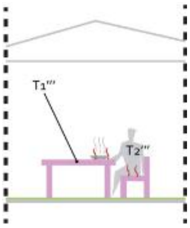
A representation of this application at the interior of a house is presented here, for the morning hours:

Figure 93: An 8.3mm interior PEP-GFRP privacy wall.

B.2.ii. Furniture made of PEPEP

By exploiting the structural capability of PEPEP non-architectural elements could be produced, such as furniture, that could assist in enhancing the thermal performance of a room, or by just being transparency changing elements- for esthetical reasons.

However, as we saw previously, the structural behavior of PEPEP changes throughout the phase change, therefore a deeper investigation on this possibility should be made.



Proposed PCM class for better performance:
PEP

Proposed panel type:
Panel B

Proposed PCMs for maximum visual dynamism:
PEP

Figure 94: Proposal of a table fabricated in PEPEP, at its solid state.

Summary

Considering heating and cooling a building, it is important to consider the extend of the heating and cooling load. In residential buildings, heating loads tend to be larger than cooling loads[33]. The opposite occurs in larger buildings like offices where the interior loads from occupants, light and equipment are much larger throughout the year.

Therefore, we can say that the primarily heating strategies (like the Solar wall or the Sunspace) are more appropriate for residential buildings, while the primarily cooling strategies (like the mechanically ventilated Ceiling and Walls) more appropriate for offices. (Brown and DeKay, 2001)

An overview of the strategies and the efficiency depending on each application is presented schematically in the following table:

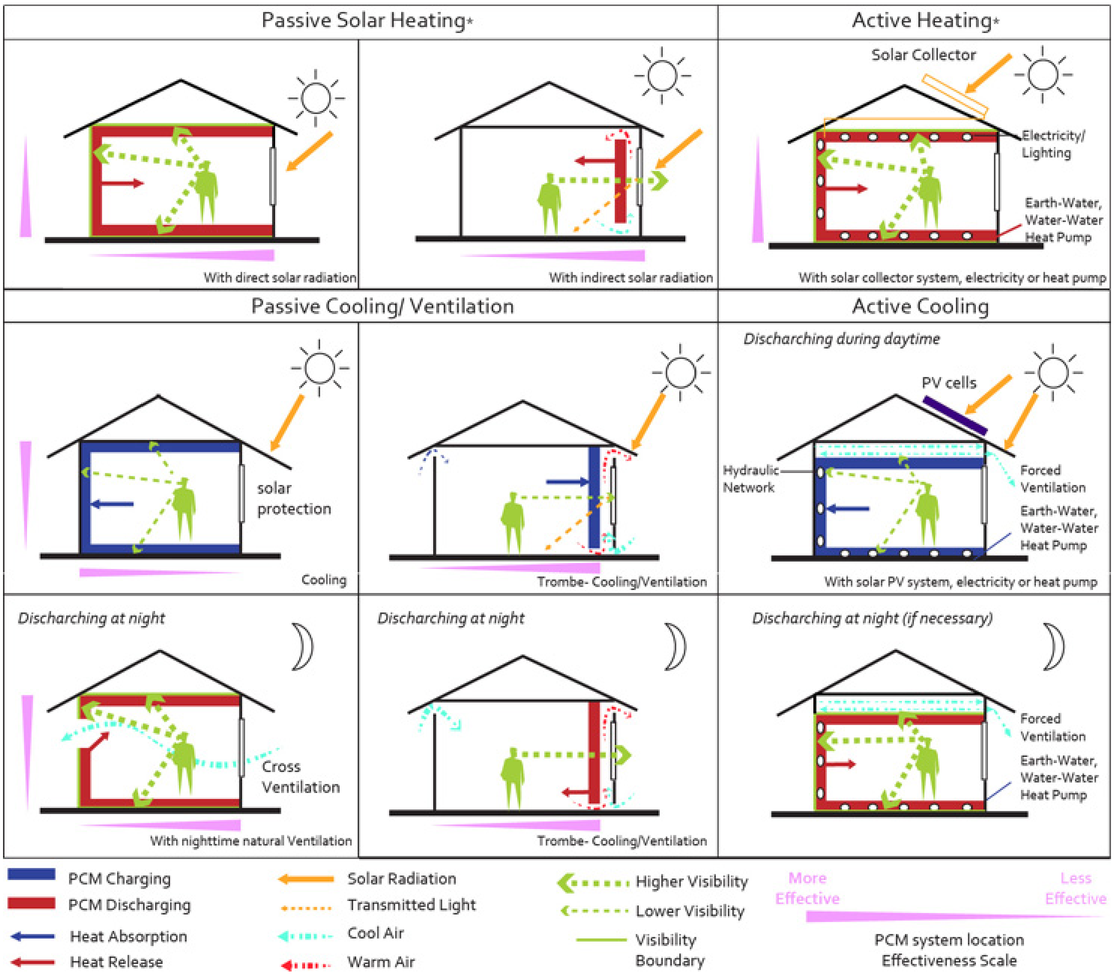


Table 13: Overview of Applications of PCM in the architectural envelope for passive and active cooling and heating.

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[33] with the exception of very hot climates

6.2 Case Study (app. A.2)

A Spacebox is a lightweight structure. Due to its needs for transportation, stacking and fast assembly, the need for low weight is of outmost importance.

Therefore, the project is fabricated in Glass Fiber Reinforced Polyester (GFRP), a lightweight and simultaneously strong material.

However, as a lightweight structure, the need for thermal mass is also crucial and challenging since low weight is the basic design parameter for GFRP manufacturers.

Therefore, a better thermal performance is sacrificed to not adding sensible thermal mass. Sensible thermal mass leads to a heavy component.

A strategy used adds a low-cost layer of cement fiberboard at the interior.

This extra addition increases the weight of the building by 15 kg/m[34] but adds thermal mass, assists in the sound insulation, and provides a stiff interior surface as a basis for the interior finish.

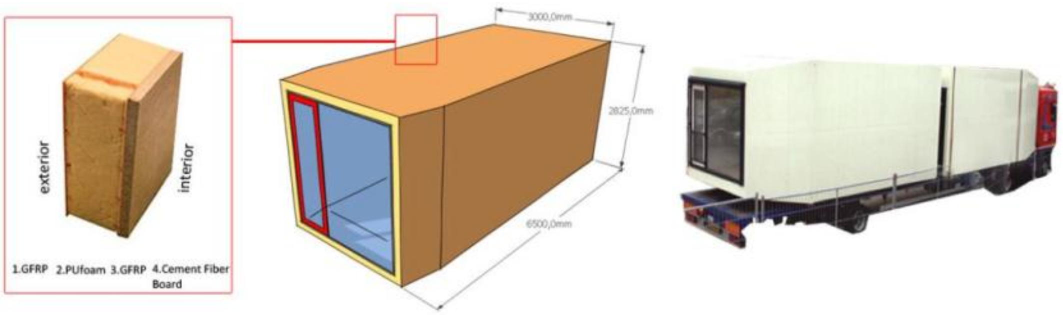

Figure 95: (left) A Spacebox and its standard wall construction layer. (Right) Two Spacebox units being transported. (source: http://50sa.tistory.com/entry/Spacebox-Spacebox-Eindhoven-2005-TUe)

In order to evaluate and the necessity of using PCMs for thermal regulation in lightweight structures, we can compare thermal performance and lightness between 3 types of walls standard heavyweight and composite construction.

In particular:

1. a GFRP sandwich wall with a PU core,
2. the same with the addition of a (as inherited from the industry practice[35]) a 10mm cement-fiber board and
3. a prefabricated insulated concrete wall.

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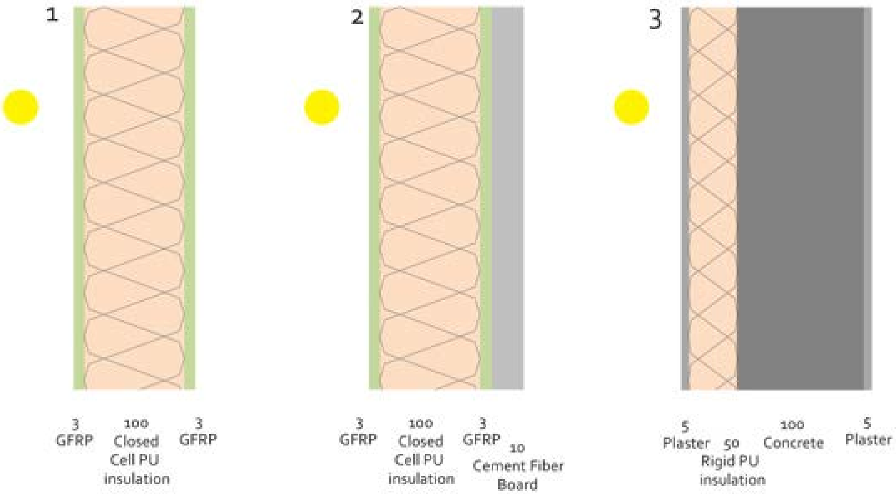
[34] Holland Composites field visit

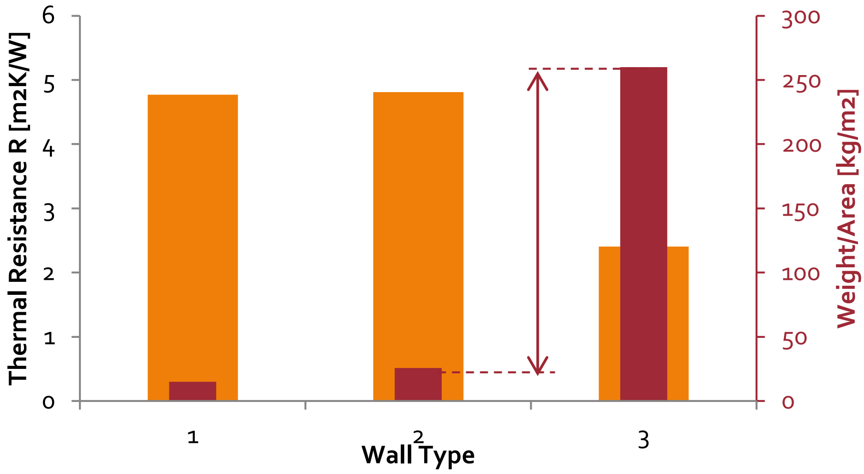
[35] Practice used by Holland Composite Industries

Comparison between 3 wall types



Scheme 43: The 3 wall types compared

The following graphs clearly depict the effect that the PU insulation layer has at the U-Value, at walls 2 and 4. Moreover, the total weight/m^2 can be up to 16 times smaller in a GFRP structure that a standard concrete one.



Wall Type	Thermal Resistance R [m2*K/W]	Area Weight [kg/m2]
1	4.76	15.0
2	4.81	25.8
3	2.40	260.0

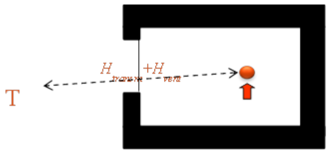
Chart 17: Comparison between the Thermal Resistance (R) and to wall area weight. Weight per The weight difference between wall 2 and 3 is 234 kg/m^2.

We can have a good estimation of the indoor air temperature rise after a time (t) = 10 hrs, using the 1-node room model[36].

---

[36] starting at 10:00 am, for Ti=Te=20°C, using our case study building that presents: a measured volume V=55m^3, a total area A_{total}=19.5 m^2, Area of walls with sensible heat storage A_{walls}=56.2 m^2, window area A_{window}=5.5m^2, with windows of solar transmission coefficient of g=0.8, U-value=0,75 W/m^2·K, a solar heat flow of q=150W/m^2, integral peak generated loads Hin=150W, and an air-change rate n=1, using the 1-node room model

1-node room model



Scheme 44: Illustration of the 1-node room model

The 1-node room model can be used to predict temperature rise within room, taking into account the Heat Loads, and the Thermal Mass of its structure.

The interior air temperature of the room (T_x), after a time t can be calculated from the formula:

$$T_x = T_{ext} + \frac{W}{H}\left(1 - e^{-\frac{H_{tv}}{M} \cdot t}\right)$$

In this formula W [W] is the summation of the Sun and Internal loads:

$$W = H_{sun} + H_{internal\_loads}$$

The loads from the sun are given by:

$$H_{sun} = q_{sun} \cdot g \cdot A_{glass}$$

where: H_{sun} [W] is the solar load (direct or indirect), q [W/m^2] is the solar load, g coefficient of transmittance (1=all, 0=none) , A_{glass} [m^2] is the glass surface

The internal loads $H_{internalloads}$ depend on the application.

The summation of the losses from conduction of envelope and ventilation:

$$H_{sun} = (H_{trans.} + H_{vent})/\Delta T$$

The ventilation heat losses:

$$H_{vent} = \rho_{air} \cdot c_{air} \cdot V \cdot n \cdot \Delta T/3600$$

where: H_{vent} [W] is the ventilation heat loss load, ρ_{air} [kg/m^3] is the density of air (1.2), c_{air} [J/kg·K] is the sensible specific heat of air (840), V [m^3] is the volume of the room, n [h^{-1}] is the ventilation rate[37], $\Delta T = T_{interior} - T_{exterior}$

The transmission heat losses:

$$H_{transmission} = \Sigma(U \cdot A) \cdot \Delta T$$

where:, H_{sun} [W] is the transmission loss load, U [W/m^{2}K] is the U-value, A [m^2] is the window surface, $\Delta T = T_{interior} - T_{exterior}$

M Is the exploitable mass of the room, concentrated in a single node:

$$M = \rho_{air} \cdot c_{air} \cdot V + \rho_{wall} \cdot c_{wall} \cdot d_{wall} \cdot A_{wall} + \rho_{ceiling} \cdot c_{ceiling} \cdot d_{wall} \cdot A_{wall}$$

The Cooling and Heating Loads can be calculated:

$$H_{cool} = H_{sun} - (H_{vent} + H_{transmission})$$

where: H_{cool} [W] is the cooling load

$$H_{heat} = H_{vent} + H_{transmission} - H_{sun}$$

where: H_{heat} [W] is the heating load

---

[37] For residential spaces, n can be deducted from standards (EUROCODE). Comfort values between 0.3 and 0.5

Performance of a GFRP room without thermal mass

As seen from the following graph, that absence of mass in the lightweight GFRP, which presents the best total U-Value amongst the other materials, increases its interior temperature more than 20.0°C, within 4 hours.

In contrast, the heavyweight concrete will cause a difference of less than 2 °C within the entire 10hr period.

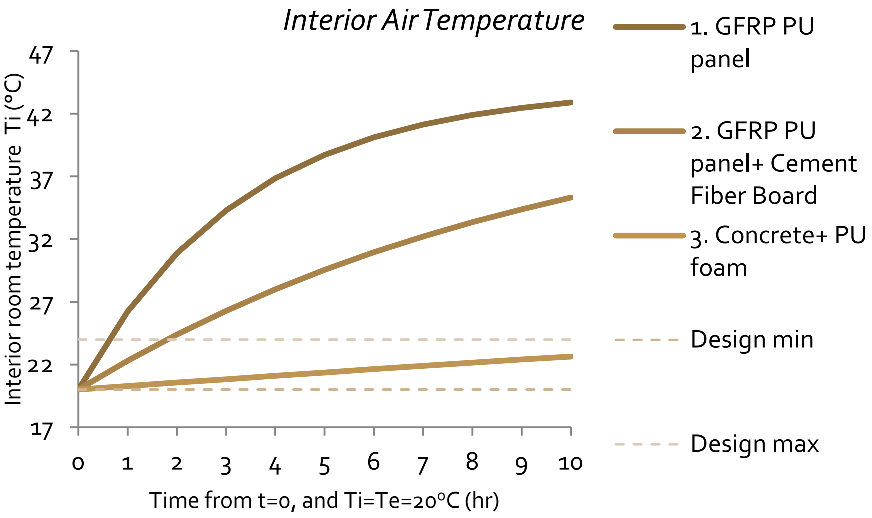
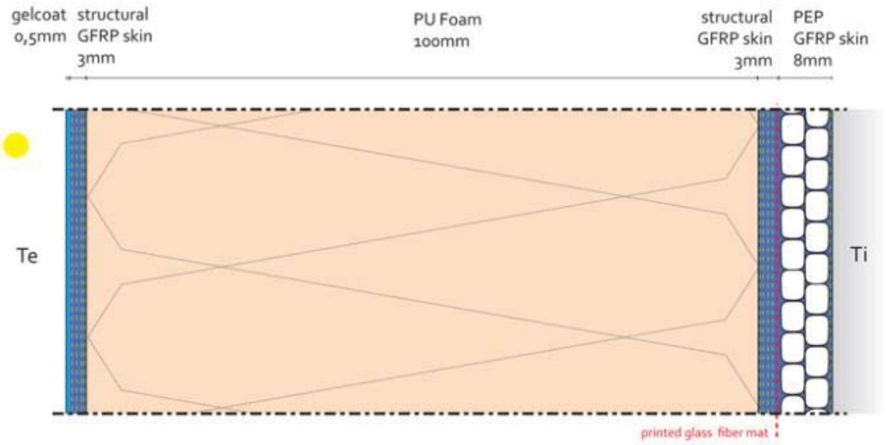


Table 14: Indoor Air temperature calculated with the 1-node room model, for an interior and exterior air starting temperature of 20 degrees, for a Thermal Mass area of Walls+Ceiling =56. 2 m^2

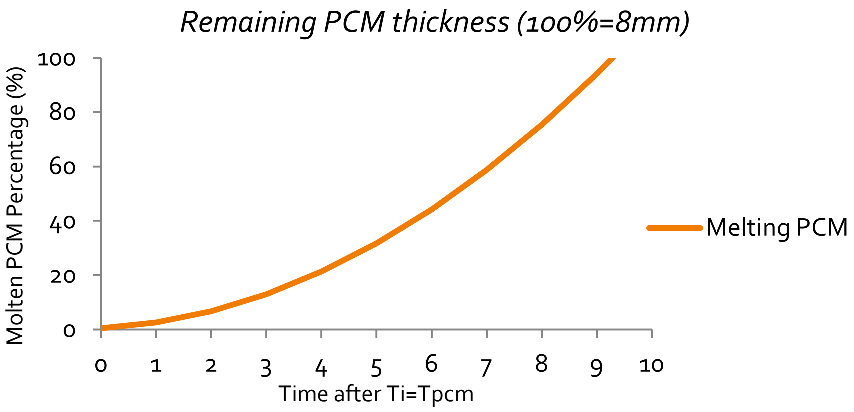
Performance of a GFRP room with thermal mass

In order to evaluate the use of the PCM at the interior of a wall surface, we can compare another wall at the previous comparison, using an 8mm inner layer of PEP PCM. The specific latent heat capacity of the PCM is 70kJ/kg, and a thermal conductivity λ=0.28.



Scheme 45: The new GFRP-PCM wall using an 8mm PEPEP at its interior layer.

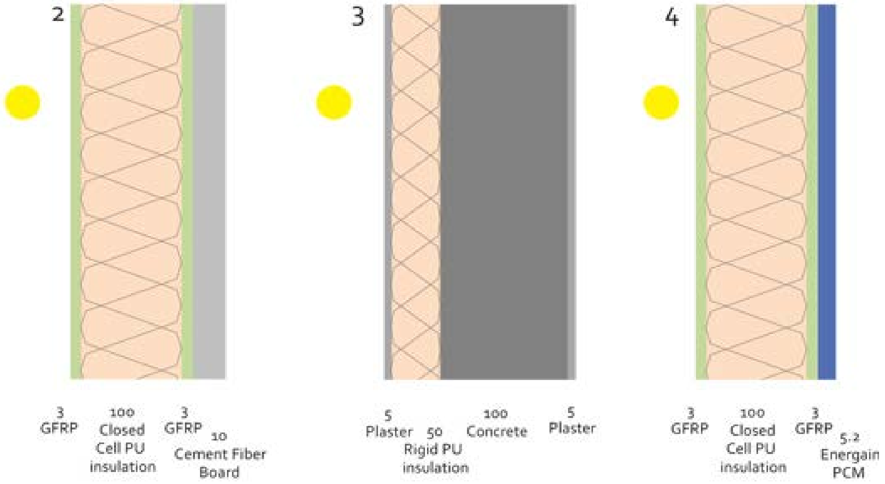
We first want to check if and how long will it take the PCM to melt. The goal is to have an economic melting which means not too fast melting or not too slow.



Time	[hrs]	0	1	2	3	4	5	6	7	8	9
Remaining Thickness	[mm]	6.9	6.8	6.5	6.0	5.5	4.7	3.9	2.8	1.7	0.4

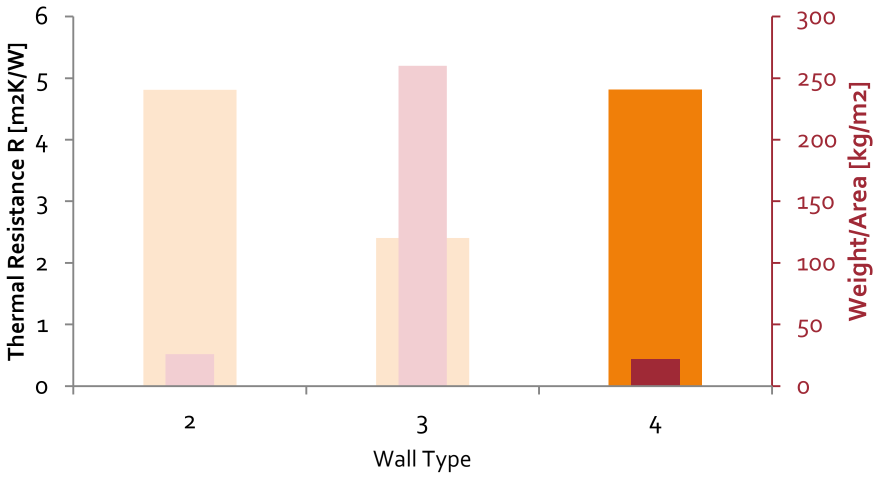
Chart 18: Remaining PCM thickness at an 8 mm PEP-GFRP (equal to 7mm PEP)

For the 8mm GFRP-PEP (having an 85% PCM by volume) for a low convective heat transfer coefficient, α=2.5 W/m2K we will have a total heat absorption in 9 hrs.



Scheme 46: The addition of the 4th wall at the previous comparison

The PCM quantity equals to the commercial ENERGAIN panel which has a thickness of 5.2mm and a density of 865kg/m^3, and adds an extra 10kg/m^2 to the construction; it is a little less than the standard cement fiberboard, 15kg/m^2.



Wall Type	Thermal Resistance R [m2*K/W]	Area Weight [kg/m2]
2	4.81	25.8
3	2.40	260
4	4.81	21.8

Chart 19: Comparison between the Thermal Resistance (R) and to wall area weight.

We can calculate the indoor air temperature, again, after a time (t) = 10 hrs.

In order to be able to use the 1 node-room model, we should make these assumptions:

- The system stores sensible heat up to the point where $T_i = T_{pc}$.
- The sensible heat storage during the PC process it is too low compared to the latent. Therefore, it can be neglected.
- The PCM melts in a linear way (contrary to chart 19) but it stores the same amount of energy at the total melting time.
- The PCM starts melting immediately as soon as the temperature room reaches the $T_{pcm.}$ As we saw during the experiments, though this is not completely true, since there is always a minor time lag.

For example, if a PCM melts within the design time (10 hrs), we can divide the total heat storage capacity to 10, and we can have the storage heat capacity per hour. In other words, what we do is emulate the latent heat to sensible heat.

The important parameter is the quantity of PCM that melted (chart 19). If 60% of the PCM melts during the design time, then we should calculate with 60% of the total latent heat.

Components	**Area [m^2]**	**Performance**
ceiling	19.5	High α_{cv}
floor	19.5	Low α_{cv}
wall1	18.36	Average α_{cv}
wall2	18.36	Average α_{cv}
total	75.72	
total exploited	56.2	

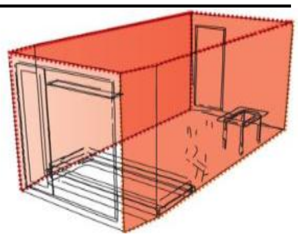


Table 15: In red, the exploited parts of the building for latent heat storage.

The results of the calculations, along with the melting time of the PCM are presented in the next chart.

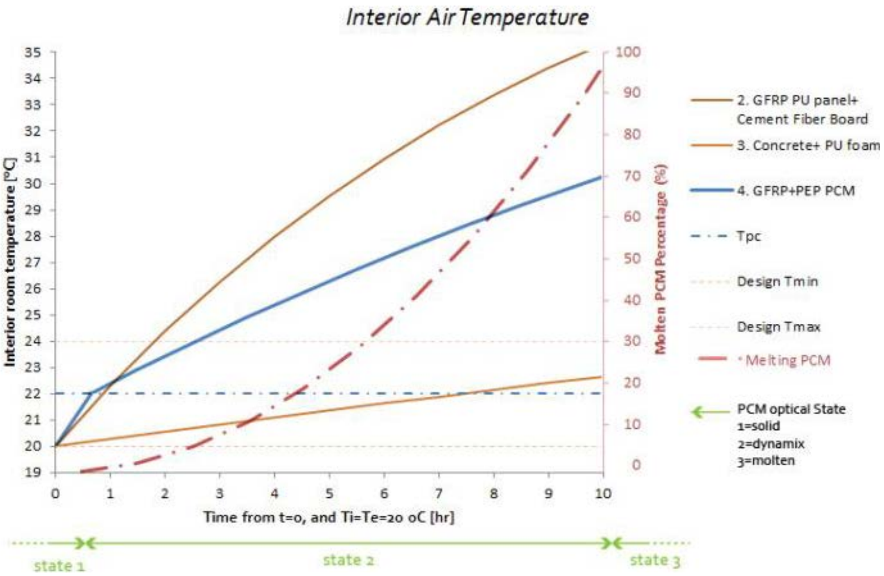


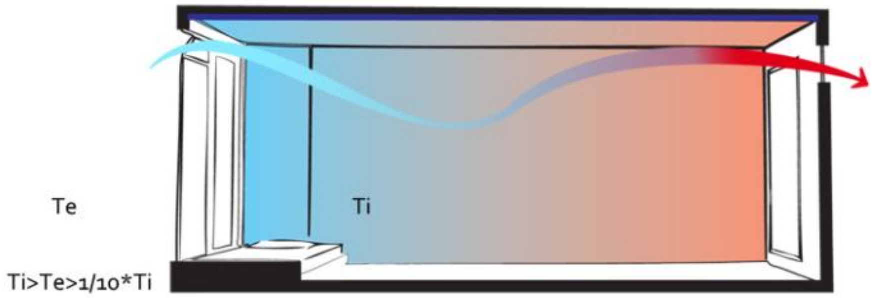
Chart 20: Interior temperature rise at a Space box, using an 8mm PEP-GFRP integrated panel (whose thermal capacity equals to the commercial ENERGAIN panel s=7mm)

We can see from the graph that the performance of the wall has doubled only with an 8mm addition of PCM material, following the Thermal Mass concept.

Apart from increase in comfort, it means savings in energy, which would be needed to cool the space down with mechanical needs.

Nighttime Ventilation

During the night, though passive cross-ventilation, if the exterior temperature allows it, the PCM would be discharged. Then it can be used again until the next day.



Scheme 47: Cross ventilation for discharging the PCM at night. It is recommended for climates where diurnal ΔT can reach maximum 10°C.

The parameters that determine if a cross-ventilation strategy is performing well or not are presented here:

Favorable Factors	Unfavorable Factors	Design Aims	Design Requirements
Cool Climate	Expected noise and pollution	Cross ventilation air flow	Operable Windows
Periodic Loads	Humidity	Avoid overcooling	Security
			Privacy

Table 16: Checklist for cross ventilation night cooling (source: (Cavelius et al., 2006))

A simple way to understand the possibilities of discharging the PCM at nighttime is to look at the heat loss formulas. Heat can be released in two ways:

a. through the envelope of the building, and

$$H_{\text{transmission}} = \Sigma(U \cdot A) \cdot \Delta T$$

b. through ventilation.

$$H_{\text{vent}} = \rho_{\text{air}} \cdot c_{\text{air}} \cdot V \cdot n \cdot \Delta T/3600$$

Nighttime Cooling:

Bigger ΔT more cooling potentials

From both the formulas, we can see that the bigger the ΔT (the difference between the interior and exterior Temperature) the bigger the cooling potential.

This is the reason why the Thermal Mass concept is optimal in climate regions where diurnal temperature differences between interior and exterior are large (ΔT). As we already saw, the ΔT can be exploited in a passive way by cross ventilating, which can be controlled by dampers automatically.
In case that the temperature changes do not favor cooling, then strategies that focus on the remaining parameters have to be taken into account.

Nighttime Cooling:

Increasing ventilation rate or altering heat transfer medium

Since V (the Volume of the room) stays the same, the parameters that can be controlled are the ventilation rate (n) or the heat transfer material (ρ_{air} and c_{air}). The strategies used based on these parameters are usually active strategies.

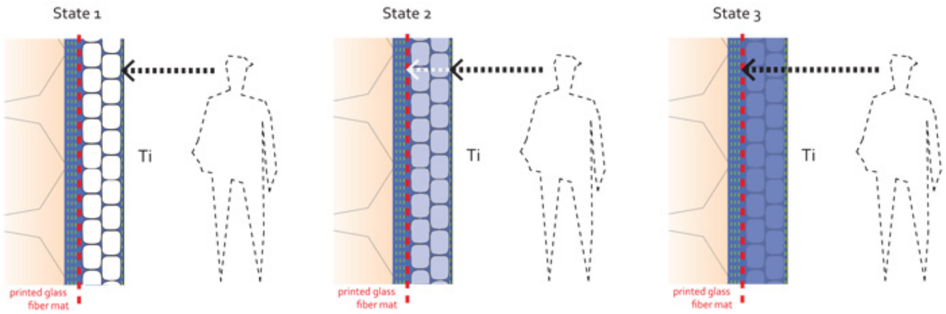
Ventilation rate (n)	Increasing the ventilation rate proportionally increases the heat exchange. For example, changing the interior air from 1 to 10 times per hour, 10 times more heat is removed from the PCM. Increasing the ventilation rate is the most used strategy adopted in office buildings. The reason is that it can be done during nighttime, when the building is not occupied. However, it is not a successful strategy in residential buildings mainly due to the noise created by the fans.
Heat transfer medium (ρ_{medium} c_{medium})	Water is the basic alternative to air as a heat exchange medium. Water presents higher ρ and higher c than air (ρ_{water}=1000,0 > ρ_{air}=1,2 [kg/m^3], c_{water}=4200>c_{air}=1012 [J/kgK]) The difference is that V now refers to the quantity of water in the piping network, and n at the water exchange rate. It is easy to see that Under-floor heating or integrated ceiling cooling systems use water running in piping of conductive materials.

Optical performance as an additional value

At the same time, the interior space changes optically.

As we saw at the experiments, during a complete melting cycle of a PCM, three optical states are visible: the solid, the in-between and the liquid.

As we see from the graph, the first state lasts for 2 hrs, the 2nd for 9, and the third until the PCM layer is discharged.



Scheme 48: Schematic Representation of the three visual states of a GFRP-PCM sandwich wall.

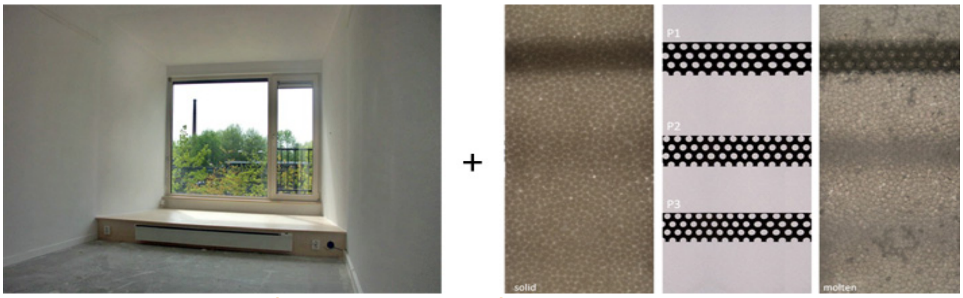


Figure 96: A Spacebox (Left) Interior as is setup for a student housing, and an 8mm PEP at its 2 optical states (1=solid, 2= molten)

Since it is a non-transparent application, in order to enhance the optical dynamism, one with a printed fabric can replace the last layer of the laminate, as we saw in the PEPEP3 panel, during the experiments.

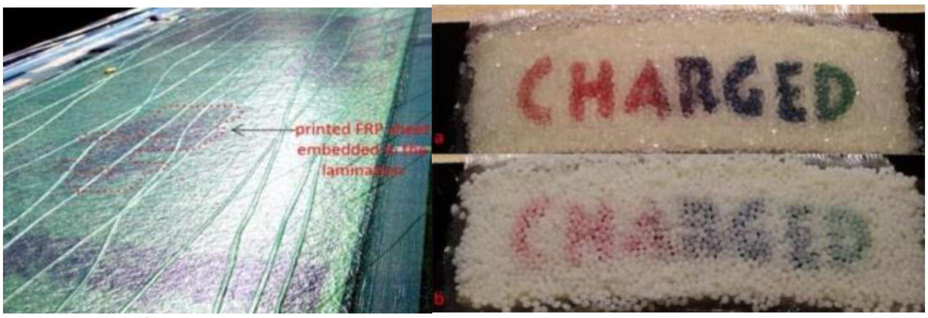


Figure 97: (left) panel laminate has a printed FRP sheet embedded in in its last layer of lamination. (right) the PEPEP3 panel at its a. charged and b. discharged state.

Throughout the day, the interior of the house would become clearer and reveal a written message, a picture, or a pattern, depending on the desire of each designer.

Representation of the expected 3 states in a diurnal cycle

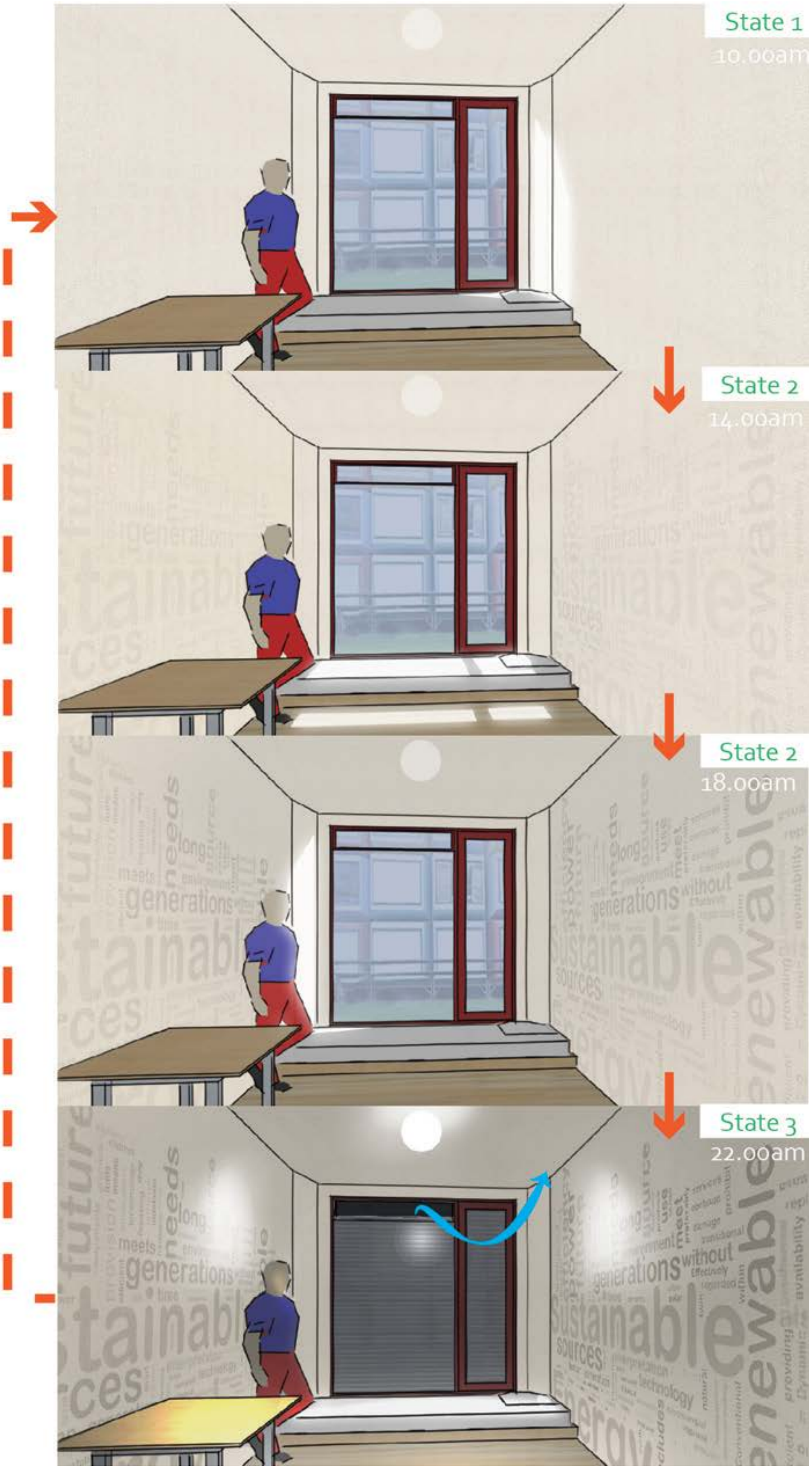


Figure 98: Illustration of the expected performance of a lightweight Spacebox interior, having an interior surface covered with 8mm of PEPEP PCM.

At the same time, through its molten state it would denote that the heat capacity of the house is saturated, provoking the tenant to open the window, or reduce the temperature of the thermostat.

Increasing performance of a PCM system

We already saw that changing the heat transfer means, is one of the most challenging yet effective way to manipulate the behavior of a PCM.

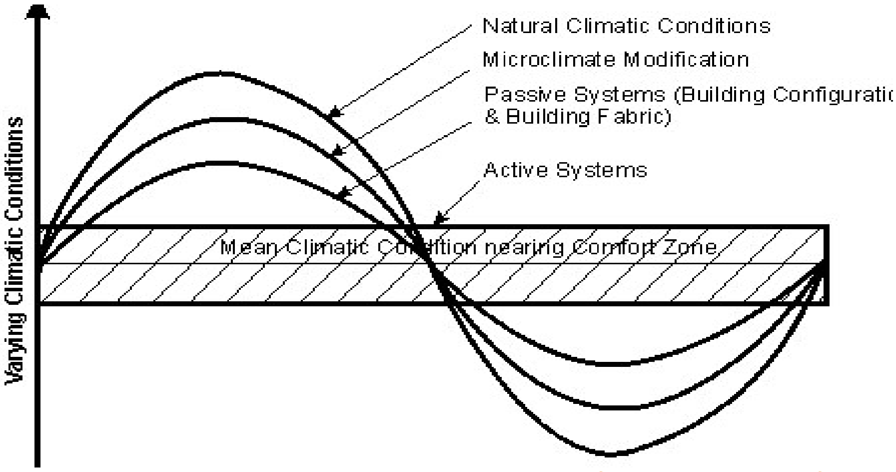
Transferring heat through convection by air (active and passive) is the most common used means, because it is relatively easy and economical to control.

However, other means are also within the specter of realistic possibilities, such as water (for examples using cast-in PVC or capillary pipe systems).

A qualitative comparison between the energy saving, dynamism and cost-effectiveness potentials are presented in the following scheme:

PCM Thickness[mm] / Heat Transfer Coefficient [W/m²K]	Small (1-5)				Medium (5-10)				Big (10-)			
	Dynamism	Energy	Cost		Dynamism	Energy	Cost		Dynamism	Energy	Cost	
			Investment	Long Term			Investment	Long Term			Investment	Long Term
Low (2.5-5.0)	🟥	🟥	🟩	🟧	🟥	🟧	🟧	🟥	🟥	🟩	🟧	🟥
Medium (5.0-15.0)	🟧	🟥	🟩	🟥	🟥	🟧	🟧	🟩	🟥	🟩	🟥	🟧
High (15.0-)	🟩	🟥	🟧	🟥	🟧	🟧	🟥	🟧	🟥	🟩	🟥	🟩

G: Good Performance M: Medium Performance P: Poor Performance

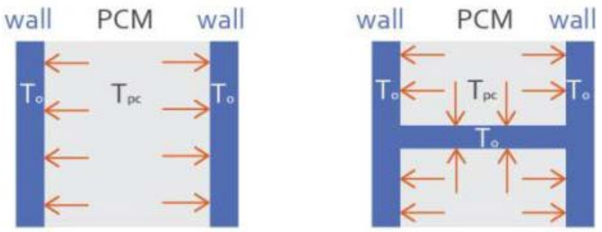


Scheme 49: Table and Diagram depicting Potential of climatic controls, from Passive to Active systems and expected performance along with comfort conditions. (Scheme source:www.new-learn.infolearnpackagesclearthermalbuildingsindex)

Adding fins to increase conductivity

When a thick encapsulating layer is unavoidable and high PC speed is required, it is common practice to turn into other ways of increasing the α_{overal} minimum.

This is use of encapsulating material for poorly conductive PCMs, a geometrical-based practice followed to increase the heat exchange in the system, is to add highly conductive fins between the encapsulation layers. The fins act as thermal bridges, and allow faster exchange, thus PC, process.

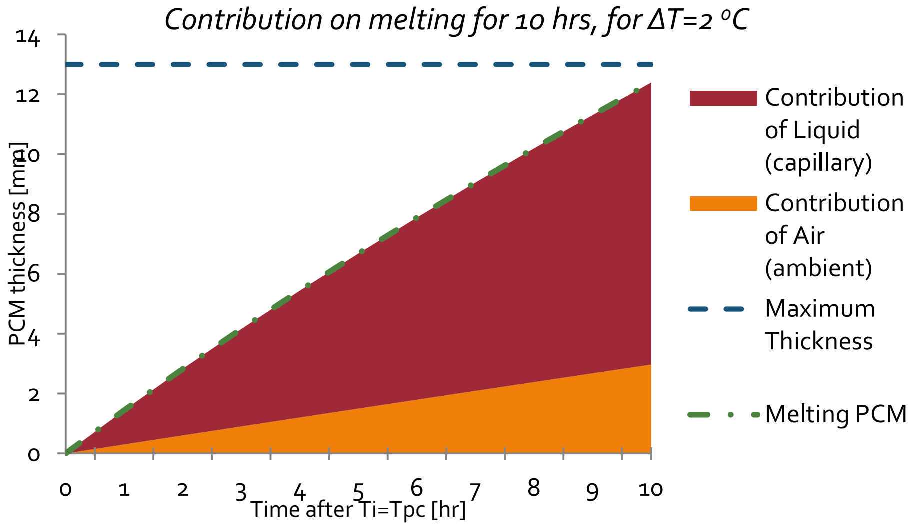


Scheme 50: A geometrical solution for faster melting/solidifying: by inserting highly conductive fins between two encapsulating layers, the heat exchange rate between the PCM and the environment is increased.

This is easier to apply in an office building, which for example could use active ventilation/cooling systems to reach this value, after work hours[38], when the office is empty. However, in residential buildings it is not easy, so different means should be considered.

Adding water as additional heat transfer means

An alternative would be the additional use of water as a liquid transfer means.
The melting speed will increase, since the liquid is an additional boundary condition.



Time	[hrs]	1	2	3	4	5	6	7	8	9	10
Molten PCM	[mm]	1.4	2.8	4.1	5.4	6.7	7.9	9.0	10.1	11.3	12.4

Chart 21: Contribution of Liquid and Ambient in the melting of a PEP PCM incorporated within an EPO matrix: α_{water}= 10.0 W/m^{2}K, α_{air} =2.5 W/m^{2}K. Calculated with the Liquid Boundary model.

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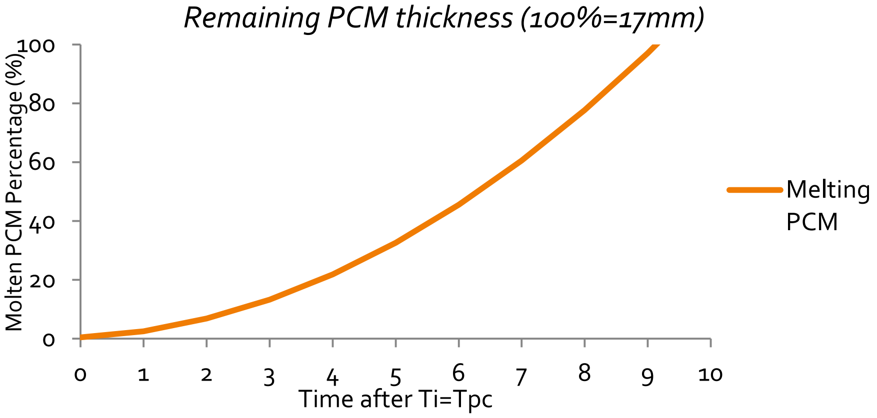
[38] For example, it could run the ventilation fans at nighttime, in double speed, when the electricity KWh pricing is lower, in order to achieve this value.

Increasing performance of the Spacebox

Using the Liquid Boundary Model, we find out that with α_{water}= 10.0 W/m²K, α_{air} =2.5 W/m²K, within 9 hrs we can melt 17 mm of GFRP-PEP panel.



Time	[hrs]	0	1	2	3	4	5	6	7	8	9
Remaining Thickness	[mm]	17.0	16.5	14.7	13.2	11.4	9.2	6.7	3.7	1.7	0.4

Chart 22: Remaining PCM thickness at a 17 mm PEP-GFRP (equal to 15mm PEP)

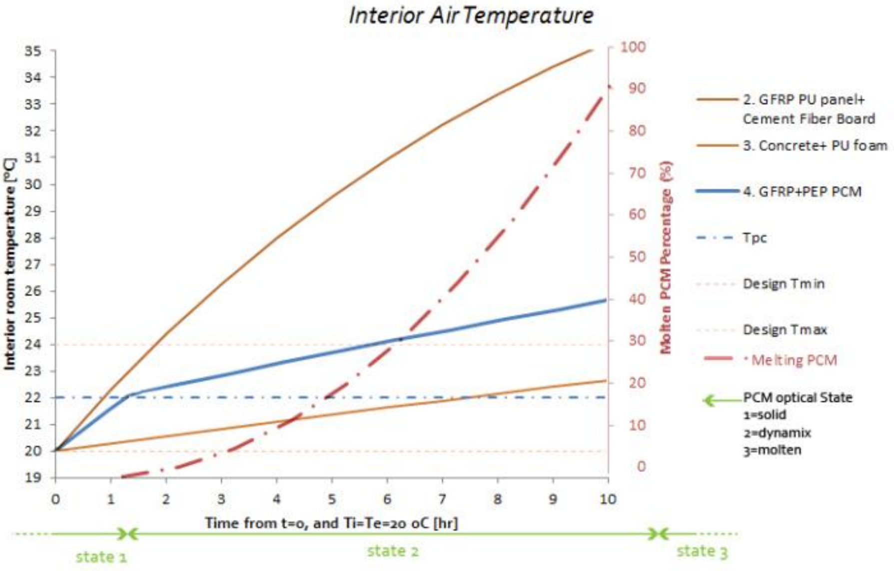
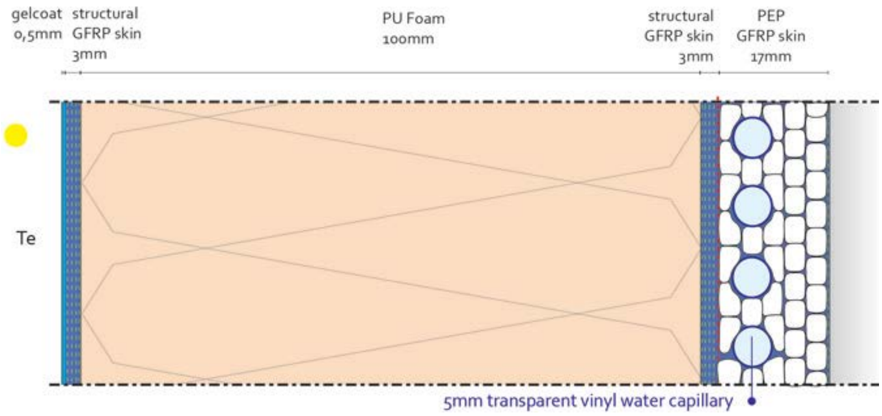


Chart 23: Interior temperature rise at a Space box, using a 17mm PEP-GFRP integrated panel (whose thermal capacity equals to the commercial ENERGAIN panel s=15mm)

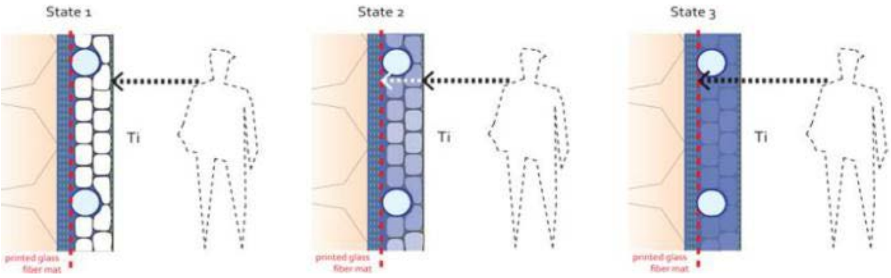
For the case study, a piping network can be integrated within the GFRP laminate that hosts the PCM, in a similar way to the PEP.

The initial investment cost and maintenace will obviously be larger. However the thermal performance can be much better, and the additional weight still low.



Scheme 51: The upgraded (active) GFRP-PCM wall using an 8mm PEPEP integrated with a 5mm capillary vinyl transparent piping at its interior layer.

Optically, the panel will behave differently, due the increased thickness of the laminate and the addition of tubes.



Scheme 52: Schematic Representation of the three visual states of a GFRP-PCM sandwich wall.

An approximation of the laminate appearance with the addition of vinyl capillary piping can be seen at the next image.

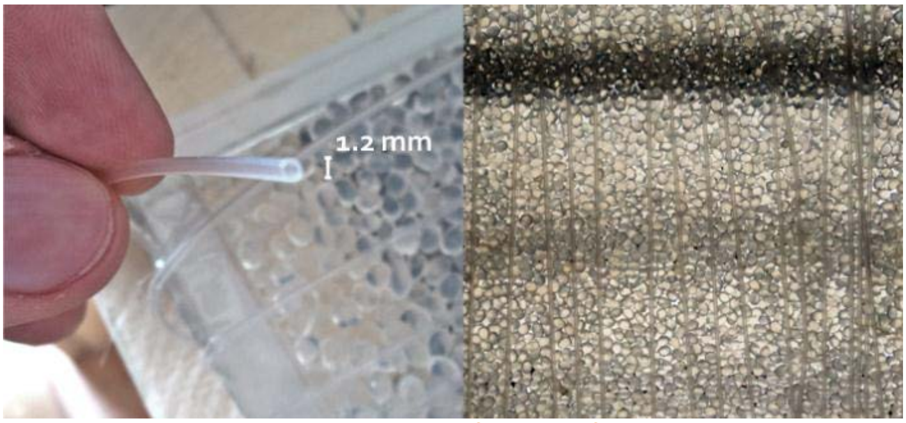


Figure 99: Experimentation on the optical performance of a PEP panel A at a molten state, with the addition of 1.2mm transparent vinyl tubes.

7 Further Research

As mentioned in the introduction, this thesis is a scouting on the possibilities of combining PCMs and GFRPs into one transparent element, which could upgrade the aesthetical values of a non-transparent PCM-GFRP system.

The scouting has showed that this combination presents numerous potentials, which could be explored in depth.

Currently (June 2012) there are many research projects in progress that focus on the combination of plastic elements (not necessarily transparent) with PCMs at a non-integrated panel A type.

The integrated panel type B, solid-'solid' PCMs (such as PEP or CLIMASEL) integrated within the matrix of a resin system, has been studied the least. Therefore, it is recommended that further research should focus on this polyvalent element, regarding the following:

Changeable Structural Properties	The tests on the structural properties of PEPEP (panel B), revealed a relation between the constituting materials' properties and the structure principle of the element as a whole ('structure principle'= sandwich or foam structure). This could be investigated further.
Increased Conductivity	Integrating the PCM within a matrix affects the conductivity of the composite element, therefore the heat transfer to the PCM. From the analysis, we saw that a slight increase in conductivity could change the performance of the panel dramatically. The exact behavior of heat flow within the PEPEP composite is unclear. This could be investigated further.
Thermal Performance	The Panel B PCM system could be tested in large-scale tests, to verify its functionality in heat absorption/release.
Optical Performance: Pigments/ Thermo chromatic	Regarding the optical performance, a topic that appeared during the process, but was not investigated due to absence of materials, was the possibility of adding color pigments in the GFRP matrix. The effect it would have in the perception of the Phase Change process is unclear. This could be investigated further.
	An interesting idea is the use of thermo chromatic pigments, instead of standard ones. In this case, the relationship between those and the visual Phase Change process should be explored within an architectural design context.
Infrared Coatings	For the Solar wall, it would be interesting to examine the potential of increasing the solar infrared-irradiation absorptance, with the use of infrared coatings or apparatus.

8 Reflection

Background

At April 2011, I enrolled at T.U. Delft's "ReVolt House" Envelope team as an MSC2 Building Technology student, which was developed from September 2010-March 2012 in T.U. Delft.

The "ReVolt House" was T.U. Delft's official participation for the *Solar Decathlon 2012*[39] competition, on a Research-and-Design project for the construction of a sustainable rotating 'boat-house', following the Dutch tradition.

Unfortunately, the project was cancelled before its completion, due to financial reasons.

Figure 100: Exterior visualization of the ReVolt House.

As a 'boat-house', its need for floatation and rotation with minimum energy consumption was of outmost importance. Following the innovation-oriented curriculum of T.U. Delft, the project was designed to be fabricated entirely in Glass Fiber Reinforced Polyester (GFRP). This material fulfilled the needs for a durable lightweight structure, while maintaining a seamless curved architectural shell.

During the research for reduction of Energy Consumption and Maintenance of Comfort Conditions, it became obvious that as a lightweight structure those were challenging goals.

It was during that research that I came across Phase Change Materials (PCMs) as a lightweight Thermal Mass strategy, which could assist in achieving those goals.

I was intrigued about these new (to me) materials, GFRPs and PCMs, and I became curious about knowing more for their use in architecture.

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[39] This competition was organized by U.S. Department of Energy as an international competition, that challenged 20 collegiate teams to design, build, and operate effective, and energy-efficient solar-powered houses.

Motivation

The necessity of PCM integration at ReVolt House and my increasing personal interest in both GFRPs and PCMs, assisted by a favorable timing (I had just entered the Graduation period) merged into the beginning of Graduation Research Thesis at December 2011.

Project Development

This thesis started as a scouting on the possibilities of combining PCMs and GFRPs into one transparent element, which could upgrade the aesthetical values of standard commercial non-transparent PCM-GFRP systems.

The original goal of this graduation project was to produce a 1:1 prototype, funded by the ReVolt House sponsors, which could be directly applied in the ReVolt house, enhancing the PCM thermal control system it was already using. However, during the initial development it became obvious that the design constraints set by the Solar Decathlon competition, as well as the economical and practical constraints regarding the construction of an actual house, were restrictive. The risk of them being counteractive to the research was too big.

The cancellation of the project assisted in removing these constraints and having a broader approach, sacrificing however the opportunity of having a 1:1 prototype.

Finally, it was decided that this research should provide an analysis framework for further exploration on the combination of a PCM and a GFRP, in respect to their basic properties and focusing on their optical properties.

Challenges

1. Specialized Literature

GFRPs and PCMs are not frequently used in architecture practice.
The majority of literature was conducted by aerospace engineers for the GFRPs and mechanical engineers for the PCMs. Looking at the majority of standard CAD and Building Physics Simulation programs, they have neither of those materials as a regular input parameter yet. For example, it was a standard practice in PCM literature for each research group to model its own evaluation tools. For a student with a background in architecture, as I am, understanding, evaluating and using information can be a time-consuming task .

It can be seen however, that information exchange on both PCMs and GFRP is simplified more and more every day; in the near future, it will probably be easier for architects.

2. Material Acquisition

Apart from literature, it was also a hard task to acquire the raw materials. This occurred for two reasons. As they are they are more frequently used in smaller scale projects and in small quantities (patching, crafting), GFRPs are generally expensive. Moreover, because of their chemical consistency and combustion risk in fluid form, their transportation almost doubles the cost. The same applies to PCMs, and especially Paraffin.

Therefore, it is recommended for the future researchers on PCMs and GFRPs to set material acquisition as a first priority.

Social Reflection

Being environmentally aware is one of the key battles we must win as citizens of 2012+ against ourselves, in order to win the battle against uncontrolled energy consumption. However, 'energy saving strategies' still sounds a complicated group of words to the environmentally untrained audience which unfortunately constitutes the majority.

The broader goal of this thesis is to assist in the development of environmental awareness towards this population, exploiting the power of Visual Communication.

"Visual communication as the name suggests, is communication through visual aid and is described as the conveyance of ideas and information in forms that can be read or looked upon It also explores the idea that a visual message accompanying a text or an object, has a greater power to inform, educate, or persuade a person or audience. "[40]

A translucent PCM system is a simple, visually self-explanatory system: when the PCM is turning transparent, it is absorbing heat; when the PCM is turning opaque, it is releasing heat.

This process might not denote something more extravagant than the way the system works, nevertheless, comparing it to the usual 'hidden' systems, it can present an additional eye-pleasing value.

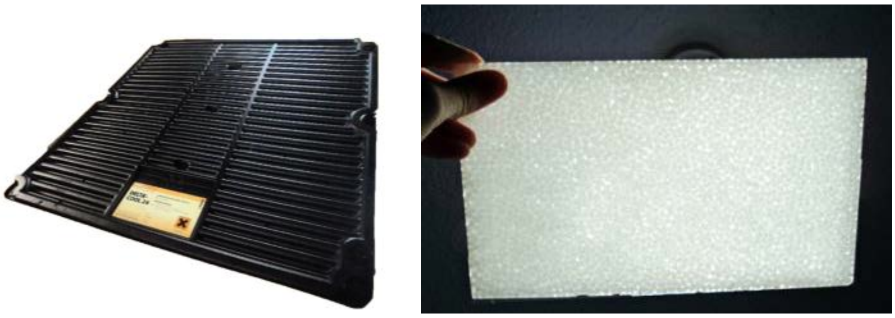

Figure 101: A standard PCM Panel (left) compared to a PEP-GFRP panel (right). The PCM from both are at the solid state.

The additional value, that this research tries to highlight, is the possibility of an energy-saving system, to not only exploit both the thermal advantages of a PCM and the structural/fabrication advantages of a GFRP, but also do it in an aesthetically attractive way.

PCMs, and many other categories of energy saving strategies, could be more attractive to users if their functions would be exposed rather than staying concealed.

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[40] source: wikipedia.com

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10 Appendix

i. Nomenclature

Symbol	Units	Description	Symbol	Units	Description
PCM	-	Phase Change Material	α_{cd}	W/m^2K	Heat transfer coefficient (conduction)
GFRP	-	Glass Fiber Reinforced Polymer	α_{cv}	W/m^2K	Heat transfer coefficient (convection)
T_{pc}	°C	PCT (Phase Change Temperature)	α_{rd}	W/m^2K	Heat transfer coefficient (radiation)
			W	kg	weight
T_λ	(ratio)	Light transmittance	s	mm	thickness
I	Lux	Light Intensity	L	mm	length
ID	-	Image Distortion	b	mm	width
n	(ratio)	Refractive index	J	mm^4	Moment of Inertia
T	°C	Temperature	E	MPa	Modulus of Elasticity
ρ	kg/m^3	Density	G	MPa	Shear Modulus
ρ_{area}	kg/m^2	Area Density	$\nu_{poisson}$		Poisson's ratio
t	(sec)	time	w	mm	deflection
l_{pc}	$J/kg \mid J/m^3$	Specific latent heat storage			
Q_{pc}	J	Latent Heat			
c_p	$J/kg \mid J/m^3$	Specific sensible heat storage			
Q	J	Sensible Heat			
I_t	$kJ*s^{-1/2}/m^2*K$	Thermal Inertia			
EPO		Epoxy resin			
PUN		Unsaturated Polyester			

ii. Companies Contacted for sponsoring.

A. Paraffin Based

Company (country) [website]	PCM Brand	Description	T_{pcm}	Contact	Contact E-mail
DuPont (LU) [energain.co.uk]	Energain	Polymer encapsulated paraffin	21.7	**Ulrike Koster** Marketing Specialist	Ulrike.Koster@lux.dupont.com
Rubitherm (DE) [www.rubitherm.de/] >>	Rubitherm RT	Paraffin (not encapsulated)	21/27	**Stefanie Loos**	stefanie.loos@rubitherm.com
	Rubitherm PK	Polymer encapsulated paraffin	idem		
Micronal (DE) [www.micronal.de]	Micronal® DS 5007	-	23	-	micronal@basf.com
Energy Efficiency System (US) [www.rgees.com]	PCM-OM21P	Paraffin	22	**Elena Gupta** Co-founder	elena@rgees.com
Mikroteklabs (US) [www.microteklabs.com]	MPCM 28	Paraffin	28	**Dawn Mantz** Business Development and Sales Account Manager	dm@microteklabs.com
Pluss (IN) [www.pluss.co.in]	HS11	Paraffin	11	**Nidhi Agrawal** Pluss Polymers Pvt. Ltd.	nidhi@pluss.co.in
PCM Products (UK) [www.pcmproducts.net]	A2	Paraffin/Polymer encapsulated paraffin	22	**Zafer URE**	z.ure@pcmproducts.net

B. Salt Hydrates Based

Company (country) [website]	PCM Brand	Description	T_{pcm}	Contact	Contact E-mail
Climator [www.climator.com]	Climsel 21, 24	ClimSel™ is a salt hydrate based PCM.	21, 24	Nils Julin R&D Manager	clim1@artech.se
Dorken [www.doerken.de]	DELTA®-COOL 24	Plastic encapsulated liquid-solid PCM	24	Dirk Ippach Business Development	dippach@doerken.de

iii. Translucency

The one most widely encountered and accepted is used in the field of Dental Restoration, and it is called "Translucency Parameter (TP)". TP is defined as "the difference in color between the specimen as it appears against the standard white background and as it appears against the standard black background[41]"(Assoc, 2010).

Figure 102: Cosmetic Dentistry deals with Translucency- Tooth translucency variations (source: http://www.drgregkerbel.com/Dental-Smile-Catalog-Photos.html)

However, TP is used for dental-oriented applications that focus on comparative specific color properties. Therefore, it does describe neither the dispersion of light nor the lightness gradient along a certain width of material, nor does it take into account any information on the texture of a translucent material core. The texture is important since that can be responsible for pattern-dominated image distortion.

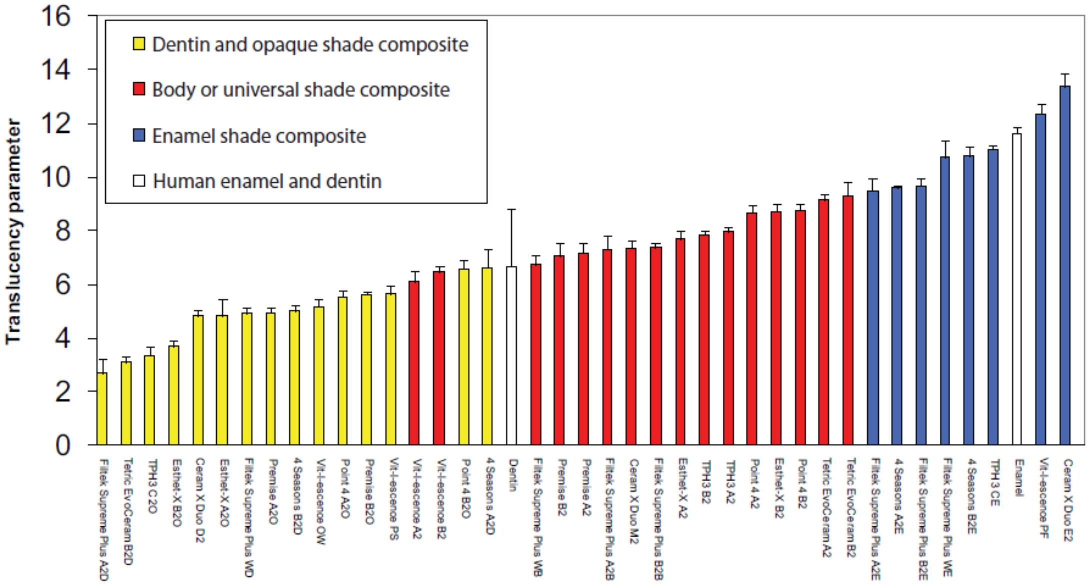

Table 17: Mean translucency parameter values, with standard deviations, in ascending order, for composite materials used in dentistry.

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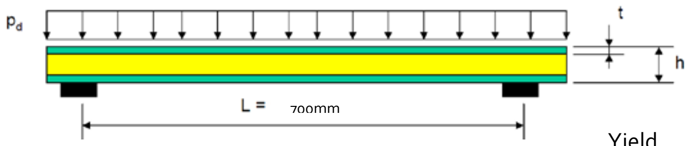
[41] According to the following equation: $TP = \sqrt{[(L_w - L_B)^2 + (a_w - \alpha_B)^2 + (b_w - b_B)^2]}$. Where L=lightness (0-100), a=(Red-Green chromatic coordinate) and b (Blue-Yellow chromatic coordinate). W refers to the values of each specimen against the white background and B refers to the values for the specimen against the black background. Higher values for the translucency parameter present greater translucency.

iv. GFRP Samples

Samples	Dimensions		Total area	Fiber Weight		Resin Weight		Total Weight	Thickness	Weight/m2	F/R Volume Ratio		F/R Mass Ratio	
	a	b									vf	vr	mf	mr
	[mm]	[mm]	[mm²]	[g]	[g/m²]	[g]	[g/m²]	[g]	[mm]	[kg/m²]	-	-	-	-
EPO80TR	267	267	71289	5.70	80.00	6.77	94.92	12.47	0.14	0.17	0.27	0.73	46	54
EPO160TR	267	267	71289	11.41	160.00	11.55	162.07	22.96	0.27	0.32	0.30	0.70	50	50
EPO300CSM	285	300	85500	25.65	300.00	46.70	546.20	72.35	0.65	0.85	0.20	0.80	35	65
EPO BI445	285	290	82650	36.78	445.00	40.62	491.48	77.4	0.68	0.94	0.65	0.71	48	52
PUN80TR	275	275	75625	6.05	80.00	6.53	86.35	12.58	0.12	0.17	0.29	0.71	48	52
PUN160TR	276	278	76728	12.28	160.00	10.43	135.98	22.71	0.20	0.30	0.34	0.66	54	46
PUN300CSM1	270	270	72900	21.87	300.00	32.67	448.15	54.54	0.46	0.75	0.23	0.77	40	60
PUN BI445	270	270	72900	32.44	445.00	54.34	745.40	86.78	0.75	1.19	0.21	0.79	37	63
PUN80160TR	272	273	74256	17.82	240.00	28.16	379.21	45.98	0.29	0.62	0.22	0.78	39	61
PUN80160TR (extra resin)	273	275	75075	17.82	240.00	32.12	427.81	49.94	0.36	0.65	0.14	0.86	27	73

v. Structural Calculation Example for a sandwich panel A, of width b=1000mm, considering a lamina, isotropic to the L direction:



	densities		E	G	Yield Strength
	[g/mm3]	[kg/m3]	[Mpa]	[Mpa]	[Mpa]
Epoxy	0.00114	1140	3500	1258	375
Aluminum	0.00265	2650	69000	26136	400
PEP PCM	0.00090	900	0.05	0.02	-

Table 18: Variables for the examined Materials.

Length	Width	Shear modulus Core Epoxy	**Percentage of joints between laminas**
L [mm]	b [mm]	G_core [Mpa]	**b' [%]**
700	1000	1258	**2**

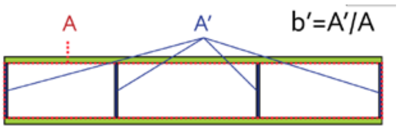


Table 19: Variables for the core.

MASS ratio	fiber	[%]	50	50	40	50	-
	resin	[%]	50	50	60	50	-
Area Weight	fiber	[g/m^2]	80	160	300	445	Energain
Thickness	fiber	[mm]	0.031	0.062	0.116	0.172	-
Area Weight	resin	[g/m^2]	80	160	450	445	-
Thickness	resin	[mm]	0.070	0.140	0.395	0.390	-
Lamina Thickness	t	[mm]	0.101	0.202	0.511	0.563	0.100
VOLUME ratio (to the total element)	fiber	-	0.31	0.31	0.23	0.31	-
	resin	-	0.31	0.31	0.34	0.31	-
Total Volume		[m^3]	0.101183191	0.20236638	0.5110159	0.5628315	-
Young's Modulus (per lamina)	E	[Mpa]	22524	22524	7000	22524	69000
Total Thickness	h	[mm]	7.70	7.90	8.52	8.63	5.20
Panel Moment of Inertia	I	[mm^4]	3001.42	6322.41	18556.27	20937.91	1352.00
Section Modulus	W	[mm3]	779	1600	4355	4855	520
Total Area Weight	p_gfrp	[g/m^2]	160	320	750	890	540
Self Load (GFRP)	p_gfrp	[N/mm^2]	0.0000016	0.0000032	0.0000075	0.0000089	0.0000054
Self Load (PEPEP)	p_pcm	[g/m^2]	3960	3960	3960	3960	3960
Self Load (PEPEP)	p_pcm	[N/mm^2]	0.0000396	0.0000396	0.0000396	0.0000396	0.0000396
Total Load	pd	[N/mm^2]	0.0000412	0.0000428	0.0000471	0.0000485	0.000045
Linear Load	pd	[N/mm]	0.0412	0.0428	0.0471	0.0485	0.045
Maximum Bending Moment	M	[N*mm]	2523500	2621500	2884875	2970625	2756250
Bending Stiffness	k	[N*mm^2]	67604556	142407218	129893904	471609582	93288000
Max. Deflection	w	mm	1.92	0.95	1.15	0.34	1.51
max allowable	wmax	mm	2.00	2.00	2.00	2.00	2.00

vi. Results of the 4-point Bending Test for Epoxy-PEP (T_{pcm}=21.7°C) Samples A and B.

Sample A was tested at surface temperature 15-18°C
Sample B was tested at surface temperature 23-24°C

	Sample A					Sample B		
State	*Solid*					*Molten*		
	Force [kN]	Displ. [mm]		Force [kN]	Displ. [mm]		Force [kN]	Displ. [mm]
1	0.001	0.003	0	0.003	0.002	7.75	0.279	7.754
2	0.017	0.249	0.25	0.016	0.254	8	0.281	8.001
3	0.048	0.502	0.5	0.040	0.505	8.25	0.281	8.255
4	0.094	0.750	0.75	0.062	0.751	8.5	0.282	8.500
1	0.139	1.002	1	0.088	1.005	8.75	0.283	8.750
1.25	0.186	1.251	1.25	0.113	1.254	9	0.284	9.001
1.5	0.231	1.500	1.5	0.136	1.501	9.25	0.286	9.253
1.75	0.274	1.750	1.75	0.159	1.751	9.5	0.285	9.504
2	0.318	2.004	2	0.180	2.001	9.75	0.287	9.755
2.25	0.355	2.253	2.25	0.202	2.253	10	0.286	10.005
2.5	0.386	2.501	2.5	0.216	2.504	10.25	0.288	10.250
2.75	0.417	2.752	2.75	0.231	2.750	10.5	0.288	10.504
3	0.435	3.001	3	0.242	3.003	10.75	0.288	10.750
3.25	0.458	3.251	3.25	0.253	3.250	11	0.289	11.001
3.5	0.481	3.503	3.5	0.257	3.501	11.25	0.290	11.252
3.75	0.500	3.754	3.75	0.259	3.752	11.5	0.290	11.504
4	0.520	4.003	4	0.256	4.003	11.75	0.291	11.750
4.25	0.539	4.253	4.25	0.254	4.250	12	0.290	12.000
4.5	0.548	4.500	4.5	0.256	4.503	12.25	0.292	12.253
4.75	0.555	4.750	4.75	0.256	4.753	12.5	0.292	12.500
5	0.561	5.000	5	0.256	5.004	12.75	0.289	12.752
5.25	0.569	5.250	5.25	0.258	5.250	13	0.288	13.002
5.5	0.573	5.502	5.5	0.259	5.501	13.25	0.284	13.253
5.75	0.578	5.752	5.75	0.262	5.752	13.5	0.283	13.504
6	0.578	6.004	6	0.263	6.000	13.75	0.277	13.754
6.25	0.584	6.251	6.25	0.266	6.253	14	0.271	14.003
6.5	0.591	6.500	6.5	0.268	6.504	14.25	0.265	14.253
6.75	0.596	6.753	6.75	0.270	6.754	14.5	0.256	14.500
7	0.597	7.002	7	0.272	7.001	14.75	0.242	14.750
7.25	0.001	7.252	7.25	0.275	7.251	15	0.227	15.002
7.5			7.5	0.276	7.503			

vii. Cost

**This section intends to give an idea of the material cost, and it should be by no chance be regarded as safe information. Since the majority of the products are based on petroleum, its prices fluctuate. Prices also vary between each manufacturer and time.

The GFRP materials used in this report were purchased from a specialized shop in the Netherlands (February 2012). The retail prices are listed here:

Resins

	€ /kg
Epoxy resin + Hardener (2:1)	26.40
Polyester Resin + 2% Hardener	15.44
MEKP hardener for 1 kg of Polyester (2%)	2.94 (50.32 Euro/kg)
PVA release agent	19.36

Fibers

	€/m^2
Woven Roving 80 gr/m^2	5.92
Woven Roving 160 gr/m^2	7.52
Woven Roving 450 gr/m^2	19.50
Chopped Stranded Mat 300 gr/m^2	4.45

** We should emphasize that these are retail prices. Bulk prices can drop to more than 50% per element.

The PCM materials used in this report were sponsored from DuPont and Climator. Average bulk prices are listed here, according to communication with the companies (February 2012):

PCMs

	T_{pc}	kJ/kg	€ /kg
Paraffin	21 °C	134[-215]	8.14[- 20.00]
Hydrated Salts/Paraffin Blend	23 °C	150	6.46
Hydrated Salts	21 °C	120 [-185]	3.95 [-5.93]
PEP	22 °C	70	-