5.7. Phase changing materials in building elements

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5.7.1 INTRODUCTION

New technologies in building construction and services are needed in order to reduce the big energy consumption in the building stock from which a major part goes for controlling of indoor climate. On the other hand, performance requirements are growing higher because of both more severe regulations and higher comfort requirements by the users – the wide use of air conditioning systems, also in houses, is just an example of this trend. Integration during the design phase among Architecture, Building Technology and Services is thus much recommended to obtain a more sophisticated "living-environment", using relatively simple strategies and avoiding extra-costs.

It is possible to tackle the problem of energy consumption with stratified lightweight skins and layers, high performance materials and integration of installations, like heat pumps for example or wind turbines, and enhancing the use of renewable energy sources by using devices like solar photovoltaic panels or solar thermal exchanger or simply by preferring natural ventilation and natural shading or re-interpreting low processing materials and using them in a clever way.

The hybrid strategy (insulated shell – inertial core) seems a logical passage in buildings, a smart evolution rather than a traumatic revolution in a slow market. Several recent sustainable projects are characterized by high-insulated envelopes with light structures and integrated solar panels and ventilation systems. The bearing structure is often dry-assembled steel or timber frame and concrete floors and staircases acting as bracing systems. The result is a well-insulated and ventilated cover and a core endowed with massive and inertial elements. In Italy, we could imagine high energy-efficient buildings characterized by a concrete bearing frame and concrete slabs, and a dry assembled insulated envelope.

Precise seasonal strategies in Southern European countries maximize the winter energy contributions from both natural sources (sun) and interior gains stored in the massive parts and retained because of insulation. In the middle seasons and in summertime, the natural ventilation could be exploited thanks to temperature differentials between opposite walls and the "stack effect" of massive floor slabs acting as "cooling sheets". A basic strategy required to save energy for cooling is the reduction of overheating inside the building. Apart from efficient shading of the glazed areas, the use of thermal mass is critical to control temperature peaks and the cycle of temperature during the day.

A possible way to use thermal mass in a building is an internal mass that contributes to the storage of energy during the day (also in winter) and releases it during the night, when the air temperatures are supposed to be lower. In well-insulated buildings, this is the most important issue about thermal inertia as the wall is almost adiabatic and the heat flow through it is practically eliminated. The required storage capacity is low, as energetic inputs are relatively small. Thermal storage can be accomplished either by using sensible heat storage or latent heat storage. Sensible heat storage has been used for centuries by builders to store thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storage. This paper aims to study potential of application of Phase Change Materials (PCM) in lightweight buildings or rather compounds (salts or paraffins) that undergo a phase change process, involving the storage, or release, of latent heat. PCM can be incorporated into a thermal storage system in order to store daytime solar energy to provide space heating and used to obtain thermal storage elements that don't add unnecessary weight to the construction and that – what is more – can be tuned to have a melting temperature coherent with the human comfort necessities.

Different PCM applications have been made in experimental buildings with light structures: an example is the Lighthouse project by Sheppard Robson, presented at BRE during the Offsite 2007 exhibition. In order to increase the thermal inertia of house and to achieve a "zero carbon emission" performance, PCM insulation panels, manufactured by Basf, have been included in suspended ceilings.

The main purpose of the paper is to present the state-of-the-art on phase changing materials in building applications.

5.7.2 OVERVIEW ON PHASE CHANGING MATERIALS USABLE IN BUILDINGS

5.7.2.1 *Physical and technical properties*

Based on a literature survey on phase changing materials (PCM), several compounds can be identified as commercially and technically feasible materials for building products and techniques.

PCM's are divided in two major groups, organic and inorganic. Organic materials may be obtained from petroleum or both from animal or vegetable sources. They can be classified in paraffins, non-paraffins and fatty acids. Inorganic materials can be classified in salt hydrates and metallic. Both organic and inorganic materials can be found with different phase change temperatures, latent heat of transition and conductivity, among other properties. Table 5.7.1 presents some substances that have been investigated by several researchers as potential PCM.

Table 5.7.1. Properties of different investigated PCM substances (Zalba et al., 2003)

	Compound	Melting Temperature (ºC)	Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m.K)
Inorganic	H_2O	0	333	0.612
	$LiClO_3.3H_2O$	8.1	253	---
	$KF.4H_2O$	18.5	231	---
	$Na_2SO_4.10H_2O$	32.4	254	0.544
	$Ba(OH)_2.8H_2O$	78	265. 7	0.653
Organic	Polyglycol E400	8	99.6	0.187
	Dimethyl-sulfoxide	16.5	85.7	---
	Paraffin C_{18}	28	244	0.148
	Paraffin C_{22}–C_{45}	58 – 60	189	0.21
	Naphthalene	80	147.7	0.132
Fatty Acids	Propyl palmiate	10	186	---
	Caprylic acid	16	148.5	0.149
	Capric acid	32	152.7	0.153
	Lauric acid	42 – 44	178	0.147
	Palmitic acid	64	185.4	0.162

Major companies such as BASF and Rubitherm GmbH (Germany), Cristopia (France), TEAP Energy (Australia), EPS Ltd. (UK), Climator (Sweden) and Mitsubishi Chemical (Japan) already offer a wide variety of commercial PCM's in a wide range of transition temperatures. Also in Portugal, Micropolis already produces PCM's based in paraffin waxes. Table 5.7.2 presents some products of the mentioned companies.

Table 5.7.2. Properties of commercially available PCM's (www…)

Company	Commercial Name	PCM	Melting Temperature (ºC)	Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m.K)
BASF	Micronal DS 5001	Paraffin	26	110	---
	Micronal DS 5008	Paraffin	23	110	---
Rubitherm GmbH	RT 6	Paraffin	8	174	0.2
	RT 20	Paraffin	22	130	0.2
	SP 22 A4	Salt Hydrate	24	165	0.6
Cristopia	SN 33	Paraffin	-33	218	---
	IN 03	Paraffin	-2.6	294	---
	AC 27	Paraffin	27	185	---
TEAP Energy	Latest 20T	Salt Hydrate	19 – 21	175	1
	Latest 32S	Salt Hydrate	31 – 32	200	0.6
EPS Ltd.	E -10	---	-10	286	0.56
	A2	---	2	225	0.21
	A22	---	22	172	0.18
Climator	ClimSel C 7	---	7	130	---
	ClimSel C 23	Salt Hydrate	23	148	---
	ClimSel C 32	Salt Hydrate	32	212	---
Mitsubishi Chemical	STL -21	Salt Solution	-21	240	---
	STL 27	Salt Hydrate	27	213	---
	STL 52	Salt Hydrate	52	201	---
Micropolis	Mikra Thermic	Paraffin	20	140	---

The most important property of PCM's is their ability to store/release heat within a narrow range of temperatures. When selecting a PCM for a special application, criteria needs to include the following characteristics: melting/freezing temperature range depending on operative conditions; high latent heat of transition enabling high energy storage; thermal conductivity and specific heat to promote easy heat transfer to/from support medium; density; little or no super-cooling during freezing ensuring full material operating efficiency; chemical stability through repetitive temperature transition cycles, during full installation life, small transition volume change and obviously price and market availability.

Both organic and inorganic materials present clear advantages and disadvantages. Among the main advantages of organic materials is their chemical and thermal stability through cycles and low or no supercooling. Their disadvantages are corrosiveness, flammability, lower enthalpy and lower thermal conductivity. On the other hand, inorganic materials present higher enthalpies, however they experience supercooling, phase segregation and corrosiveness.

5.7.2.2 *Application in building products*

Over the years different techniques to integrate PCM into the building materials have been studied. These techniques included mainly immersion and encapsulation.

In the immersion process the porous building material is dipped into the hot melt PCM, which is absorbed by capillarity. This is easy to perform but PCM may interact with the structure, changing the properties of the materials matrix by reacting with it or by leakage.

Encapsulation of the PCM in tubes, pouches, spheres or panels is an effective way of containing the material, however, macro-capsules heat transfer rates decrease due to low heat transfer coefficients during freezing, preventing the system to fully discharge. More, this method requires protection of the containers from destruction during integration.

Micro-encapsulation allows easy integration of the PCM into conventional porous materials, preventing the interaction of the PCM with the matrix, good stability and larger heat transfer surface, affecting however mechanical strength of the elements.

For wallboards for example, direct incorporation at the mixing stage is preferred because little additional process equipment and labour is required, however, if no contention mechanisms are used, leakage may be a problem. Nevertheless, PCM wallboard and conventional wallboard characteristics present flexural comparable strengths, around 15% difference in thermal conductivities depending on the PCM used and its amount and excellent fire resistance. For radiant floor applications shape-stabilized PCM plates are most common.

Major concerns with safety codes and flammability requirements imposed to construction materials lead to the development of techniques to prevent fire hazards. Adding fire retardants in materials composition is usually an effective measure. Examples include, non-flammable surface materials such as aluminium foil or rigid PVC film for plasterboards and brominated hexadecane and octadecane combined with antimony oxide for other applications, since it self extinguishes.

During the last 25 years several research studies have been conducted to develop different PCM solutions. These studies are divided in two major groups:

1) Incorporation in building materials to increase lightweight buildings thermal mass, contributing to interior temperature regulation and reducing heating and cooling demands;
2) Strategic combination with constructive elements, techniques and external heat or cool power supply equipments.

The first and widest investigated building material incorporating PCM is gypsum wallboard. Several researchers have conducted studies using different incorporation techniques, support materials, PCM substances and quantities.

An early research conducted by Athienitis et al., showed that an increase of up to 10 MJ heat transferred between the wall surface and the room could be obtained (15% of the total heating load), with 13 mm gypsum-PCM board as wall lining.

Darkwa at al. performed a simulation comparing the effectiveness of a 12 mm gypsum-PCM board randomly mixed with a 10 mm gypsum wallboard lined with a 2 mm laminate PCM and concluded that the laminated solution increased minimum room temperature in 17%.

During winter, the indoor thermal environment was studied by Shilei et al., by comparing the performance of a room lined with a phase change wallboard (9.5 mm thick) and without it. With PCM both maximum temperature and thermal flow through wall decreases were registered, respectively, 1.2 ºC and 8 W/m^2.

Still in the domain of wallboards application for lightweight envelope buildings, Ahmad et al. [13] compared the thermal performance of polycarbonate and PVC panels, using paraffin granulates and PEG600 as PCM. Though polycarbonate panels showed no significant effect, presenting a small time temperature lag of 1-2.5 hours, PVC panel presented temperature swings around 5 ºC with 2-3 hours time lag.

Different support materials and constructive elements have also been studied. Lai and Chiang investigated the performance of hollow thermal insulation bricks incorporating octadecane paraffin as PCM, during summer, registering a peak temperature difference of almost 5 ºC lower in the PCM brick. PCM bricks also presented a temperature control capacity of 23 ºC-h higher than conventional bricks.

Cabeza et al. setup an experiment in which a concrete cubicle incorporating only 5%-wt. PCM in the south, west and roof panels, showed a 1 ºC lower maximum room temperature appearing 2 hours later and a 2 ºC higher minimum temperature, effect of the thermal inertia introduced by the PCM.

Several strategic combinations of constructive elements and external power sources for space heating and cooling have been developed and studied. Examples include the integration of PCM’s in systems such as radiating floors, air conditioning and ventilation, solar collectors, heat pumps, photovoltaic panels and double glazed windows with moving PCM panels.

Lin et al. developed a new kind of radiating floor, using shape stabilized PCM plates. In their experiments, a prototype house installed with a 150 W heat source was tested. Results showed that 3.3 kWh were shifted to off-peak periods, corresponding to over 50% of the total energy consumption.

PCM integrated in a mechanical ventilation system for free cooling a low-energy building, was investigated by Arkar and Medved. The researchers concluded that, during summer, 6.4 kg of PCM per m^2 of floor area corresponded to an air change rate of 5h^{-1} night-time cross ventilation, to maintain temperatures in 25 ºC and in 26 ºC during day-time.

5.7.3 EXPERIMENTAL RESEARCH ON GYPSUM-PCM PLASTER

5.7.3.1 *Manufacture of gypsum-PCM plaster*

A gypsum plaster was selected as a material in which PCM would be incorporated, since it is one of the materials most widely used for interior revetment of residential buildings, due to its good hygrothermal properties. The type of PCM was selected as a technical grade hexadecane paraffin wax, microencapsulated in a melamine-formaldehyde resin, with an average particle size distribution of 20-30 μm, a melting temperature around 20 ºC and a latent heat of fusion of 140 kJ/kg.

The microencapsulated PCM was mixed directly in the plaster (Figure 5.7.1), since it also presents in the form of a powder. Systems configuration could this way respect traditional constructive systems and techniques, without adding any extra labour to the process.

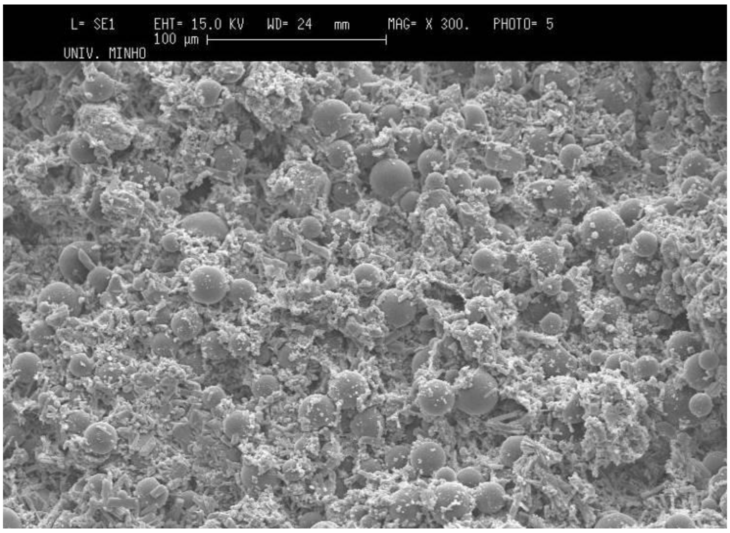

Figure 5.7.1. SEM picture of the PCM microcapsules inside the gypsum matrix.

The temperature range definition was based in the new Portuguese Regulation for Buildings Thermal Behaviour Characteristics (Min. of PW,T&C, *Regulations* ..., 2006) that sets both winter and summer indoor comfort temperatures, respectively in 20 ºC and 25 ºC. Since most of the energy is spent for heating purposes, rather than for cooling, a PCM with a freezing/melting range around 20 ºC was chosen. From bibliographical research and results achieved, the amount of PCM to be incorporated was set in 20% in weight of the final plaster. Production costs were also taken into account, since this is a very expensive product.

5.7.3.2 *Experimental programme*

An experimental research programme was carried out at the University of Minho in order to study the influence of the gypsum-PCM plaster on the thermal performance of a room. The programme consisted of determination of the material properties and temperature measurements in a test room.

Mechanical tests were carried out in accordance with the standard EN13279 in order to define bending, compressive and adhesive strengths of the gypsum-PCM plaster.

Table 5.7.3. Mechanical properties of the gypsum-PCM plaster (Silva et al., 2007)

Bending Strength, (MPa)	Compressive Strength, (MPa)	Adhesion Strength, (MPa)
1,77	2,70	0,48

The influence of the gypsum-PCM plaster was studied through temperature measurements in the an adiabatic test cell of the Building Physics and Technology Laboratories at the University of Minho in Guimarães. The measurements were done in two different test arrangements built inside the test cell: the tested material was involved in the first space, and in comparative test not.

The length of the cell is 4.24 m, the width 2.58 m wide and height 3 m (Figure 5.7.2). A hollow ceramic brick wall of thickness 110 mm was built to dividing the cell in two rooms (east and west). To allow plastering, instrumentation and maintenance of the east room, an aperture was left (this opening was then closed with a double layer of expanded polystyrene 5 cm thick plates and polyurethane foam). Each surface of the wall was then covered with projection gypsum plaster. After 24 hours, three very thin layers of finishing plaster were manually applied in both façades. In the West façade gypsum-PCM mixture was used as solution in study (Figure 5.7.2), while in the East façade gypsum plaster was used as Reference solution. Table 5.7.4 presents the characteristics of both systems.

Both rooms were instrumented with temperature and relative humidity sensors and thermocouples were installed in the different plaster layers and walls surface. Monitoring was carried between the 21st July and the 8th August, 2007.

Table 5.7.4. Test cell system characteristics

Property	Reference Solution	Studied Solution
Internal cell dimensions (L x W x H in m)	4.10 x 2.50 x 2.60	
Plastered area (m^2)	9.74	
Gypsum plaster used (kg)	10	7.5
PCM used (kg)	---	1.9
Plaster specific consumption (kg/m^2)	1.03	0.77
PCM specific consumption (kg/m^2)	---	0.20
Storage capacity (Wh/m^2)	---	7.6

Figure 5.7.2. West room of the adiabatic test cell – Gypsum-PCM façade.

During the above mentioned period both room temperature and relative humidity were monitored, as well as surface temperatures. Figures 5.7.3 and 5.7.4 present the results achieved both during the cold and the warm period monitored.

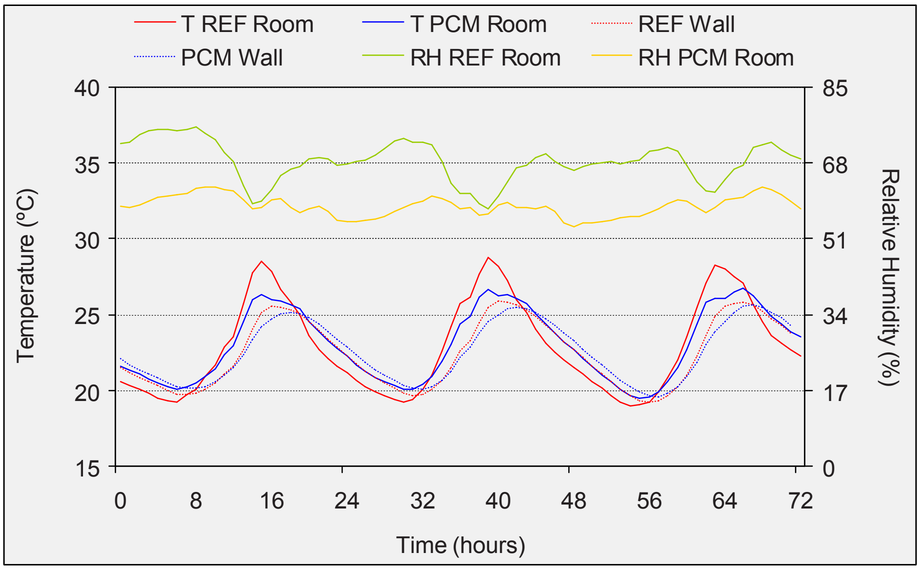

Figure 5.7.3. Temperature and relative humidity profiles for the period hosting the coldest day (9.6ºC<T_{out}<25.8ºC).

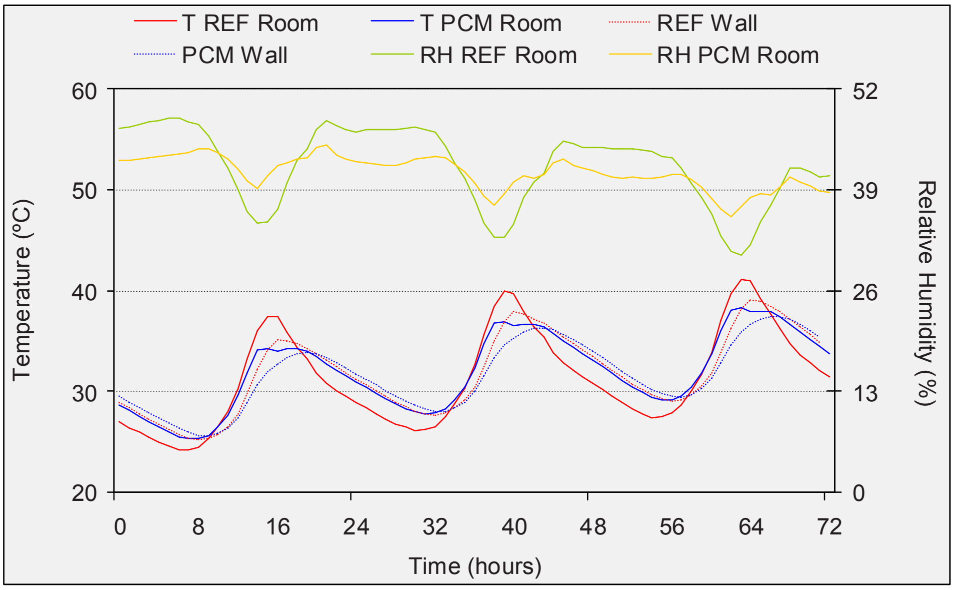

Figure 5.7.4. Temperature and relative humidity profiles for the period hosting the warmest day (14.9ºC<T_{out}<36.8ºC).

For the period represented in Figures 5.7.3 and 5.7.4, the maximum and minimum measured temperatures are shown in Table 5.7.5. For the whole monitored period, the most important feature of the measurements, is presented in Table 5.7.6, where both temperature and time measured amplitudes are shown.

Table 5.7.5. Maximum and minimum registered temperatures during the monitored period

	Outside	**Reference Room**	**PCM Room**	**Reference Wall**	**PCM Wall**
T_{Max} (ºC)	36.8	42.2	38.1	39.2	37.5
T_{Min} (ºC)	9.0	19.1	19.2	19.2	19.6

Table 5.7.6. Maximum and minimum temperature amplitudes and time delays between Reference and PCM rooms

	Temperature / Time Delay	
	Maximum	*Minimum*
ΔT (ºC)	-4.9	1.4
Δt (h)	3	2

Assuming equal heat loss through the envelope for both rooms and neglecting conductive heat transfer through the wall, the heat fluxes between the wall surface and the room were determined according to equation:

$$Q = U.A.\Delta T = \frac{\Delta T}{R} \qquad \text{where}$$

U is the Overall Heat Transfer Coefficient, in $W/m^2.{}^oC$;
A is the Heat Transfer Surface, in m^2;
ΔT is the Temperature difference between room medium and wall surface, in ºC;
R, is the Horizontal Thermal Resistance through walls, in.

In this case, $R = 0.13\ m^2.{}^oC/W$ defined by RCCTE, the Portuguese Regulation of Energy Performance of Buildings (Min. of PW,T&C, *Regulations* ..., 2006). Results are shown in Table 5.7.7.

Table 5.7.7. Calculated heat flux differences. ΔQ is the heat flux, from wall surface to the room, difference between PCM and reference room; T refers the total monitored period; h refers to one hour; Wall refers per wall area; Floor refers per floor area; Wall.Floor refers per wall and floor area

ΔQ_T (W)	ΔQ_h (W)	ΔQ_{Wall} (W/m^2_{Wall})	ΔQ_{Floor} (W/m^2_{Floor})	$\Delta Q_{Wall.Floor}$ ($W/m^2_{Wall}.m^2_{Floor}$)
24788	21.3	2.2	4.3	0.44

From the results obtained in the test cell was possible to verify that PCM has a benefit effect in room environment, decreasing maximum temperature up to 5ºC and increasing minimum temperature up to 1.5ºC. More, the registered minimum and maximum temperatures in the PCM side, where observed with a time delay of 2 and 3 hours respectively, after reference side peaks been achieved. This data is very important due to the potential of peak shifting energy consumptions to periods when energy's less expensive.

Considering the heat flux, from wall surface to the room, difference between PCM and reference room calculated per wall and floor area presented in Table 5.7.5, and taking as an example a room between 12 to 16 m^2, the possible cooling power savings with this system would be around 15% (valid only for the period analyzed). Considering a fan or AC supply of 1000 W and 0.1143 €/kWh (Portuguese energy price), up to almost 2 c€/h could be saved.

Another important feature of the system is shown in Figures 8 and 9, where the relative humidity (RH) of both spaces is compared. Not only has the PCM side presented, in general, lower RH for both colder and warmer temperatures but also its variation is narrower (RH between 35-45% *versus* 30-50% during the hottest period and 53-62% *versus* 57-76% during the coldest period). This data is important attending that for higher RH, higher condensation problems may occur.

5.7.4 THERMAL MONITORING OF BUILDINGS JANUARY 2008- APRIL 2008

Thermal monitoring in full scale residential building was performed from January 2008 to April 2008, in Vila Nova de Familicão, Braga. The buildings had a high thermal mass typical for buildings in Portugal, with outer walls built in double panel “Monolite” system and inner walls in single panel “Monolite” system.

The first stage of this phase consisted in the evaluation and comparison of both PCM and reference systems performance, when subjected only to solar gains as heating source and with no ventilation being provided.

Two houses (Reference and PCM) and two rooms in each house (Figure 5.7.5) were selected. Within each house, one of the rooms faces north while the other faces south. Both walls and ceilings in each room were plastered. Table 5.7.8 presents the characteristics of both systems.

a) b)

Figure 5.7.5. Selected Reference and PCM rooms in the a) Southern façade and in the b) Northern façade.

Table 5.7.8. Residential building system characteristics

Property	Reference (MA)		Studied (PCM)	
	North Room	South Room	North Room	South Room
Room area (m^2)	17	21.5	17	21.5
Total plastered area (m^2)	54	62	54	62
Gypsum plaster used (kg)	60		40	
PCM used (kg)	---	---	10	
Plaster specific consumption (kg/m^2)	0.52		0.35	
PCM specific consumption (kg/m^2)	---	---	0.086	
Storage capacity (Wh/m^2)	---	---	**3.3**	

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The four rooms were instrumented as shown in Figure 5.7.6, with thermocouples in the walls, ceiling and double glass window surface. Outside and room temperatures are also monitored. In the north façade rooms, an oil radiator (2500 W nominal power) was placed in order to work as an external heat source providing the extra necessary heat to increase temperature above melting range of the PCM.

Figure 5.7.6. Schematic view of instrumentation placed (reference south room)

The set of measurements carried consisted in outside, inside and walls surface temperature monitoring, for the south façade rooms depending only on solar gains and for the north façade rooms depending both on solar and the external heat source, according with heating cycles shown in Table 5.7.9. All doors were sealed with expanded polystyrene (5 mm thick) and polyurethane foam and no ventilation were provided.

Table 5.7.9. Heating cycles carried on the north façade rooms

	Heating Cycles					
ON	00H00	04H00	08H00	12H00	16H00	20H00
OFF	02H00	06H00	09H00	13H00	17H00	22H00

Results for rooms in both façades are shown in Figures 7 and 8.

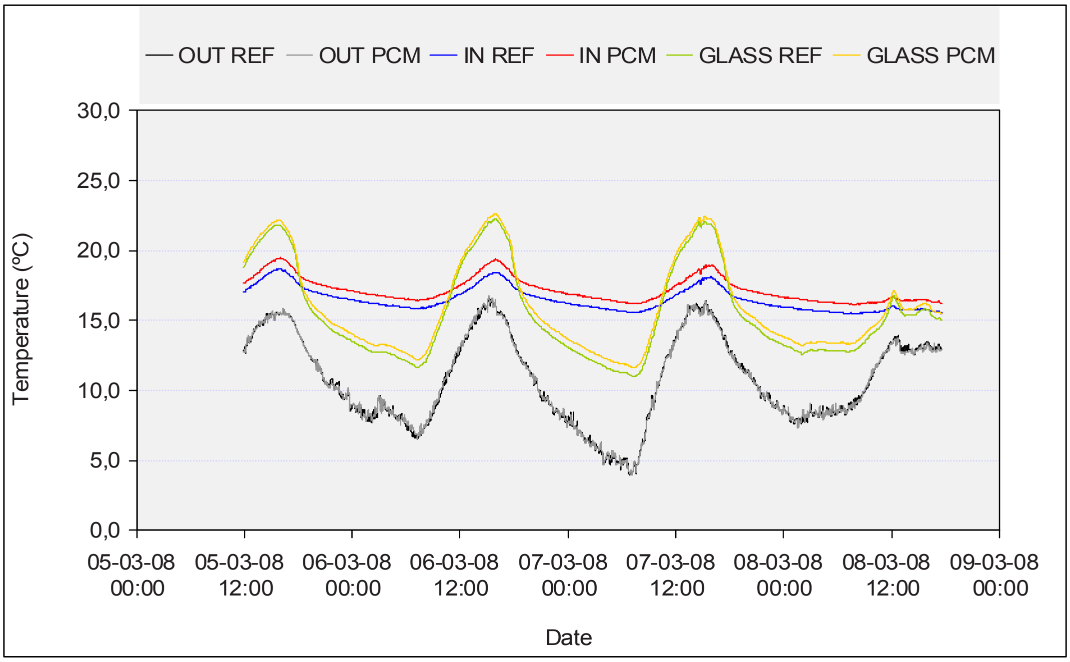

Figure 5.7.7 In-situ outdoor, indoor and glaze temperature profiles, for the south façade rooms

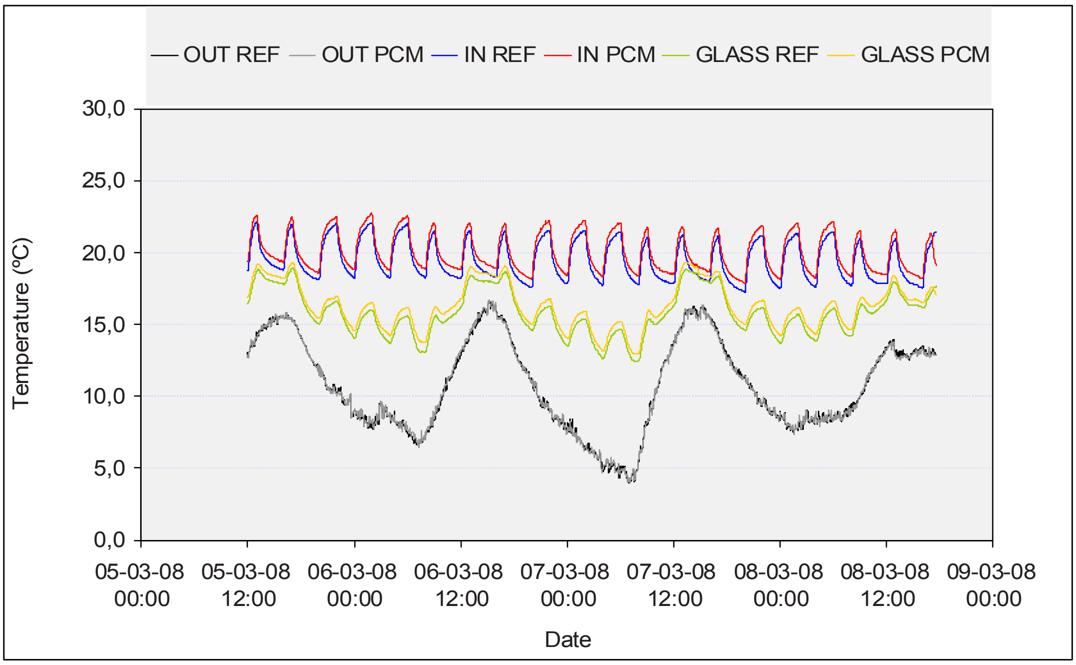

Figure 5.7.8. In-situ outdoor, indoor and glaze temperature profiles, for the Northern façade rooms.

From Figures 7 and 8 is clear that no significant difference was so far verified between Reference and PCM rooms. The low winter solar gains and consequently PCM room temperatures below PCM fusion temperature (around 20 ºC), inhibit the PCM to change its state, from solid to liquid, therefore regulating temperature.

High thermal inertia introduced by the PCM is however verified, with higher temperatures being achieved in the PCM rooms for both façades. As regard for Figure 5.7.8, it is clear that no sufficient cooling is provided in order to permit the PCM full transition to solid state. As stated earlier, the “Monolite” system, provides both good thermal insulation, due to its single/double polystyrene foam layer but also and unlike Adiabatic test cell, high thermal mass due to the filling concrete structure, in the double layer walls and both inner and outer mortar lining.

Based on the results achieved so far, night ventilation may be necessary to promote PCM solidification and that way evaluate the thermal behaviour of both solutions. The installation of energy meters side by side with the already installed thermocouples, will also allow temperature and energy consumption control and comparison. In one way it will be possible to measure temperature fluctuations and time delays in both rooms when the same external heating power source is provided but also heat provided for the same desired room temperature.

5.7.5 SUMMARY

Phase change materials have proven to be an interesting and efficient solution to thermal energy storage in several research fields and applications, with great success being achieved in particular areas such as refrigerating equipments, solar panels or radiating floor systems.

Regarding material applications, the increase of lightweight buildings thermal mass by its incorporation in wallboards, plaster and concrete has been studied.

One of the limitations of the present work is the small amount of PCM incorporated, in respect with the total thermal mass of the building, in order to produce significant results. The high production cost of the PCM may inhibit higher incorporation content in the final plaster and generalized use, concerning the traditional Portuguese constructive techniques. Also, it would significantly reduce mechanical properties regarding the EN-13279 standard.

Other limitations are associated with the achievement of comparable temperature and energy consumption profiles. Different construction systems and materials (for example double brick walls versus thermally insulated concrete “monolite” systems) may request more than one PCM phase transition range to be fully effective and require experimental time ranges sometimes not achievable, especially concerning different weather conditions throughout seasons (for example winter versus summer). While limiting a particular research, this also opens possibilities for further investigation, concerning a specific system optimized both for cooling and heating purposes.

This research work aiming the development of a gypsum plaster based in conventional construction techniques had the opportunity to test the system in a real residential building in order to evaluate and verify its feasibility. Results in test cells allowed stepping with further confidence into the real application.

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