Challenges of phase change materials for building applications

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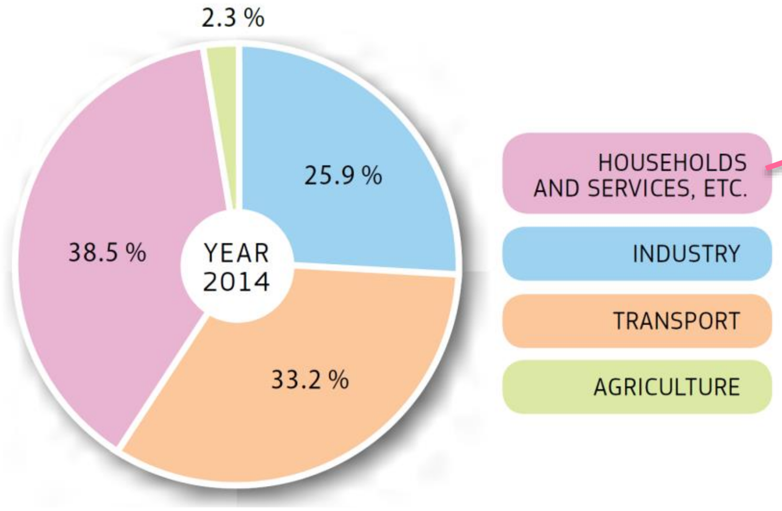
Context

➢ Energy transition

Environmental restrictions
Availability of energy resources

➢ **to develop technologies and to use them more rationally**

Improving energy efficiency
Better control of energy demand
Reducing of CO_2 emissions



Energy end-uses in households:
- Space heating
- Water heating
- Cooking
- Space cooling
- Lighting and electrical appliances
- Other uses

Final Energy Consumption – EU-28 BY SECTOR (Mtoe)
Statistical pocketbook 2016 European Union

Context

➢ Key challenge in buildings

Reduce energy consumption and greenhouse gas emissions

Without compromising thermal comfort needs

➢ Use of high insulation levels

To reduce energy use.

Dynamic behavior of thermal mass?

➢ Energy storage

Separate the production from the use of energy in time and space.

For a rational use of energy

To develop the use of intermittent sources of energies

Combination of insulation and storage technologies

➢ Phase Change Materials (PCMs), a new challenge in construction

Summary

- **Principles for Thermal Energy Storage**
- **Phase Change Material (PCM)**
  - Generalities
  - Methodology of selection
  - Shortcomings of PCMs
- **New challenges in construction**
- **PCM building applications**
  - **PCM integration methods**
  - **Passive and active systems**
    - Wall applications
    - Ceiling applications
    - Underflow applications
  - **Other building applications**
    - Domestic hot water systems
    - Seasonal heat storages
- **Conclusions**

Principles for Thermal Energy Storage

- **Sensible energy**

- principle: heat capacity and temperature difference

- Example: DHW tanks, reservoirs, aquifers, ground/soil

- **Latent energy**

- principle: phase change (melting, crystallisation, evaporation,…)

- Example: water, organic and inorganic PCMs (Phase Change Material)

- **Thermochemical energy**

- Principle: physical (adhesion) or chemical bond (reaction enthalpy)

- Example: adsorption and absorption, chemical reactions

Energy density

Maturity

Storage of thermal energy by liquid solid phase change

Using Phase Change Materials (PCM)

What is a Phase Change Material?

Phase **C**hange **M**aterials (PCMs) are materials that undergo the solid-liquid phase transformation (melting-solidification cycle), at a temperature within the operating range of a selected thermal application.

Liquid water
(0° C)

Solidification
(heat release)

333 kJ/kg

Melting
(heat absorption)

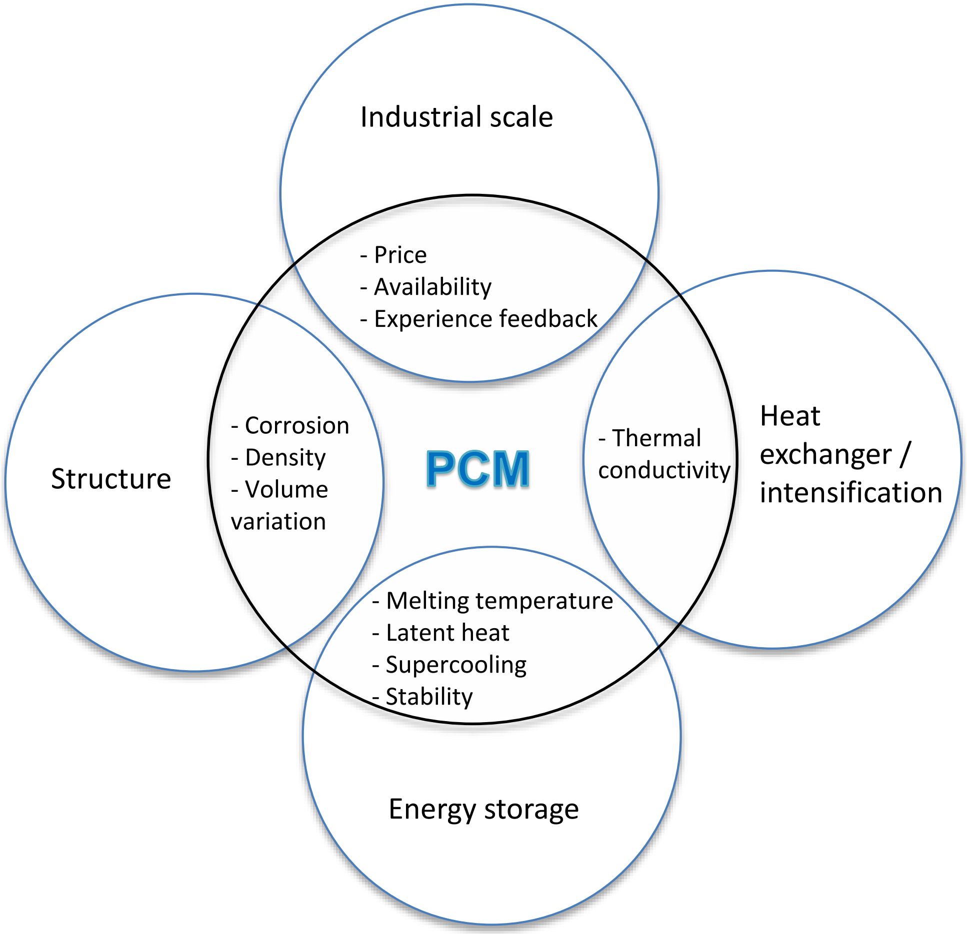
Solid water-Ice
(0° C)

The energy that is either absorbed or released during the melting-solidification cycle is known as the latent heat of fusion

Properties

Latent heat

$$H_2 - H_1 = M\,c_S\left(T_F - T_1\right) + \boxed{M\,L_F(T_F)} + M\,c_L\left(T_2 - T_F\right)$$



Technological barriers

- PCM at a cost suitable for the application
- Aging of the material (performance degradation)
- Return of power

Scientific obstacles

- Identification of PCM
- Thermophysical characterization of PCM : need to fully understand the properties of PCM to simulate power / dimension / optimize
- Intensification of PCM

Methodology

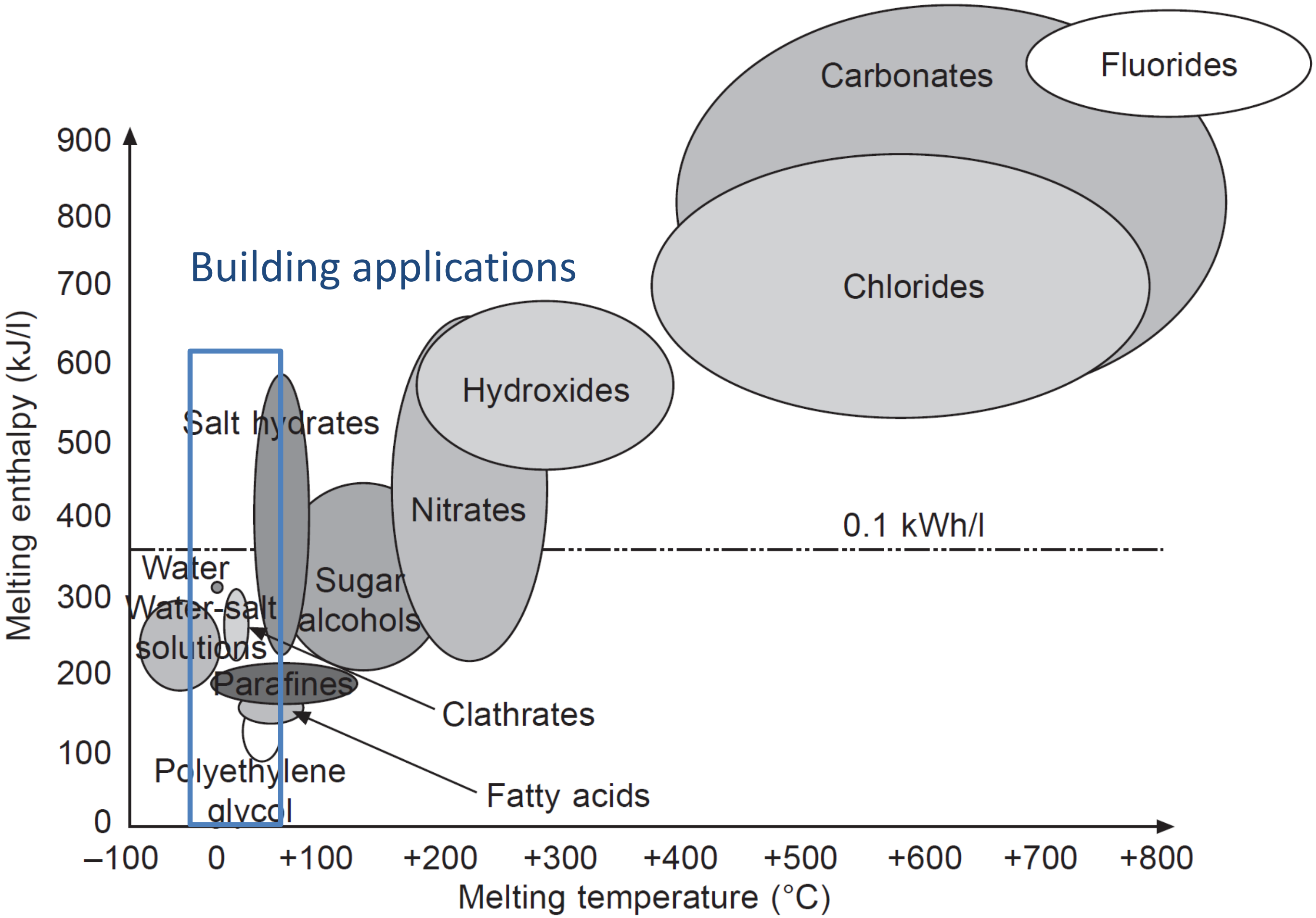
Coupling experimentation-modeling

- Selection of the PCM
  - **- Adapted melting temperature - high latent heat**
  - - high density
  - - low cost
  - - low danger and toxicity
  - - stability over time
  - - reliability of containment materials
  - - low supercooling (delay at liquid –solid transition)

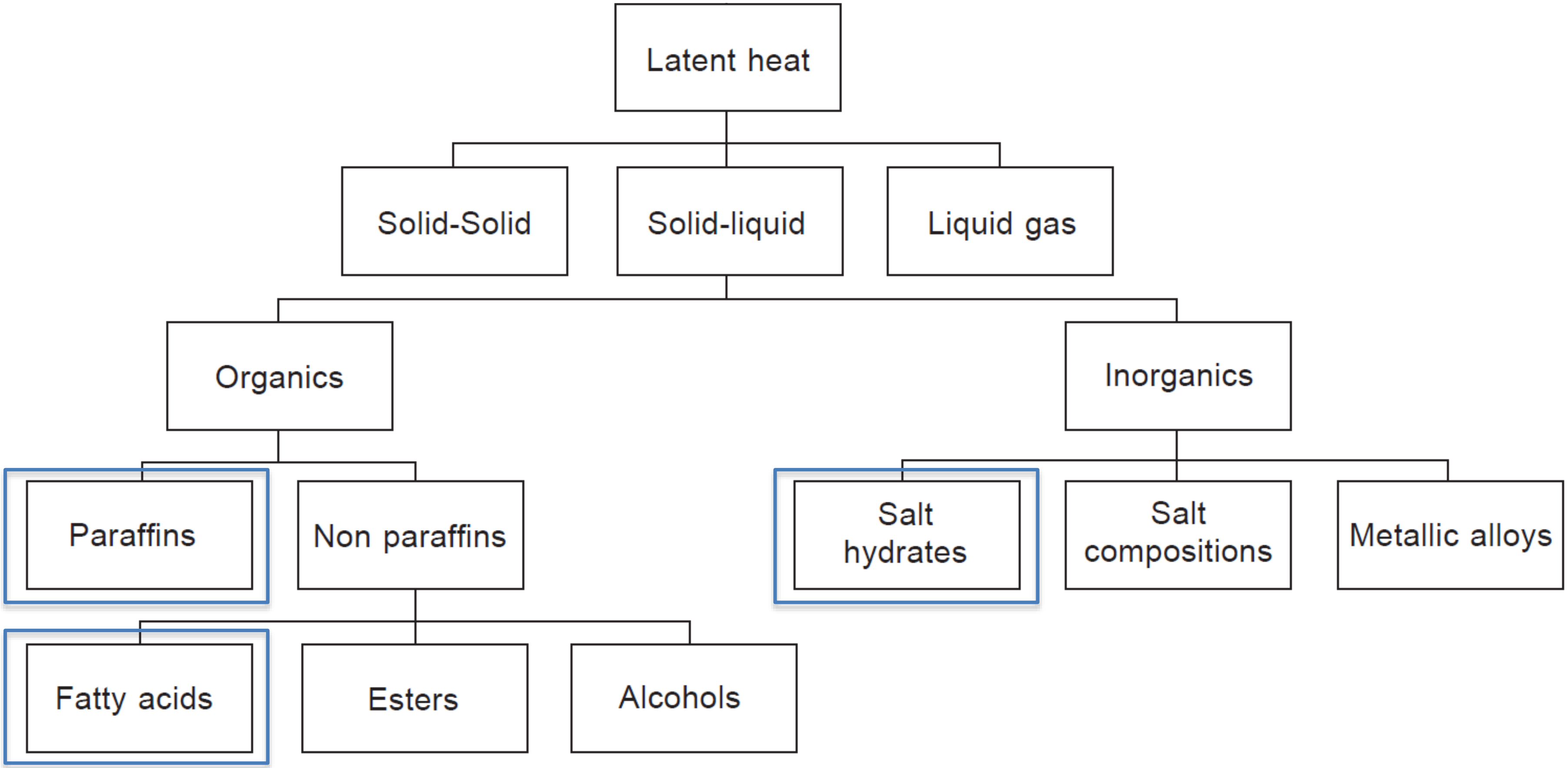
Study of energy and thermal behaviour of systems incorporating PCM

⇨ Pass with a detailed understanding of the phase transition process

- Thermophysical characterization
- Study of the phase change kinetics (melting - crystallization)
- Experiments on a real scale (buiding…)



Melting temperature and melting enthalpy of common PCM candidates (ZAE Bayern)



Classifications of phase change materials (Cárdenas and León, 2013)

Organic PCMs - Paraffin (C_nH_{2n+2}) and Fatty acids ($CH_3(CH_2)_{2n}COOH$)

Advantages

- Availability in a large temperature range
- Low or no supercooling
- Compatibility with conventional material of construction
- No segregation
- Chemically stable
- Good melting heat
- Safe and non-reactive
- Recyclable

Disadvantages

- Low thermal conductivity in their solid state (High heat transfer rates are required during the freezing cycle).
- Flammable.
- Due to cost consideration only technical grade paraffins may be used which are essentially paraffin mixture.

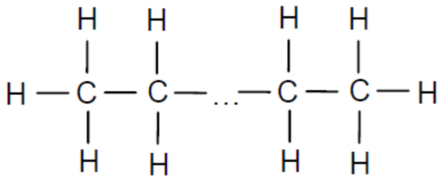
Inorganic PCMs - Salt hydrates (M_nH_2O)

Advantages

- Low cost and easy availability
- Good melting heat
- Non-flammable

Disadvantages

- Change of volume is very high
- Supercooling



Chemical structure of linear alcanes

C_nH_{2n+2}

Melting point and latent heat of fusion: paraffins

No. of carbon atoms	Melting point (°C)	Latent heat of fusion (kJ/kg)
14	5.5	228
15	10	205
16	16.7	237.1
17	21.7	213
18	28.0	244
19	32.0	222
20	36.7	246
21	40.2	200
22	44.0	249
23	47.5	232
24	50.6	255
25	49.4	238
26	56.3	256
27	58.8	236
28	61.6	253
29	63.4	240
30	65.4	251
31	68.0	242
32	69.5	170
33	73.9	268
34	75.9	269

Sharma et al. ; Renewable and Sustainable Energy Reviews 2009

PCM name	Type of product	Melting point [°C]	Heat of fusion [kJ/kg]	Source
RT 20	Paraffin	22	172	Rubitherm GmBH
Climsel C23	Salt hydrate	23	148	Climator
ClimselC24	Salt hydrate	24	216	Climator
RT 26	Paraffin	25	131	Rubitherm GmBH
RT 25	Paraffin	26	232	Rubitherm GmBH
STL 27	Salt hydrate	27	213	Mitsubishi chemical
S27	Salt hydrate	27	207	Cristopia
RT 30	Paraffin	28	206	Rubitherm GmBH
RT 27	Paraffin	28	179	Rubitherm GmBH
TH 29	Salt hydrate	29	188	TEAP
Climsel C32	Salt hydrate	32	212	Climator
RT32	Paraffin	31	130	Rubitherm GmBH

Physical properties of some paraffin's

Paraffin[a]	Freezing point/ range (°C)	Heat of fusion (kJ/kg)
6106	42–44	189
P116[c]	45–48	210
5838	48–50	189
6035	58–60	189
6403	62–64	189
6499	66–68	189

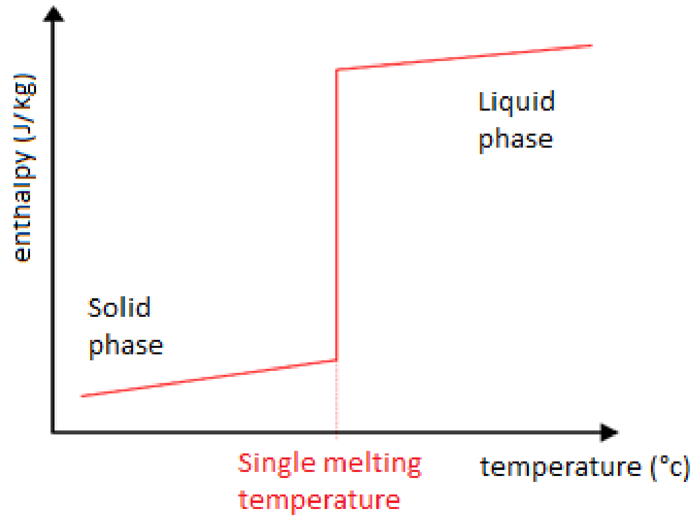
[a] Manufacturer of technical grade paraffin's 6106, 5838, 6035, 6403 and 6499: Ter Hell Paraffin Hamburg, Germany

[c] Manufacturer of technical grade paraffin P116: Sun Company, USA

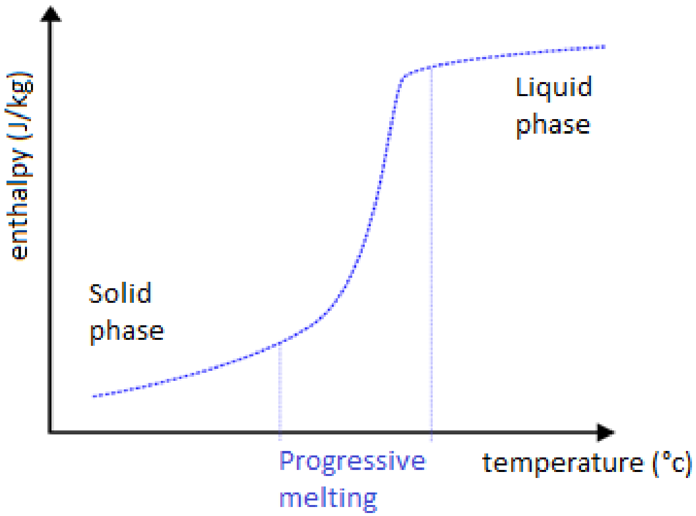
Sharma et al. ; Renewable and Sustainable Energy Reviews 2009

Thermal characterisation of PCM

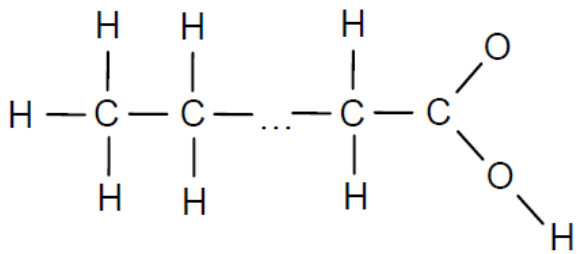
Melting temperature, latent heat, Specific heat



PCM enthalpy
Pure component (ideal)



PCM enthalpy
Mixture of components



Chemical structure of fatty acids

$CH_3(CH_2)_{2n}COOH$

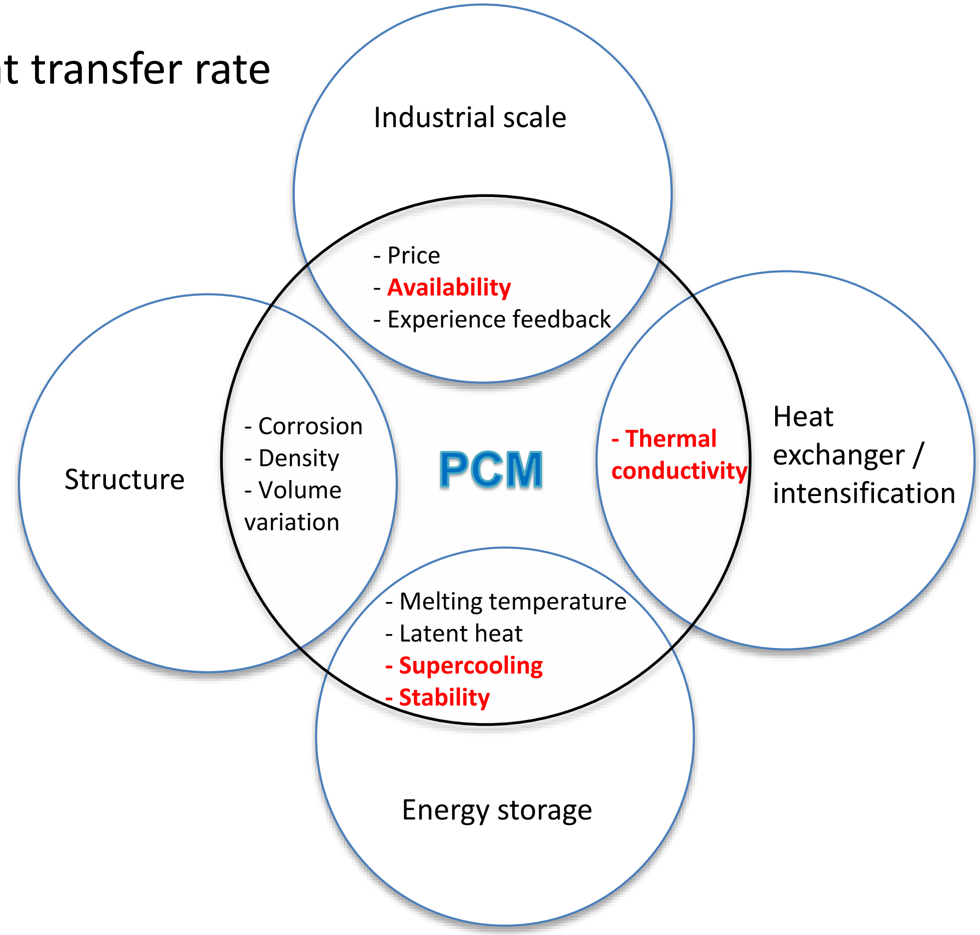
Melting point and latent heat of fusion: fatty acids

Material	Formula	Melting point (°C)	Latent heat (kJ/kg)
Acetic acid	CH_3COOH	16.7	184
Polyethylene glycol 600	$H(OC_2H_2)_n \cdot OH$	20–25	146
Capric acid	$CH_3(CH_2)_8 \cdot COOH$	36	152
Eladic acid	$C_8H_7C_9H_{16} \cdot COOH$	47	218
Lauric acid	$CH_3(CH_2)_{10} \cdot COOH$	49	178
Pentadecanoic acid	$CH_3(CH_2)_{13} \cdot COOH$	52.5	178
Tristearin	$(C_{17}H_{35}COO)C_3H_5$	56	191
Myristic acid	$CH_3(CH_2)_{12} \cdot COOH$	58	199
Palmatic acid	$CH_3(CH_2)_{14} \cdot COOH$	55	163
Stearic acid	$CH_3(CH_2)_{16} \cdot COOH$	69.4	199
Acetamide	CH_3CONH_2	81	241
Methyl fumarate	$(CHCO_2NH_3)_2$	102	242

Sharma et al. ; Renewable and Sustainable Energy Reviews 2009

Shortcomings of PCMs

- Availability at the industrial scale
- Incongruent melting/phase separation
- Supercooling
- Low thermal conductivity and heat transfer rate
- Insufficient long-term stability



Shortcomings of PCMs

Incongruent melting/phase separation

The liquid phase is not exactly the same chemical composition as the solid phase

Decomposition versus temperature or number of cooling-heating cycles

To prevent incongruent melting :

- addition of suspension media or thickening agents :

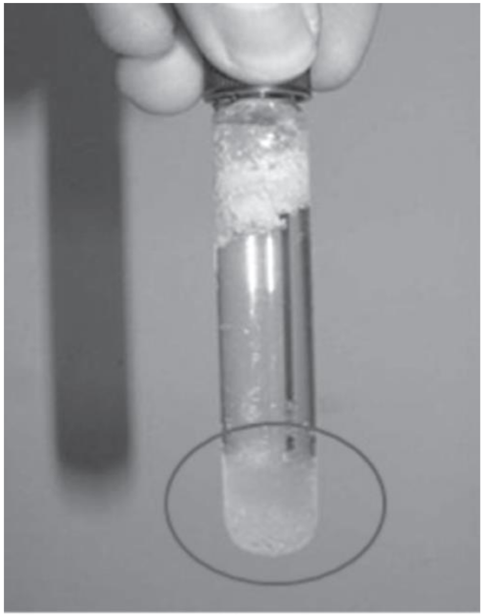
To keep the PCM in suspension → thus assists in re-crystallisation.

Problems: thickening agents displace a part of the PCM in the system (the volumetric heat storage capacities are lower than those of the pure substance).

- dynamic melting

To mix the PCM when it is in the liquid state.

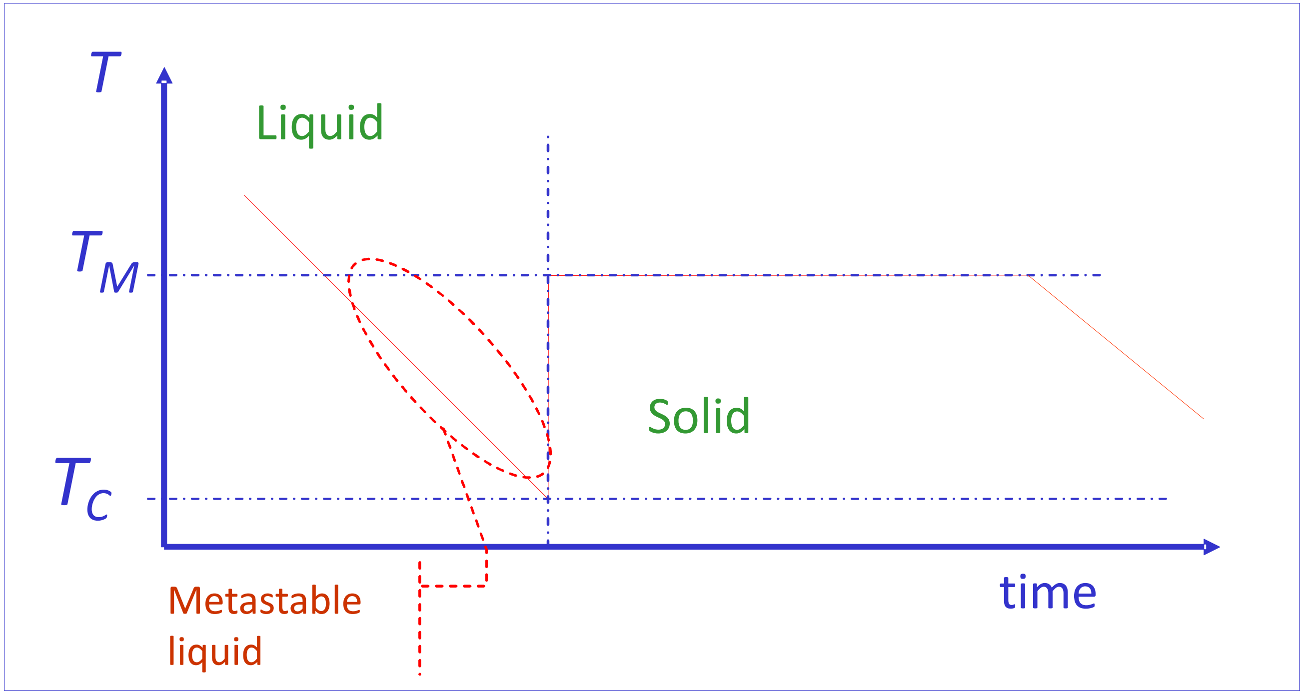
Problems: Require a method of mixing the PCM



Incongruent melting in hydrated salt
(Streicher, 2006).

Shortcomings of PCMs

Supercooling



- Supercooling degree : $DT = T_M - T_C$
- Stochastic phenomenon (erratic)

Nucleation theory

Nucleation

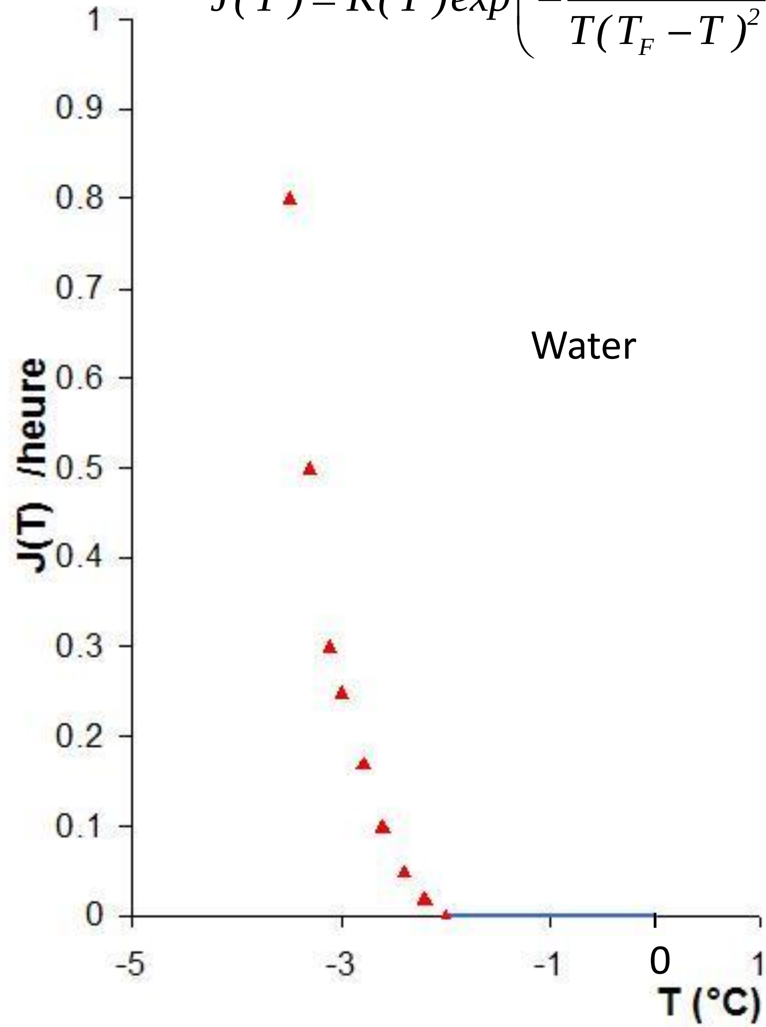
Small agregates ⇒ Crystallisation

Homogeneous nucleation	Heterogeneous nucleation
$\Delta A^{*}_{\mathrm{hom}}$	ΔA^{*}_{het}
Energy barrier	Energy barrier

$$\Delta A^{*}_{het} < \Delta A^{*}_{\mathrm{hom}}$$

Erratic character $\Rightarrow$

$$J(T) = K(T)\exp\left(-\frac{B}{T(T_F - T)^2}\right)$$



Crystallisation probability of a sample (cm^3) by unit time (hour)

Supercooling

The supercooling depends on several parameters:

- Sample volume: V ↘ ΔT ↗

Examples:

	0,3 l	mm^3	μm^3
Water	*8 K*	*20 K*	*36 K*
Paraffin	*	*< 0,5 K*	*12-14 K*
Organic substances		*20 K*	*> 100 K*
Metal		*1-2 K*	*> 200 K*

- Thermal history (former *cycles crystallisation-fusion*)

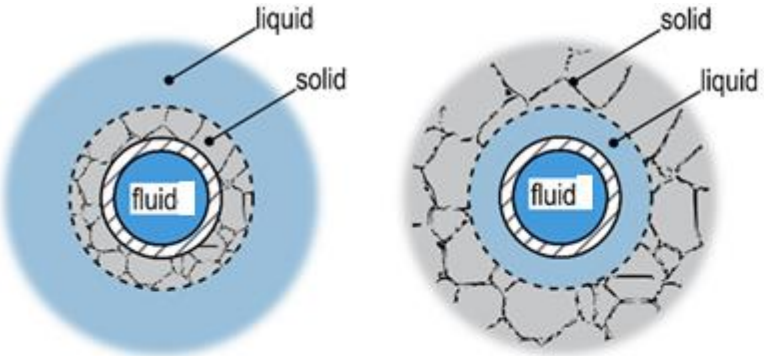
The supercooling can be decreased:

- Use of nucleating agents (crystal structure similar to that of the PCM)
- Cold finger technique: *A nucleating device is maintained cooler than the maximum supercooling temperature.*
- Application of a surface roughness: *to create a site of nucleation*

Shortcomings of PCMs

Low thermal conductivity and heat transfer rate

PCMs are known to have a low thermal conductivity (usually between 0.2 and 0.7 W/m K)
A low thermal conductivity reduces the transfer of the energy in and out of the PCM



Generally, the melting process of the PCM is much faster than the solidification process. This is due to the effect of buoyancy during the melting process assisting the heat transfer process.

To resolve the problem of low heat transfer rate, several heat transfer enhancement techniques are available

Shortcomings of PCMs

Low thermal conductivity and heat transfer rate

➢ graphite / PCM composites

- High increase of thermal conductivity
- High cost
- Stability

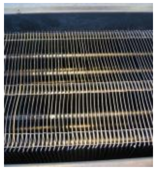
➢ metal / PCM composites

- Metal powders
- Metal matrice
- Metal foam

corrosion

➢ Larger heat exchanger surface

- Metal fins
- Graphite fins
- Different fin geometries



Finned Tube Design
effective Lamda >10 W/(mK)

➢ other solutions

- Microencapsulation
- Direct contact between the heat transfer fluid and the PCM.
- …

Shortcomings of PCMs

Insufficient long-term stability

Due to the poor stability of PCMs and sometimes the corrosion between PCMs and containers.

Appropriate PCMs must be capable of undergoing a large number of cycles of melting and freezing without their properties degrading.

This must be experimentally tested.

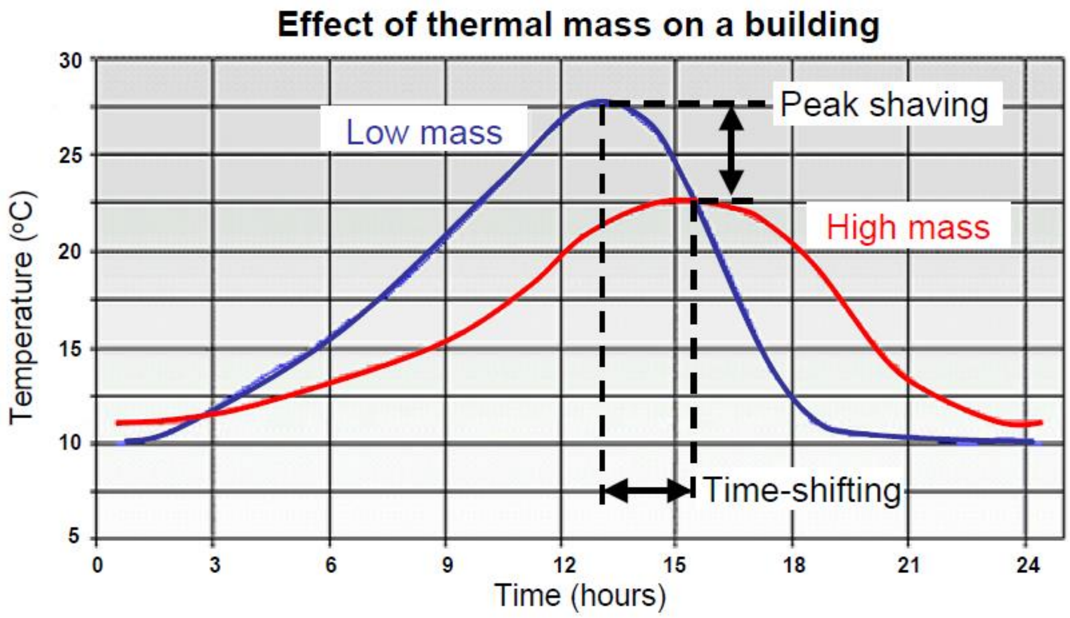
New challenges in construction

Observation

Today's construction are using modern lightweight building methods with highly insulating materials

→ **Lack of thermal storage mass** → **negative impact on indoor climates**

Impact comfort and energy use for cooling/heating

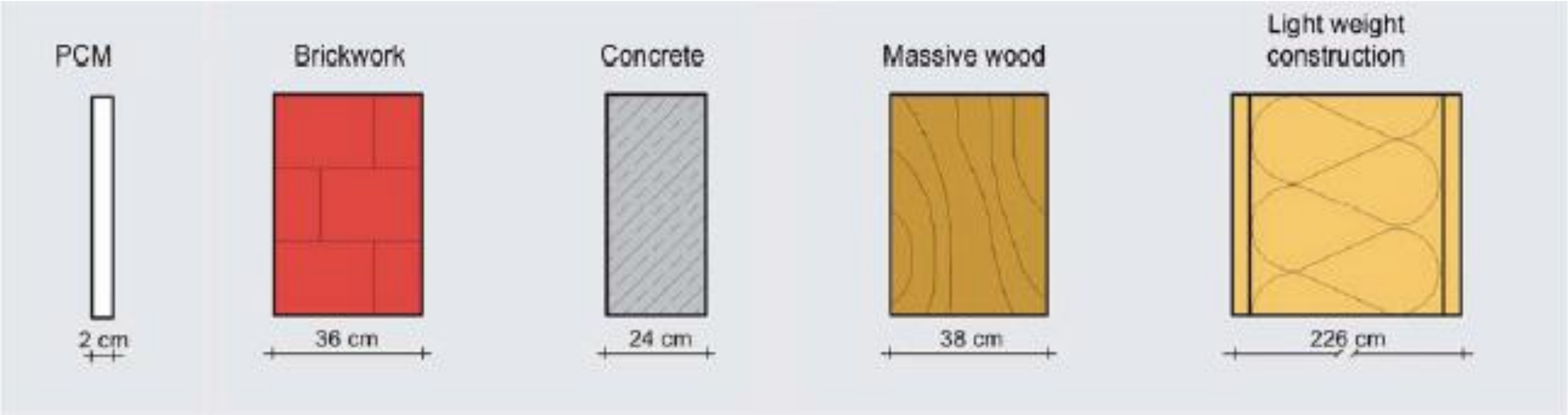


New challenges in construction

Axis of enhancement:

Find a solution to increase thermal mass without increasing building total mass.
And use it as a benefit for comfort and energy conservation

Comparaison of thermal masses:



Equivalence of different materials in thermal mass
heat capacity: approx. 5700 kJ – Temperature range 10 K
(Source : Latent heat storage in concrete, University of Kaiserslautern, dept of construction physics, Prof H.Heinrich)

New challenges in construction

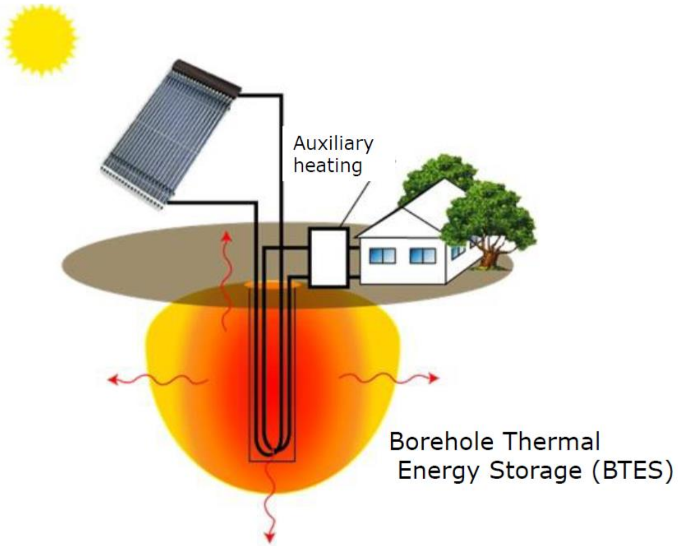
Use of solar energy

Main application in buildings

→ **Heating**
Domestic Hot Water

But intermittent resource of energy

→ **Energy storage**
- diurnal
- seasonal



Axis of enhancement:

More compact and efficient systems

PCM building applications

Basically, two different ways to use PCMs for heating and cooling of building are as follows:

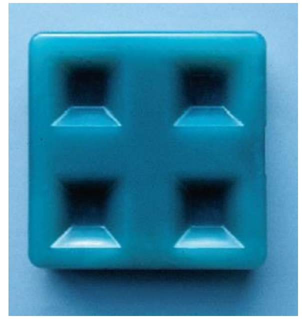
1. PCMs in building components (walls, floor, ceiling, roof, …);
   Depending on the system and location of the building, melting ranges from approximately 20° C to 30° C are used

2. PCMs in heat and cold storage units located in building interior or exterior, such as storage tank.

PCM integration methods
Macroencapsulation

Macrocapsule PCMs

polymers



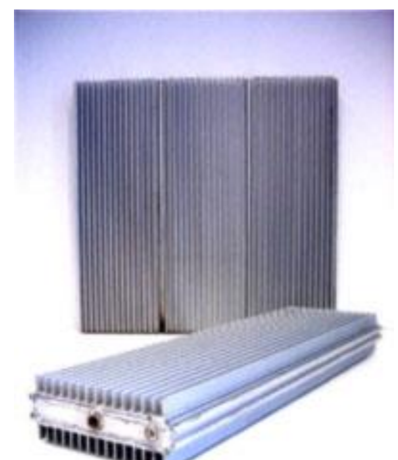
PCM in plastic containers (Rubitherm)

Encapsuled in plastic or metallic packaging

aluminium

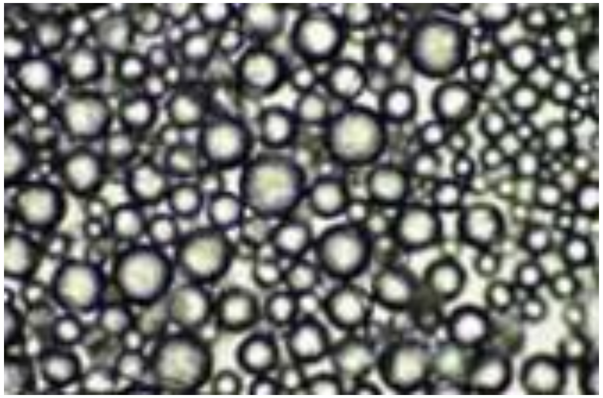
steel

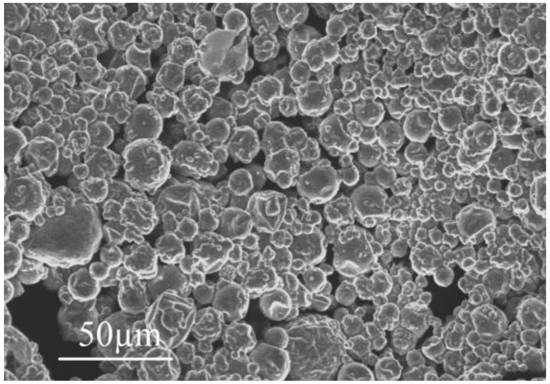
PCM in aluminium case (Rubitherm)



Aluminum profiles with fins (Climator)

PCM integration methods
Microencapsulation





Microencapsulated PCMs

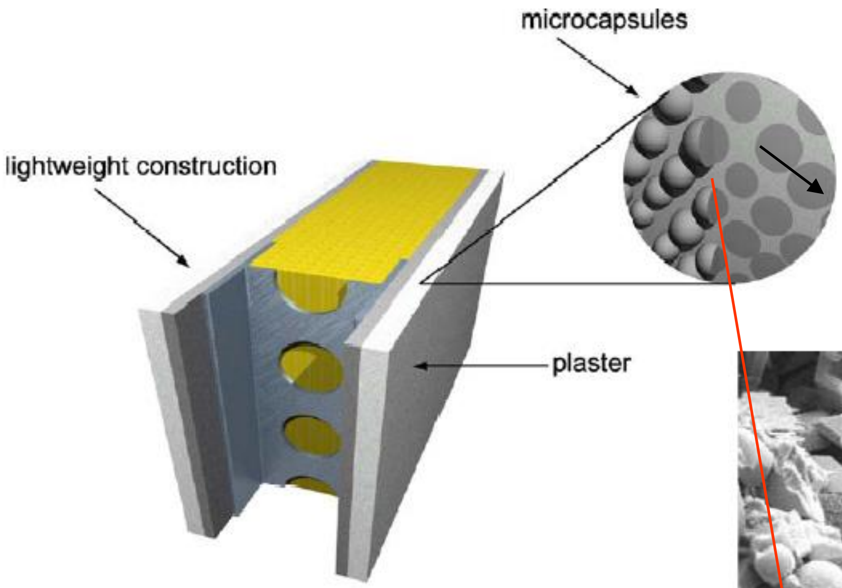
SEM micrographs of A micrograph of dispersed PCM microcapsules.

Šavija, B.; Schlangen, E. Use of phase change materials (PCMs) to mitigate early age thermal cracking in concrete: Theoretical considerations. Constr. Build. Mater. 2016, 126, 332–344

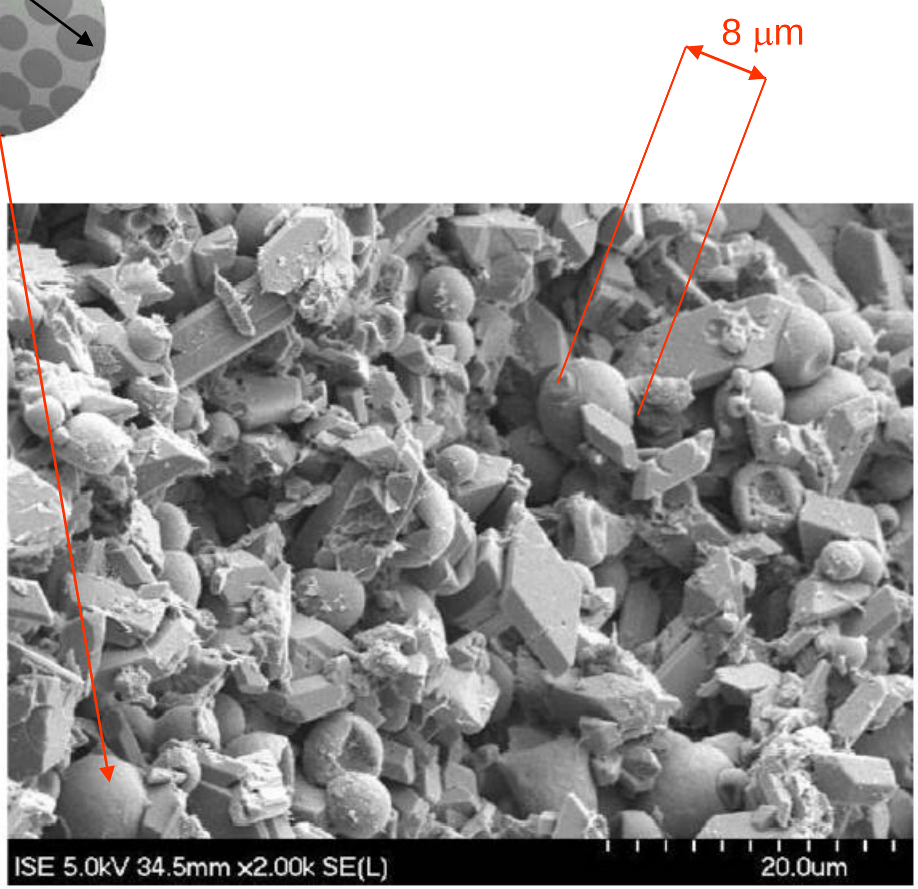
Impregnation porous materials as panelboard and concrete

Example for building applications

Schematic view of a lightweight wall



Images from P. Schossig et al., Micro-encapsulated phase-change materials integrated into construction materials, Solar Energy Materials and Solar Cells 89 (2-3) (2005) 297 – 306.



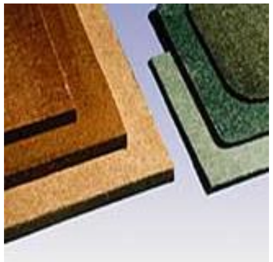
SEM (Scanning *Electron Microscope)* image of PCM micro-capsules in gypsum plaster

PCM building applications

Passive systems

Achieves the functions of collecting, storing, and releasing heat by building structure itself

- Wall



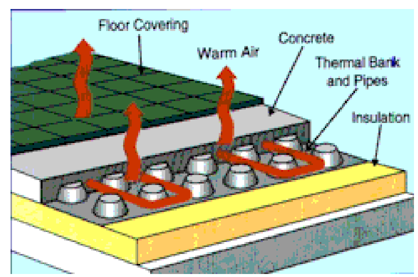
Rubitherm

An effective ventilation system may also need to be installed in order to increase the efficiency of the PCM

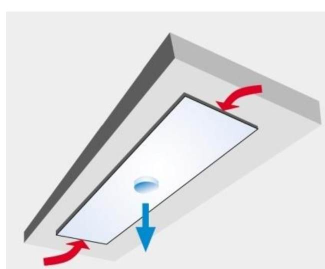
Active systems

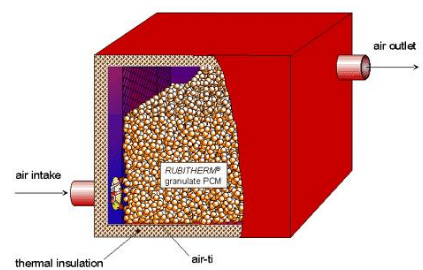
Active system needs to rely on pumps or fans to convey heat transfer medium

- underfloor



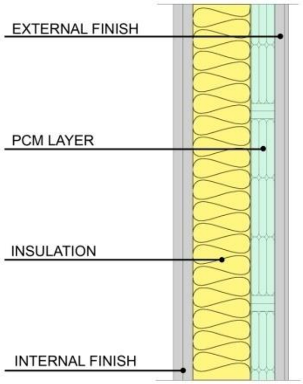
- Ceiling



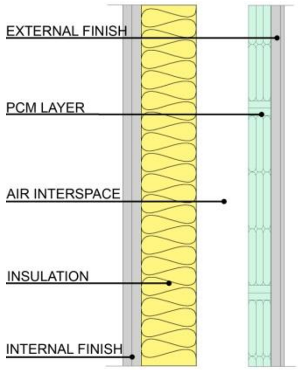


Wall applications

A PCM layer can be placed within wall constructions to increase the thermal mass of the house



- Conduction

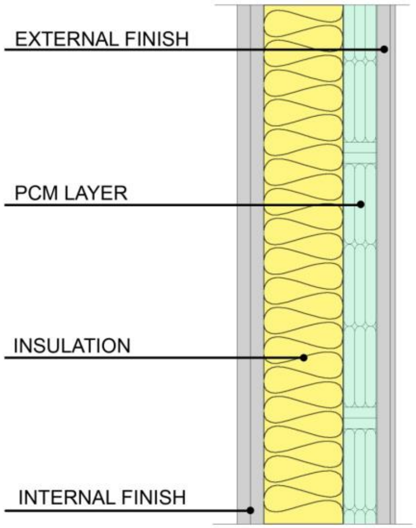


- Natural Ventilation

The heat exchange is facilitated with the natural air flow

Wall Application – 1

A PCM layer within the wall close to the external layer



Day

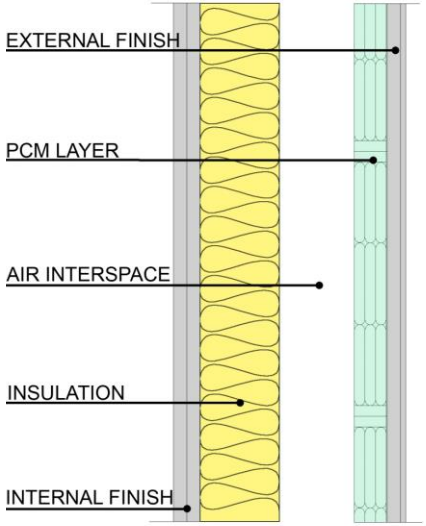
The PCM layer in warm days stores a great part of the energy that flows through the wall

Night

The PCM layer releases energy stored in the day outside and inside the building

Wall Application – 2

A PCM layer within the wall close to the external layer with a ventilated air chamber



Day

The PCM layer in warm days stores a great part of the energy that flows through the wall

Night

The PCM layer releases the energy stored in the day

The ventilation in the chamber evacuates part of the energy stored

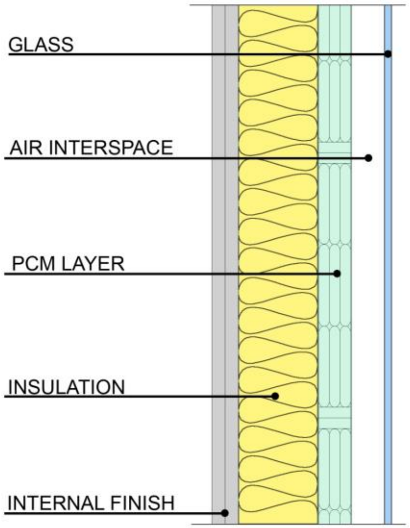
Wall Application – 3 A PCM layer behind a glass and an air chamber

Day

The PCM layer is directly heated by solar radiations and store the energy

Night

The PCM releases the energy store in the day within the building
If the energy want to be evacuate outside, the air chamber will be open and becomes ventilated

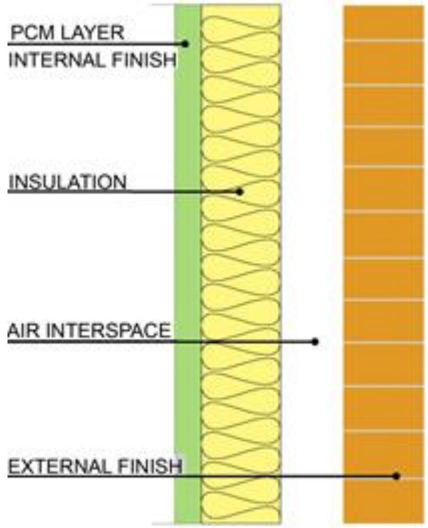


Wall Application – 4 A PCM layer within wall constructions to increase the thermal mass of the house

The PCM is contained to the internal finish and exchanges energy with the room

Store energy when the air temperature is higher than the melting temperature

Release energy stored when the air temperature is lower than the melting temperature



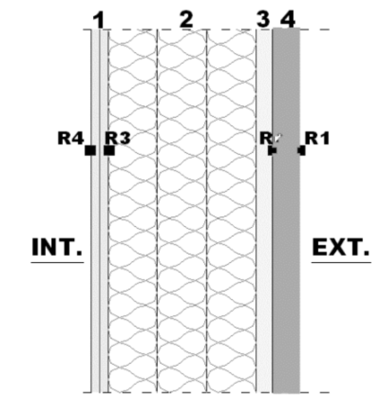
Wall - confrontation

Glauber salts

$Na_2SO_4 \cdot 10H_2O$

melting temperature 32° C, density 1450 kg/m³, latent heat of fusion $1.9 \cdot 10^5$ J/kg, specific heat in the liquid and solid state equal to $3.6 \cdot 10^3$ J/(kg·K).

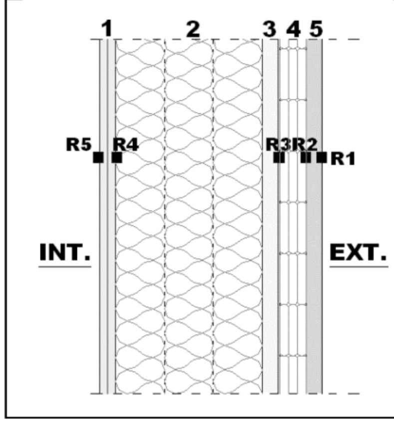
Box n° 1 (Benchmark)



N	*Layer*	*Thick. (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	Cement aggregate	0.025

Box n.1 - reference box

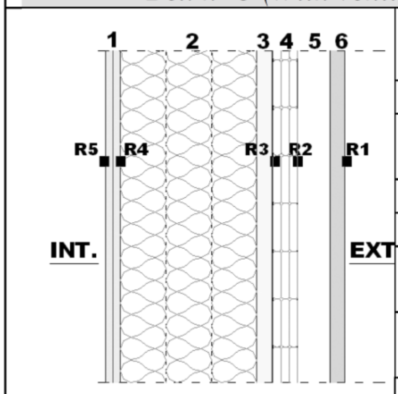
Box n° 2 (Without ventilated air layer)



N	*Layer*	*Thick (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	*PCM*	*0.03*
5	Cement aggregate	0.025

R_i positioning of the temperature sensors

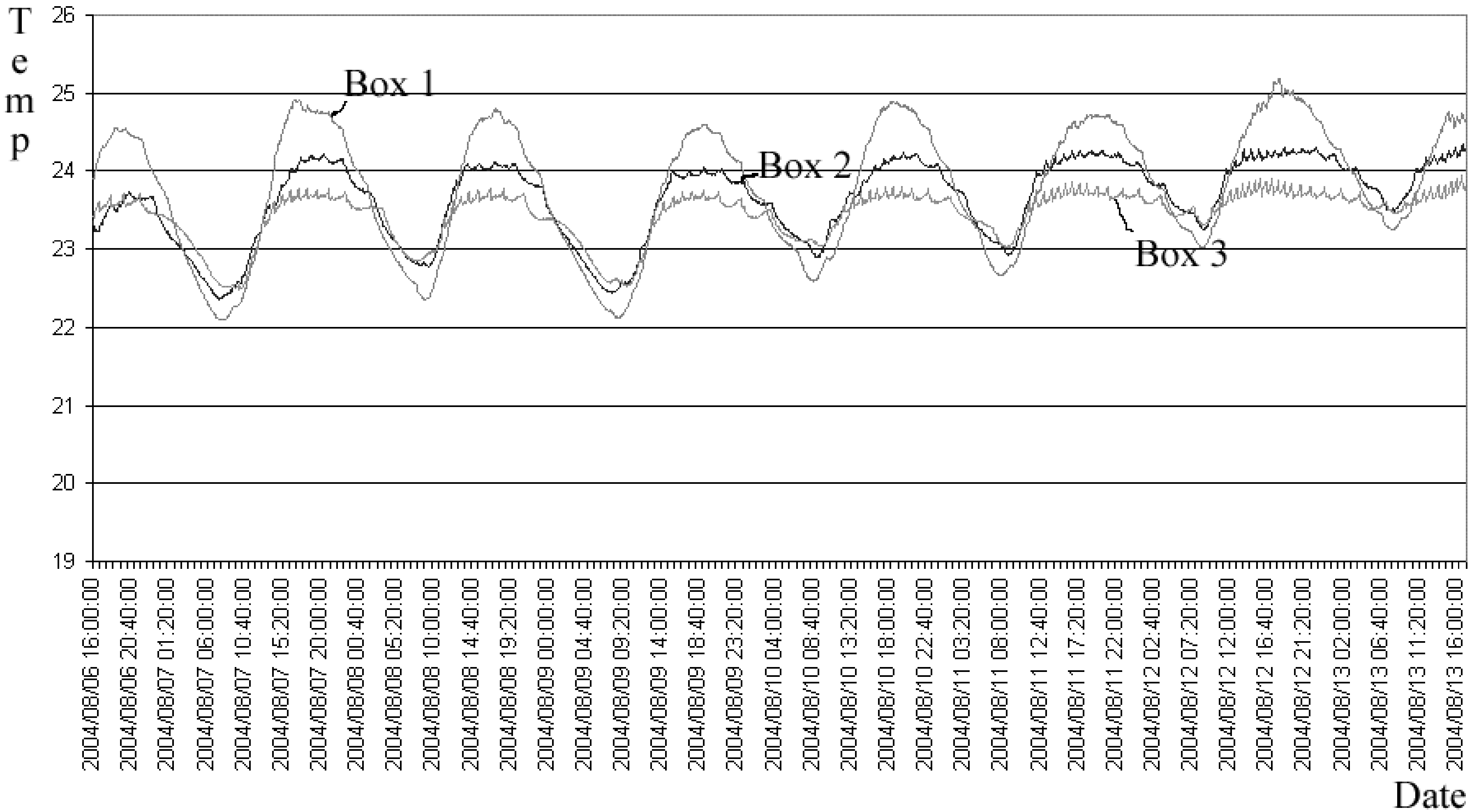
Box n° 3 (With ventilated air layer)



N	*Layer*	*Thick (m)*
1	Plaster	0.025
2	Mineral wool	0.225
3	Chipboard	0.02
4	*PCM*	*0.03*
5	Ventilated air layer	0.05
6	Cement aggregate	0.025

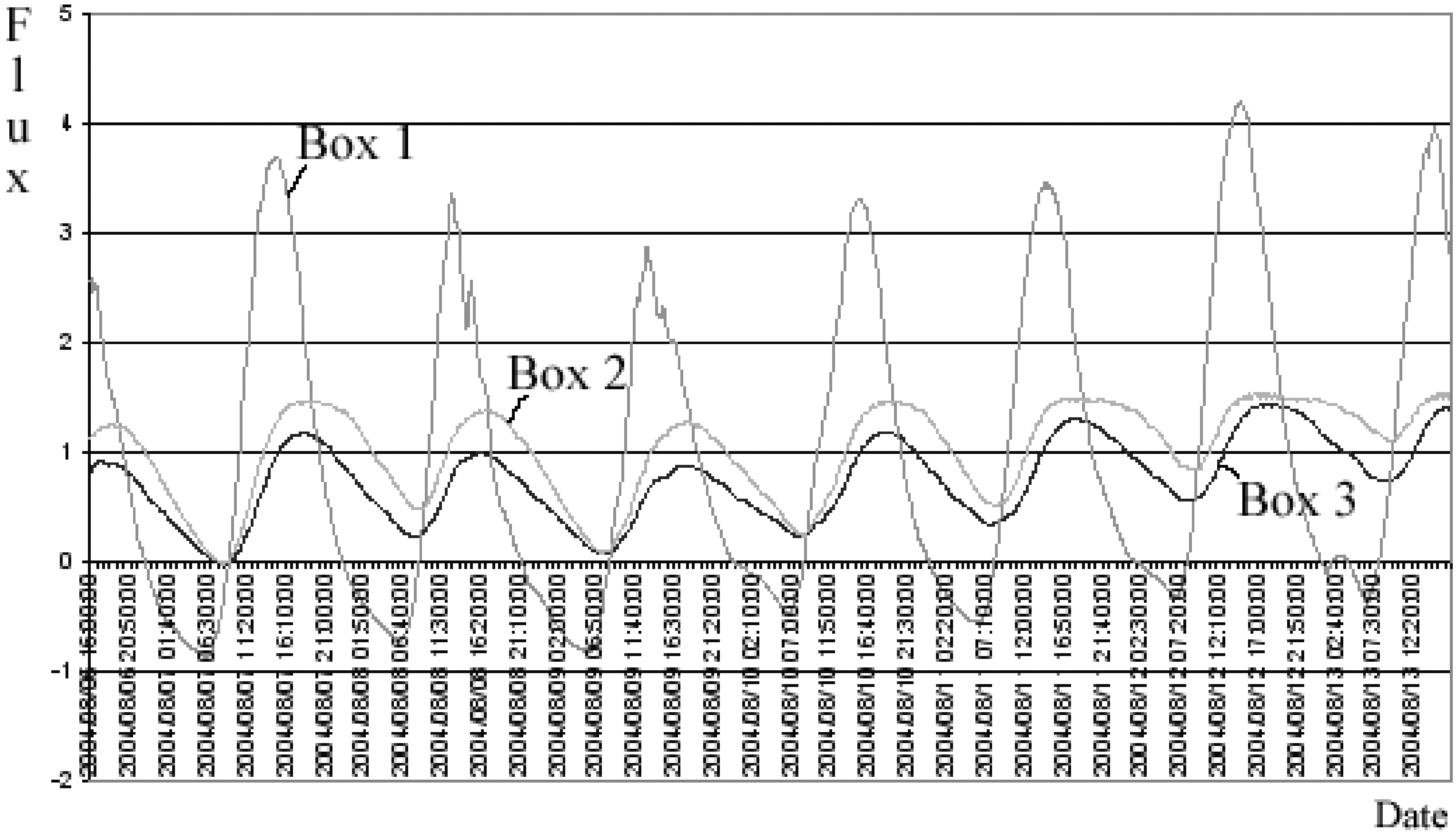
Principi P. et al., “Passive and Low Energy Cooling for the Built Environment”, May 2005, Santorini, Greece

Air temperature (interior surface)



Comparison between the temperatures (South wall) of the three boxes during the period between August 6th and 13th

Thermal flow (Wm^{-2}) through south wall



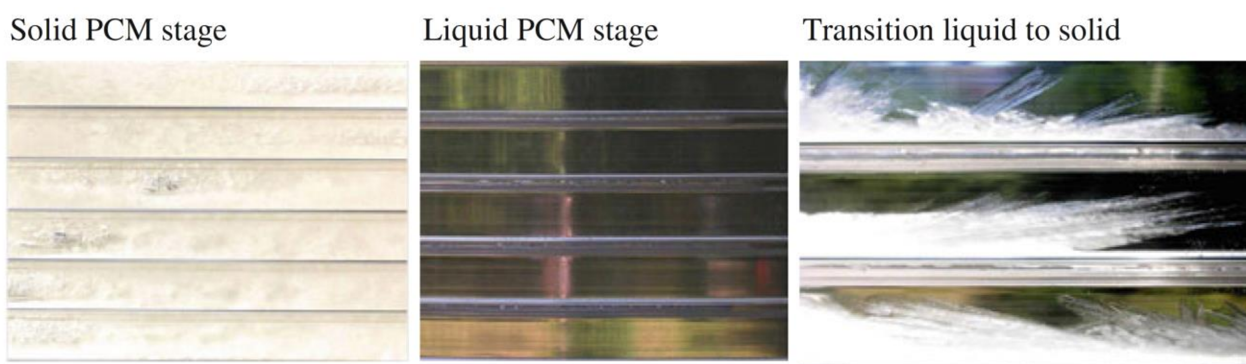
Passive systems Transparent PCM façade panel

Advantages of a daylighting element and of an energy storage

Many PCMs are **highly transparent for the visible part of solar radiation** whereas the **infrared part is absorbed within the PCM**.

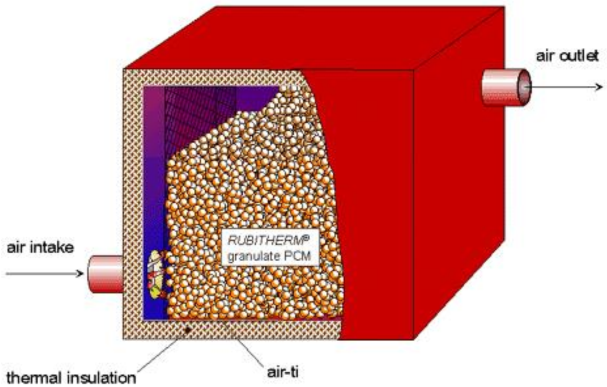
GLASSX®crystal

Double glazing façade
H. Weinlader et al. Solar Energy 78 (2005) 177–186



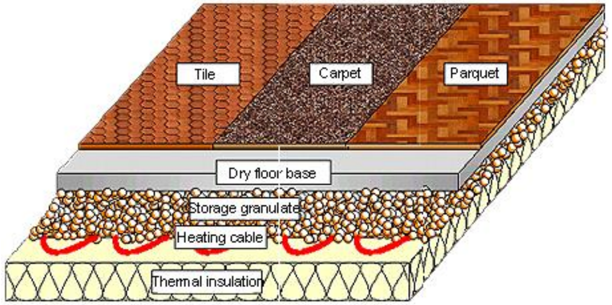
PCM-enhanced window component with variable optical properties, Dorken, Germany

Active systems



- Artificial ventilation

The heat exchange is improved with mechanical system of ventilation



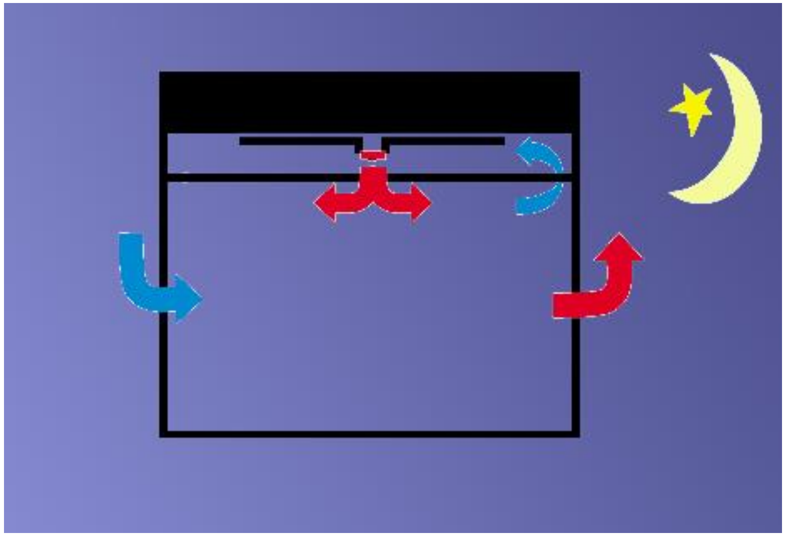
- Hydraulic system

The energy is carried through a system with water or other liquid

Active systems

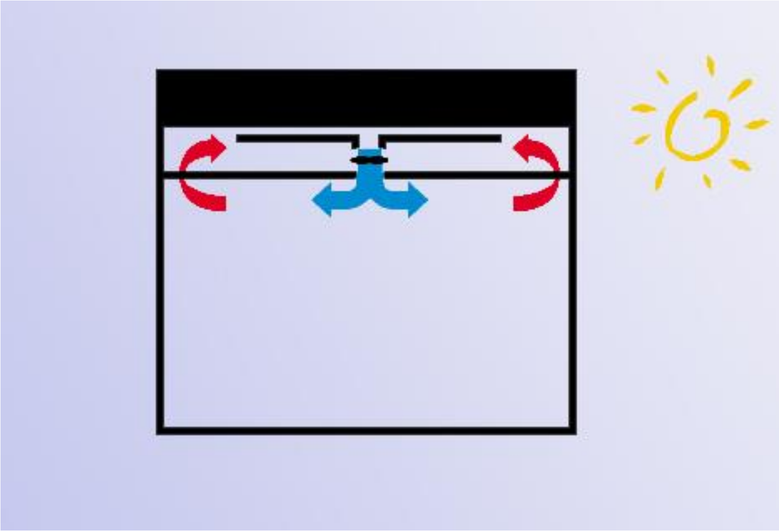
Ceiling air exchanger

Night store outside cooling



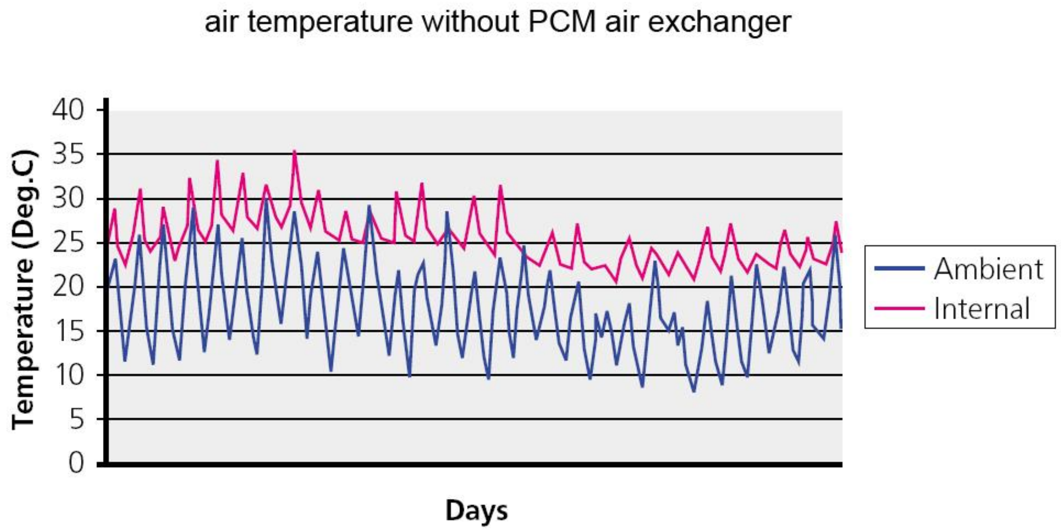
Night behaviour

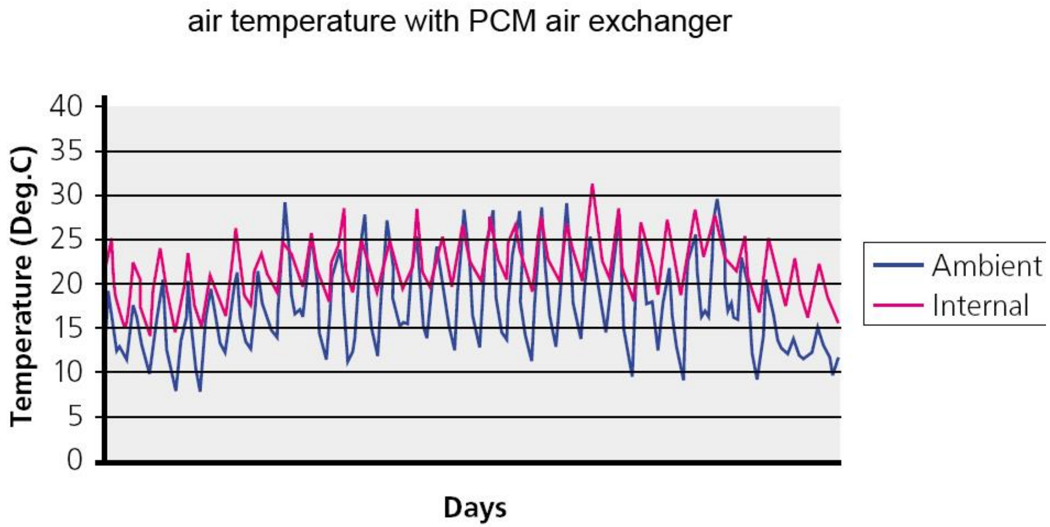
Day release stored cooling



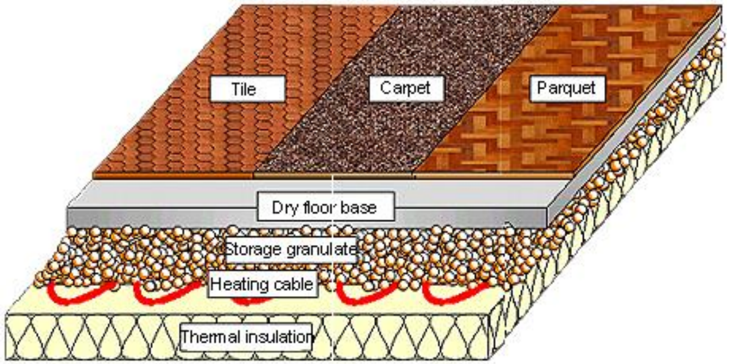
Day behaviour

Active systems Ceiling air exchanger



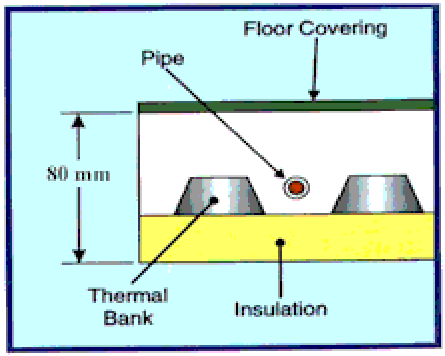


Floor applications



built up in layers

TEAP Australia



The aim to activate the circulation of hot water only when the solar energy or low tariff electricity is available.

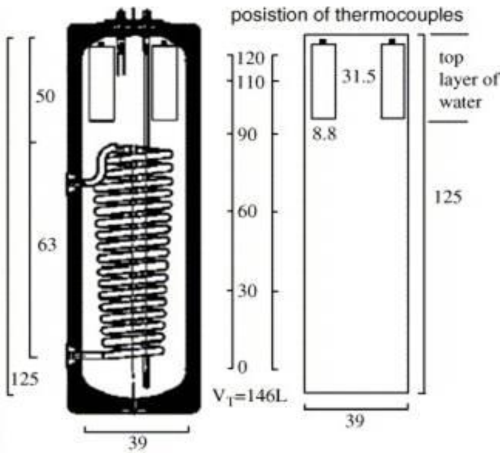
Objective

Reduce the running costs to a minimum by heating the living space, during the high electrical tariff periods, from only the heat stored in the PCM

Other building Applications

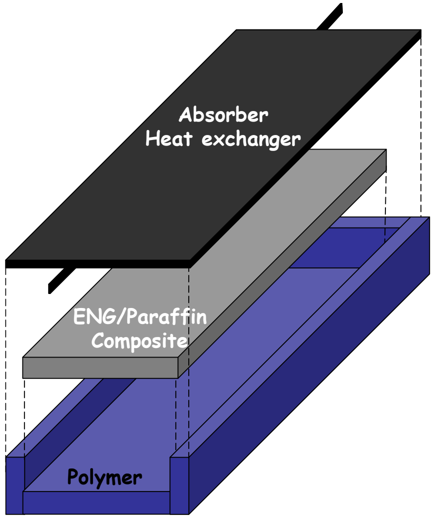
Domestic hot water systems (solar or not)

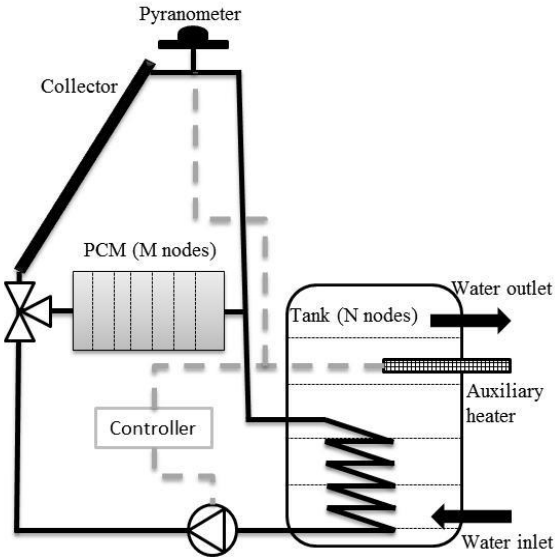
•Where the PCM can be added to optimise the system?



Cabeza LF et al. Sol Energy Mater Sol Cells 2006;90:1273–82.

Energy gains due to the PCM during a day are counterbalanced by the thermal losses undergone by the storage during the night



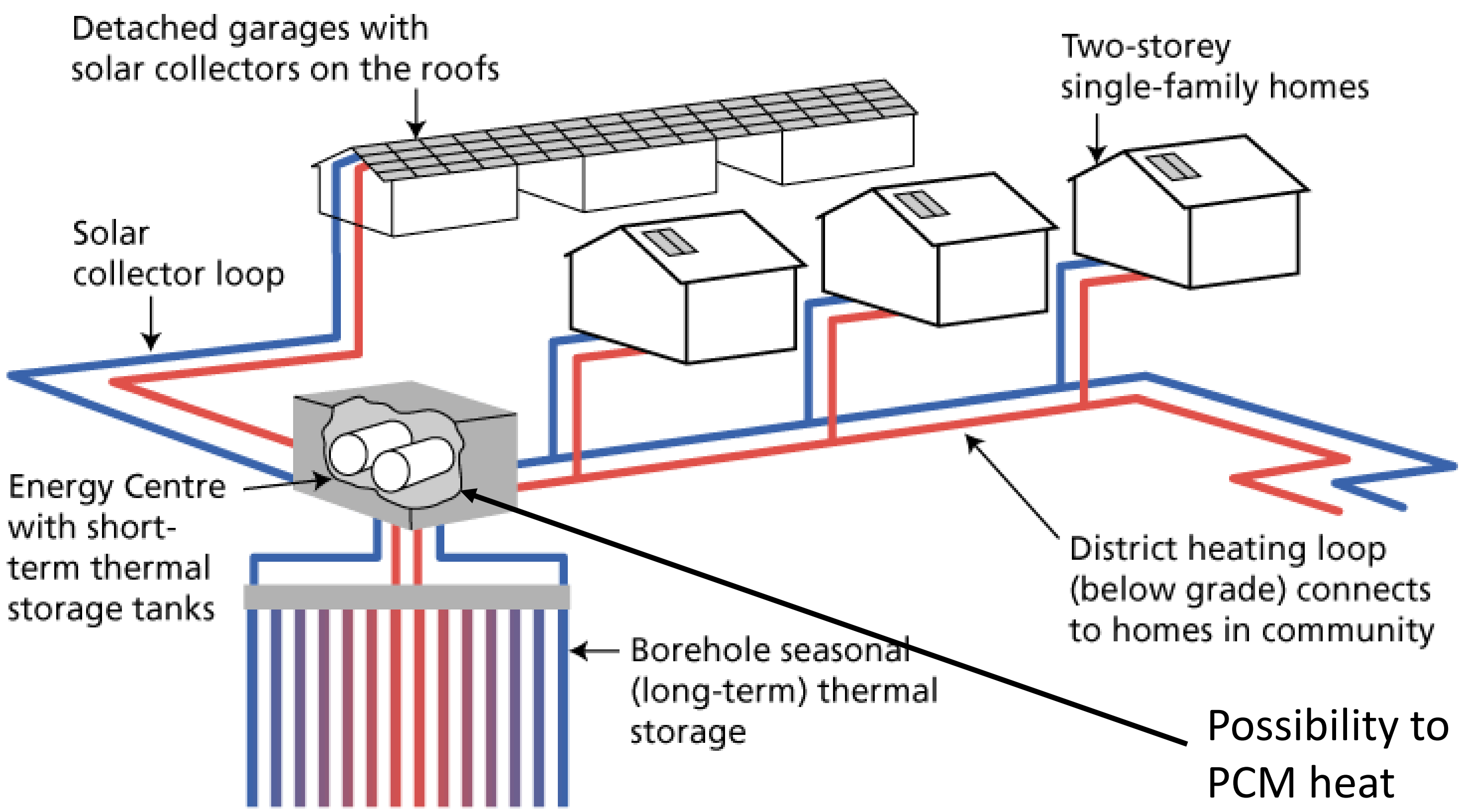


Haillot D et al., Sol Energy 2012;86:64–77

The storage medium imposes its temperature to the absorber
The heat losses of the collector (especially at night) are too important to allow an efficient daily storage

Other building Applications

Seasonal solar storage



Possibility to use PCM heat storage tanks

D R A K E L A N D I N G S O L A R C O M M U N I T Y (Okotoks, Alberta, Canada), High Performing Buildings, Summer 2015

Conclusions

PCM

Direct impact on thermal comfort in buildings

But requires a delicate choice of the PCM and the associated technology

1. PCMs in building components (walls, floor, ceiling, …)

Passive or active systems

→ **increase thermal mass**

2. Thermal Energy storage

Solar energy, Domestic hot water

- Separates the production from the use of energy in time and space

→ **Better control of energy demand**

PCM

- Methodology of selection
- Shortcomings

More studies focusing on real full-scale buildings and real operation conditions should be carried out to prove the authenticity and reliability of current researches.

Thank you for your attention

Challenges of phase change materials for building applications

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