

# LATENT HEAT STORAGE IN BUILDING MATERIALS

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**Abstract:** Thermal storage by latent heat was recognised early as an attractive alternative to sensible heat storage in the building fabric. Early efforts in the development of latent heat storage used inorganic phase change materials (PCMs). However, in an effort to avoid some of the problems inherent in these, an interest was developed in the use of organic PCMs for this purpose. Recent research has looked at the incorporation of organic PCMs into porous building materials, creating functional and effective building elements which can effect significant energy savings. The rationale for using latent, as opposed to sensible heat storage in buildings is explained. Research to date into the use of PCMs in building materials is reviewed. Applications of PCM technology in the built environment are discussed. The main obstacles to the widespread use of PCM-impregnated building materials are discussed, and recommendations are given.

**Keywords:** Thermal storage, phase change materials, latent heat, energy conservation, peak reduction, passive solar design.

## INTRODUCTION

In an attempt to conserve energy and reduce dependency on fossil fuels, it has become necessary to seek effective means of reducing peaks in power consumption and to shift portions of the load from periods of maximum demand. The development of improved means of thermal storage is thus a very important aspect of energy conservation in buildings.

The utilisation of phase change materials (PCMs) in active and passive solar buildings has been subject to considerable interest since the first reported application in the 1940s. The appeal of PCMs is that they can store heat energy in a latent, as well as sensible fashion, leading to greater heat storage capacity per unit volume than that of conventional materials. As the ambient temperature rises, the chemical bonds within the PCM break up as the material changes phase from solid to liquid (as is the case for solid-liquid PCMs which are of particular interest here). The phase change is a heat-seeking (endothermic) process and therefore, the PCM absorbs heat. As the environment cools down, the PCM will return to solid phase and reject the heat it had absorbed.

Until recently, research has been primarily concerned with salt hydrate type-PCMs, which require support and containment and cannot therefore be directly incorporated into a building material. In the last decade, the use of organic type-PCMs has been investigated, throwing open the possibility of porous building materials being impregnated with the PCM, thus creating a direct-gain storage element. Recent research (Feldman *et al.* 1993, Athientis *et al.* 1997, Peippo *et al.* 1991) has shown that PCM-impregnated building materials show great promise as functional and effective building elements which can effect significant energy savings. It will be seen that

besides a direct reduction in energy consumption, these energy-storing building materials can reduce peaks in demand by creating a more even load-time characteristic. Further, appropriate thermal storage can be used to effect a significant reduction in equipment cycling frequency and thus achieve a noticeable increase in operating efficiency.

## **THERMAL STORAGE IN THE BUILDING FABRIC USING PHASE CHANGE**

### **MATERIALS**

The sensible heat storage capacity of stone building materials has been recognised since ancient times. However, in order for sensible heat storage to be effective in modern buildings, a number of problems arise such as high cost, excessive mass and undesirable temperature fluctuations. Hence, the rationale for the development of latent heat storage in building materials.

The characteristics of PCMs make them inherently suitable for use in buildings for energy conservation purposes without the complications brought about by other thermal storage devices requiring separate plant and space. The improved thermal distribution, cost and space-saving implications are but some of the advantages of this type of thermal storage.

With respect to thermal comfort criteria, the isothermal storage of heat energy is one of the most attractive features of a PCM as a component building material. Within the human comfort temperature range (approximately 16-25°C), latent heat storage materials have been found to be very effective. Indeed, research has shown that PCM-impregnated building materials can store 5-14 times more heat per unit volume than their conventional sensible storage counterparts.

### **TYPES OF PHASE CHANGE MATERIAL**

PCMs may be organic or inorganic materials. The phase changes comprise predominantly

solid-liquid transitions for thermal storage applications in buildings.

(i) *Inorganic PCMs*

Early efforts in the development of latent heat storage materials used inorganic PCMs. These materials are salt hydrates, including Glauber’s salt (sodium sulphate decahydrate), which was studied extensively in the early stages of research into PCMs. The phase change properties of these materials are shown in Table 1. These PCMs have some attractive properties including high latent heat values, they are not flammable and their high water content means that they are inexpensive and readily available. However, their unsuitable characteristics have led to the investigation of organic PCMs for this purpose. These include corrosiveness, instability, improper re-solidification, and a tendency to supercool. As they require containment, they have been deemed unsuitable for impregnation into porous building materials.

**Table 1:** *Salt hydrate PCMs (typical values)*

PCM	Melting Point (°C)	Heat of Fusion (kJ/kg)
KF·4H <sub>2</sub> O Potassium fluoride tetrahydrate	18.5	231
CaCl <sub>2</sub> ·6H <sub>2</sub> O Calcium chloride hexahydrate	29.7	171
Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O Sodium sulphate decahydrate	32.4	254
Na <sub>2</sub> HPO <sub>4</sub> ·12H <sub>2</sub> O Sodium orthophosphate dodecahydrate	35.0	281
Zn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O Zinc nitrate hexahydrate	36.4	147

Source: Feldman *et al.* 1993

(ii) *Organic PCMs*

Organic PCMs have a number of characteristics which render them useful for latent heat storage

in certain building elements. They are more chemically stable than inorganic substances, they melt congruently and supercooling does not pose as a significant problem. Moreover, they have been found to be compatible with and suitable for absorption into various building materials, as will be discussed in more detail later. Although the initial cost of organic PCMs is higher than that of the inorganic type, the installed cost is competitive.

However, these organic materials do have their quota of unsuitable properties. Of the most significant of these characteristics, they are flammable and they may generate harmful fumes on combustion. Other problems, which can arise in a minority of cases, are a reaction with the products of hydration in concrete, thermal oxidative ageing, odour and an appreciable volume change.

Appropriate selection and modification have now eliminated many of these undesirable characteristics. It has been found that the thermal oxidative ageing of PCMs concerned can be inhibited by the use of a proper antioxidant. Research is still underway (Feldman *et al.*) to assess the flammability and fume generation of some of the more effective PCMs such that a fire rating may be established. Also, efforts are being made to extend the number of PCMs which are compatible with concrete. The most promising selection of these organic PCMs is shown in Table 2.

**Table 2:**      *Organic PCMs (typical values)*

PCM	Melting Point (°C)	Heat of Fusion (kJ/kg)

CH <sub>3</sub> (CH <sub>2</sub> ) <sub>16</sub> COO(CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub> Butyl stearate	19	140
CH <sub>3</sub> (CH <sub>2</sub> ) <sub>11</sub> OH 1-dodecanol	26	200
CH <sub>3</sub> (CH <sub>2</sub> ) <sub>12</sub> OH 1-tetradecanol	38	205
CH <sub>3</sub> (CH <sub>2</sub> ) <sub>n</sub> (CH <sub>3</sub> ) <sub>2</sub> Paraffin	20-60	200
45% CH <sub>3</sub> (CH <sub>2</sub> ) <sub>8</sub> COOH 55% CH <sub>3</sub> (CH <sub>2</sub> ) <sub>10</sub> COOH 45/55 capric-lauric acid	21	143
CH <sub>3</sub> (CH <sub>2</sub> ) <sub>12</sub> COOC <sub>3</sub> H <sub>7</sub> Propyl palmitate	19	186

Source: Feldman *et al.* 1993

## COMPATIBILITY OF PCMS WITH POROUS BUILDING MATERIALS

The principles of latent heat storage can be applied to any porous building material, although current research has been primarily concerned with gypsum wallboard and concrete blocks, and they will be of foremost concern here. Other research (H. Kaasinen, 1991) has looked at the absorption of certain organic PCMs into a wide range of building materials including wallboards, timber and brick. The findings of this and other studies will be discussed in more detail later.

Experiments carried out by Feldman *et al.* (1993) found gypsum wallboard to be compatible with a broad range of PCMs, including fatty acids and esters. The compatibility of concrete blocks is basically dependent on the presence of calcium hydroxide (Ca(OH)<sub>2</sub>) in the block, since certain organic PCMs will react with it.

Feldman *et al.* subjected specimens of wallboard and concrete block to hundreds of six-hour cycles of freeze-thaw testing, during which the wallboard was covered with common types of paint, adhesive and wallpaper. In addition, other specimens had various types of materials embedded in them representing fasteners or other objects with which wallboard normally comes

into contact. The impregnated specimens were also tested for volatile emissions, off-gassing and liquid discharge over a two-year observation period. The results can be summarised as follows:

#### *Wallboard*

- 25-30% PCM by weight resulted in most satisfactory performance
- No significant off-gassing
- No detectable liquid discharge
- Volatile emissions no different from plain specimens

#### *Concrete*

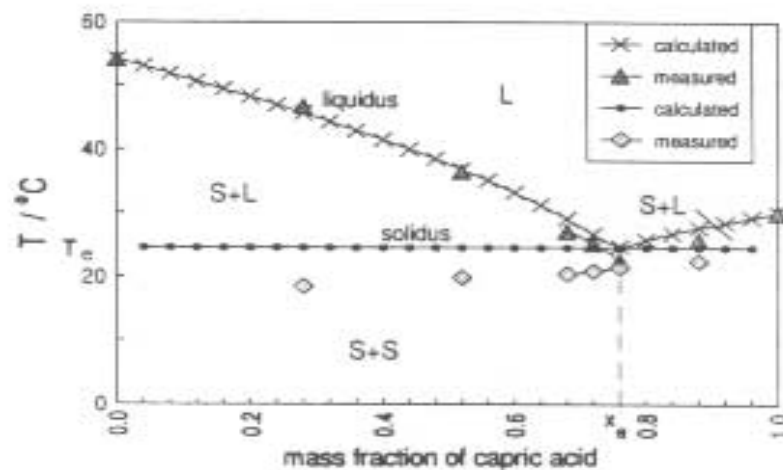
- Except in the case of one very porous test mix, loss of PCM during cycling was negligible

Wallboard can absorb some PCMs in amounts up to about 50% of its own weight, and depending upon the type of concrete block used, up to 20% by weight of PCM can be absorbed. It was found that the PCM-impregnated specimens all fared better than the unimpregnated (plain) specimens because of reduced freeze-thaw damage due to lower moisture absorption.

Therefore, the suitability of wallboard and concrete block for this type of thermal storage in the building fabric is evident. It should be noted that the structure of these materials is such that, even in the liquid state, these PCMs will be retained by the host material by virtue of surface tension. In the case of other materials, particularly when fatty acid (*carboxylic acid*) is the PCM, it is necessary to coat the material to prevent leakage.

Similar work carried out by Peippo *et al.* (1991) developed a very useful procedure which may be used to select a PCM with a predictable melting points adjustable to the optimum temperature

of the application. This investigation was primarily concerned with the range of fatty acids which may be used as PCMs. The thermal properties of various binary mixtures of fatty acids were investigated with the object of determining the *eutectic point* of the mixture. At the eutectic point the mixture melts isothermally and a mixture showing a eutectic point at the optimal melting point is searched for here.



**Figure 1:** Calculated and measured phase diagram of a mixture of capric and palmitic acids: S = solid, L = liquid.

Source: Peippo *et al.* 1991

The heats of fusion reported here are high enough to justify their use in the building fabric. The data obtained from this type of analysis is very useful and could be used as a catalogue for selecting the appropriate PCM for a given application. For detailed results see Appendix A.

## INCORPORATION OF THE PCM INTO THE BUILDING FABRIC

Knowing the suitability of various PCMs for a particular application and building material, the actual method of incorporation must then be considered. Feldman *et al.* (1993) investigated various means of incorporating the PCM, the most promising of which are given in

Table 3.

**Table 3:** *Means of PCM Incorporation*

Method of Incorporation	Method Used	
		Wallboard (12.7 mm)
Direct incorporation (at time of mixing)	Add liquid PCM to mix	Add powdered PCM to mix Add small PCM cylinders to mix Add pre-impregnated aggregate to mix
Immersion	Immerse board in liquid PCM at 80 °C for several minutes	Immerse block in liquid PCM at 80°C for required period
Encapsulation	-	Macroencapsulation*

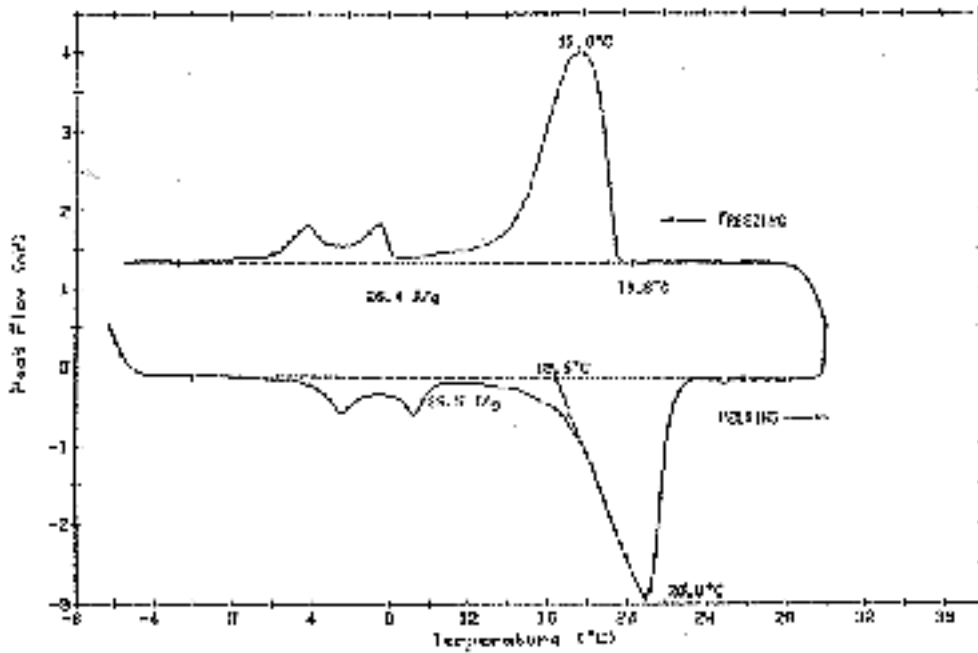
\*Further development required

Source: Feldman *et al.* 1993

Whereas several means of incorporation can be used for wallboard, direct incorporation appears to be the most economical procedure. Considerable effort was expended in developing a technique for incorporating PCM in wallboard so that its standard characteristics are not significantly affected and this was eventually achieved. A major factor in this process is the use of appropriate amounts of various dispersing agents. In the case of concrete block, both immersion and direct incorporation were found as practical means of incorporating PCM.

## PERFORMANCE

The thermal performance of PCM building materials can be evaluated using Differential Scanning Calorimetry (DSC), an example of which is shown in Figure 2. An ideal curve will have sharply defined transition points, a regular shape and a narrow opening temperature range.



**Figure 2:** Differential scanning calorimeter melting and freezing curves for butyl stearate in wallboard.

Source: Feldman *et al.* 1993

A series of tests conducted by Feldman *et al.* (1993) to compare the characteristics of energy-storing wallboard with that of conventional wallboard yielded some very promising results. It was found that physical attributes such as flexural strength, thermal conductivity and weight were not significantly affected. Durability after freeze-thaw cycling is completely satisfactory, fire resistance is excellent and flame travel is slightly greater than for the conventional board. PCM wallboard absorbs less than a third of the moisture absorbed by conventional wallboard and is comparably more durable in a moist environment. Energy-storing wallboard exhibits an eleven-fold increase in energy-storing capacity (through a 4°C rise) when compared to conventional wallboard. Table 4 sets forth the principal thermal characteristics of a few of the more promising gypsum-PCM combinations.

Similar tests were carried out on PCM concrete blocks comparing them with conventional blocks. Again, it was found that physical attributes were not significantly affected. Durability after freeze-thaw cycling is greatly improved, fire resistance is very good and flame spread minimal. Energy storage capacity of PCM concrete is in the order of 200-230% of that of conventional blocks through a 6°C change.

It will be noted that the temperature difference used for testing the PCM concrete (6°C) is greater than that used for PCM wallboard (4°C) as it was felt to be somewhat more practical. Table 5 illustrates the thermal properties of a few concrete-PCM combinations.

**Table 4:** *Thermal characteristics of various gypsum-PCM combinations*

PCM	Melting Point (°C)	Freezing Point (°C)	Average Latent Heat of Impregnated Gypsum (kJ/kg)
45/55% Capric-lauric acid plus fire retardant	17	21	28
Butyl stearate	18	21	30
Propyl palmitate	19	16	40
Dodecanol	20	21	17

Source: Feldman *et al.* 1993

**Table 5:** *Thermal characteristics of various concrete-PCM combinations*

Type of	Melting Point	Freezing Point	Average Latent Heat of	Age*

Concrete	PCM	(°C)	(°C)	Impregnated Concrete (kJ/kg)	(days)
ABL	BS	15.2	19.3	5.7	692
REG	BS	15.4	20.4	5.5	391
PUM	BS	15.9	22.2	6.0	423
EXS	BS	14.9	18.3	5.5	475
ABL	DD	10.8	16.5	3.1	653
REG	DD	5.0	9.6	4.7	432
PUM	DD	14.9	12.0	12.7	377
REG	TD	26.2	32.0	5.7	406
PUM	TD	32.2	35.7	12.5	404
REG	PAR	52.4	60.2	11.9	428
ABL	PAR	53.2	60.6	18.9	421
PUM	PAR	52.9	60.8	22.7	407
OPC	PAR	51.7	60.4	7.6	407

\* This is the age of the specimen after impregnation with PCM.

ABL = autoclaved block; REG = regular concrete block; PUM = pumice concrete block;

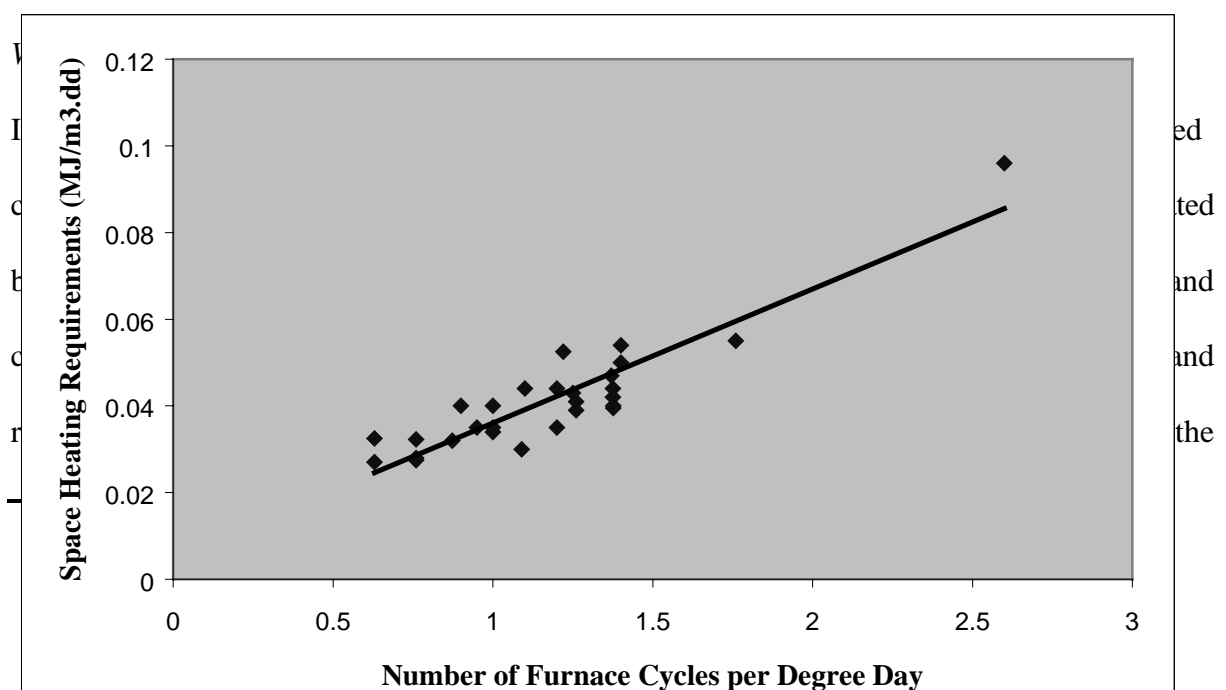
EXS = expanded shale (aggregate) block; OPC = ordinary portland cement concrete;

BS = butyl stearate; DD = dodecanol; TD = tetradecanol; PAR = paraffin.

It will be noted that the melting and freezing points for DD and TD are outside the human comfort zone and would require normal air mixing techniques as with conventional air conditioners and furnaces.

Source: Feldman *et al.* 1993

Figures 5, 6 and 7 show the potential heat storage values for various concrete-PCM combinations through a temperature rise of 6°C at the PCM melting point.



benefit will be realised because 100 MJ of thermal storage can result in very significant reductions in furnace cycling with a corresponding increase in boiler efficiency. Studies have shown (Feldman *et al.*, 1993) that the resulting reductions in fuel consumption could average up to 30 % (see Figure 3 below). Similar improvements would also apply to heat pumps and chillers. With regard to cooling, excess heat gain from occupants and equipment inside the building can be absorbed by the PCM-wallboard and thus reduce the cooling load.

**Figure 3:** *Relationship between furnace cycling and energy consumption*

*Source:* Feldman *et al.* 1993

### *Concrete Performance*

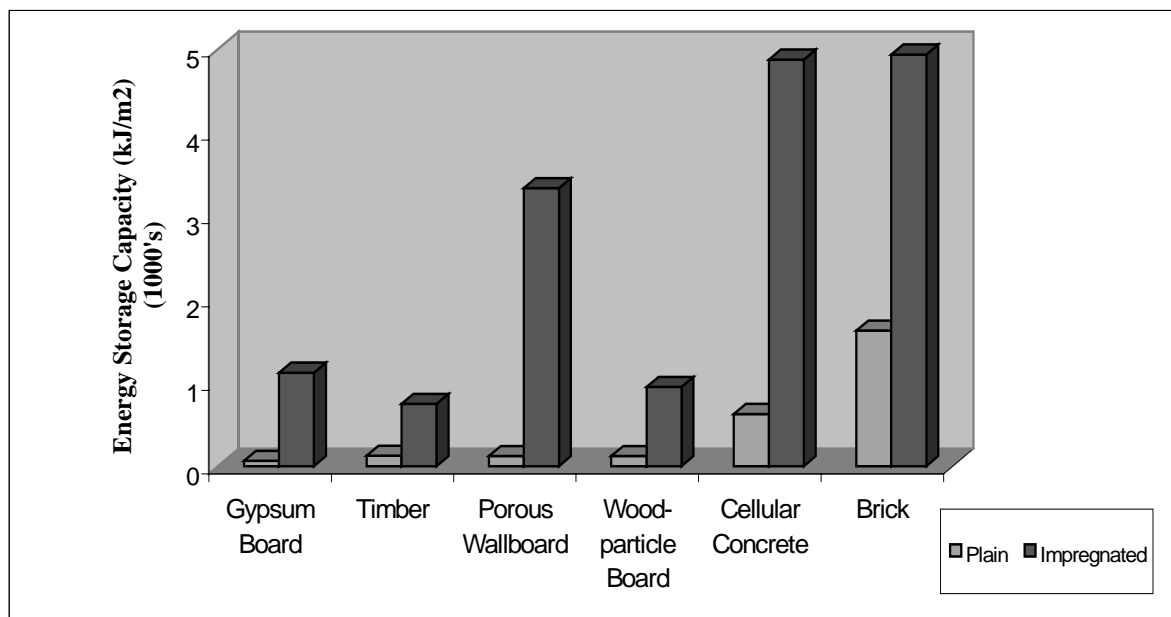
If the external wall of the building is constructed from PCM concrete blocks, a thermal storage capacity approximately four times that of the energy-storing wallboard can be achieved. This could significantly reduce the furnace and chiller cycling and/or peak demand for space heating and cooling energy. If used in conjunction with an alternative energy source where the demand for heating energy may be asynchronous with the supply from a source such as an active solar array or low-energy waste heat source, this application of energy storage could be even more effective. The amount of storage would, of course, vary with the climate and building characteristics.

In certain applications, the circumstances of climate, application and temperature of thermal energy acquisition could warrant the combined use of PCM wallboard and PCM concrete. An example of this would be PCM wallboard for short-term diurnal storage to reduce equipment cycling and peak energy demand while PCM concrete could be used in conjunction with an alternative energy source to reduce fuel consumption and sustain the more even time-load

characteristic.

### *Other Materials*

H. Kaasinen (1991) investigated the absorption of certain organic PCMs (carboxylic acids and polyalcohols) in a range of commonly used building materials. He found that materials impregnated with carboxylic acids yielded far better results in terms of thermal storage capacity than those treated with polyalcohols. The main findings are summarised in Figure 4 below.

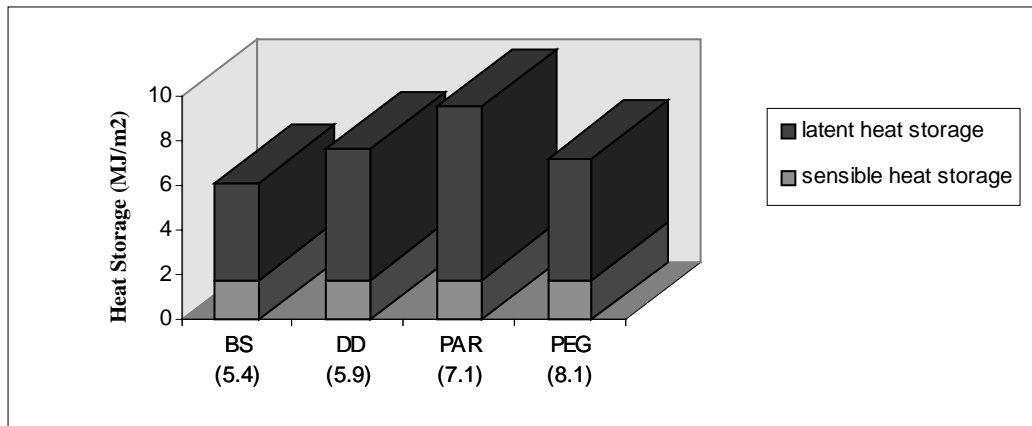


**Figure 4:** *Energy storage capacities of some building materials, with and without PCM (carboxylic acid)*

Source: Kaasinen et al. 1991

In addition to energy reduction, thermal storage building materials have great potential for power

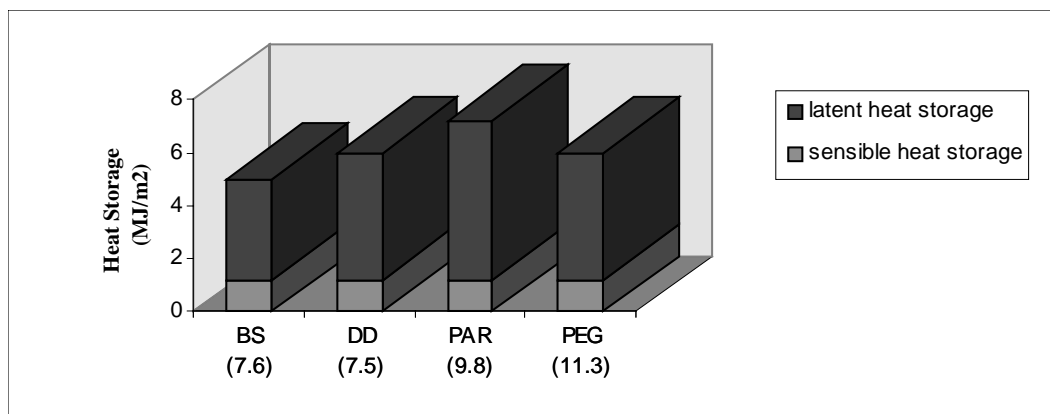
load shifting and hence electrical load reduction. If space heating and cooling requirements can be shifted from peak to off-peak time through thermal storage, a significant reduction in electricity generation, transmission and distribution facilities can result. This feature applies not only to electric utilities but to gas and district heating systems as well.



**Figure 5:** Potential heat storage values of regular concrete block showing added heat storage capacity of impregnated PCM.

BS= butyl stearate; DD = dodecanol; PAR = paraffin; PEG = polyethylene glycol. Figures in parentheses show the weight of PCM as a % of dry concrete weight.

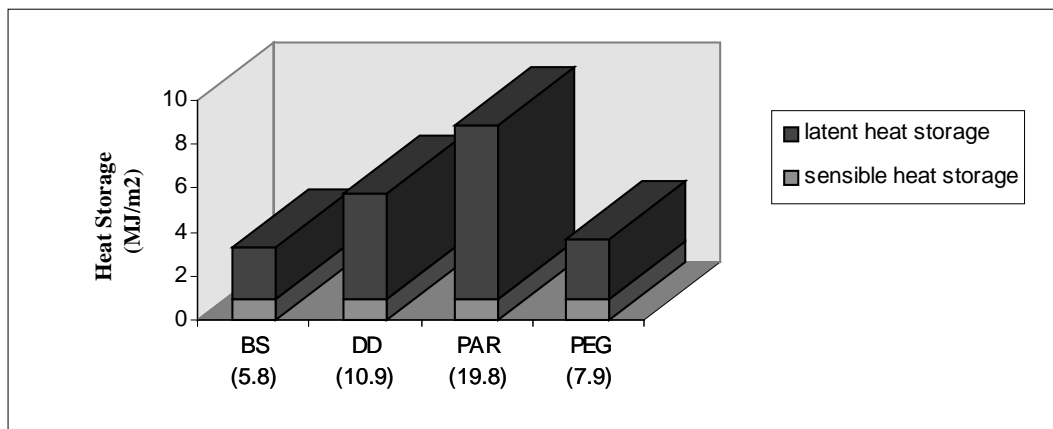
Source: Feldman et al. 1993



**Figure 6:** Potential heat storage values of autoclaved concrete block showing added heat storage capacity of impregnated PCM.

BS= butyl stearate; DD = dodecanol; PAR = paraffin; PEG = polyethylene glycol. Figures in parentheses show the weight of PCM as a % of dry concrete weight.

Source: Feldman *et al.* 1993



**Figure 7:** Potential heat storage values of pumice concrete block showing added heat storage capacity of impregnated PCM.

BS= butyl stearate; DD = dodecanol; PAR = paraffin; PEG = polyethylene glycol. Figures in parentheses show the weight of PCM as a % of dry concrete weight.

Source: Feldman *et al.* 1993

## THERMAL COMFORT

As regards the performance of PCM construction materials in terms of thermal comfort, an experimental and numerical simulation study was fielded by Athientis *et al.* (1997) to this end. It was shown that the utilisation of PCM gypsum board in a passive solar building may reduce the maximum room resultant temperature by 4°C during the daytime and can reduce the heating load at night significantly. The experimental results showed a significant reduction in the room radiant temperature due to the absorption of solar gains in the PCM board. It can therefore be concluded that PCM applied over a large surface area in a passive solar building is effective for storage of solar gains and improvement of thermal comfort.

## ECONOMIC VIABILITY

Peippo *et al.* (1991) conducted studies into the economic viability of using PCM wallboard in two different climatic zones for the reduction of heating energy consumption:

Helsinki, Finland (60°N) and Madison, Wisconsin (43°N). From a UK point of view, it is more appropriate to look at the analysis relating to the latter, more moderate climate.

**Table 6:** *Yearly weather conditions in Helsinki (Finland) and Madison (Wisconsin, USA) for the winter period (October-March)*

	<b>Helsinki</b>	<b>Madison</b>
Latitude (°N)	60	43
Insolation on a horizontal surface (GJ/m <sup>2</sup> )	3.4	4.9
Insolation on a vertical surface (GJ/m <sup>2</sup> )	3.1	3.6
Winter insolation on a vertical surface (GJ/m <sup>2</sup> )	0.9	1.6
Average ambient temperature (°C)	4.7	8.0

*Source: Athientis et al. 1997*

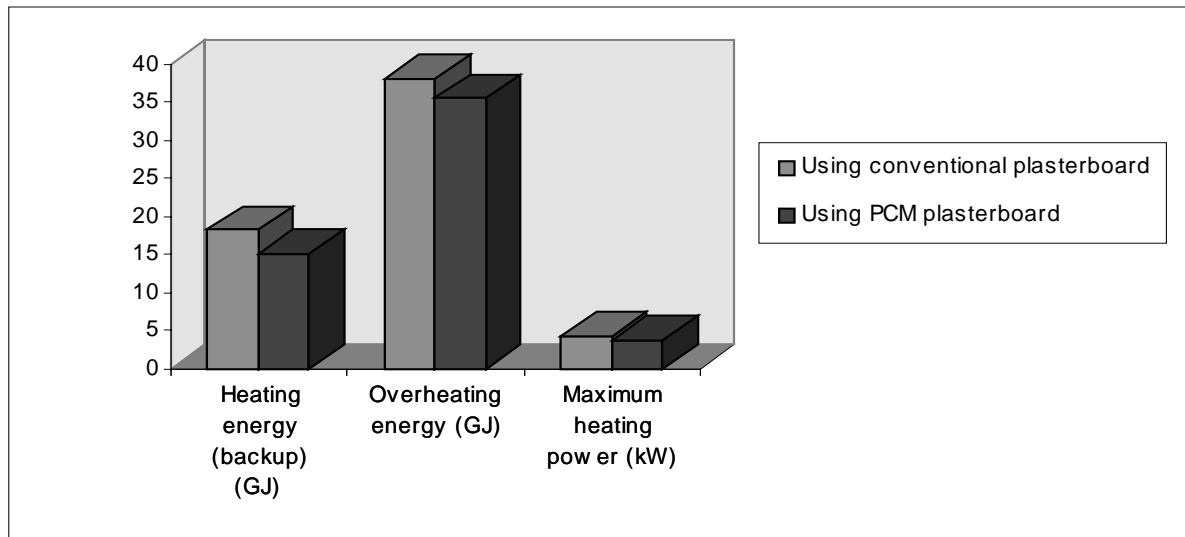
Numerical simulations based on a finite difference approach and using hourly weather data were carried out over the heating period (October-March) for the two climates. The PCM wallboard considered was equivalent to about 30% fatty-acid-impregnated plasterboard at a thickness of 13mm. As the temperature control strategy plays a key role in building energy management, two different approaches were chosen for analysis, minimum energy (18 – 26°C) and maximum comfort (19 – 21°C).

The conclusions obtained from the study relating to Madison, Wisconsin were as follows:

- The proposed PCM wall reduces the auxiliary heating energy by approximately 3 GJ per annum or 15%. The same relative reduction occurs also in the maximum auxiliary heating power.
- Interestingly, the energy savings are slightly larger with maximum comfort temperature control. If a large temperature swing is allowed, the storage reduces the actual temperature fluctuation typically by 1 - 2°C.

- Climatic conditions (available solar insolation levels) significantly effect the performance of the storage as is evident from the fact that larger savings were experienced in Madison.
- As could be expected, when more conventional construction with less insulation is used, the energy savings may be increased significantly.

With the present cost of heat of about \$15/GJ, the annual benefit from the PCM storage is about \$60 in Madison. The material cost of industrial grade fatty acids is about \$1.5/kg. For the 110 m<sup>2</sup> PCM surface required in this test structure, this cost adds up to \$600 for the 400 kg of fatty acids used. The resulting simple payback period is 10 years in Madison and twice that in Helsinki, making the investment just barely profitable in terms of direct energy savings only. If the reduction in heating system power with a value of \$500/kW is also accounted for, the storage could then be regarded as economically attractive. Further optimisation of the structure should only improve these rather conservative estimates. Important, but not easily expressed in terms of an economic benefit is the increased thermal comfort that PCM storage may provide for energy efficient solar buildings.



**Figure 8:** *Annual energy balance of the test structure in Madison which uses PCM plasterboard compared with an identical structure using conventional plasterboard*

Source: Athientis et al. 1997

## SUMMARY

It has been seen that the impregnation of PCMs into porous building materials is a concept which merits continuing consideration. The development of energy-storing building materials holds great promise as a solution to the ongoing quest for energy conservation, and also to improving the indoor environment in which people work and live. With respect to the energy savings obtainable, annual direct energy savings of the order of 15% may be expected in a thermally moderate environment. This modest estimate does not take into consideration the indirect energy savings, caused by reduced equipment cycling and the downsizing of equipment, which results. In terms of thermal comfort, it is envisaged that the indoor environment of a building which uses PCM construction materials will have significantly lower mean radiant temperatures and more thermal stability, having less likelihood of overheating and fewer temperature fluctuations.

Out of the broad range of phase change materials available, butyl stearate and paraffin appear to be the most effective. Readily available fatty acids are also regarded as very suitable materials for this application since the melting point of fatty acid mixtures can be easily adjusted to suit the particular application. These organic PCMs have been found to be very suitable for impregnation into porous building materials, of which plasterboard and concrete block appear as the most appropriate and effective PCM absorbers.

Immersion of wallboard and concrete block provide a simple means of incorporating PCM which has the advantage of allowing building products from stock to be converted to PCM building materials. On the other hand, direct incorporation of PCM during the mixing process is obviously the simplest and cheapest method of production which requires modest additions to the mixing equipment. Existing manufacturing facilities may be easily adapted to handle either process.

## **APPLICATIONS**

In general, PCMs have many and varied uses, from electronics to ceramics. With respect to building design, PCMs have the following main areas of application:

- (i) As the thermal storage medium in a thermal energy store (TES). The TES may be used to take advantage of off-peak electricity and is not unlike an ice store in principle. These systems may be used to store heat or coolth, and may be coupled with an air based solar collector and a heat pump.
- (ii) In a Latent Heat Storage Panel, as devised by Fuanca *et al.* and Hauer *et al.*, 1978. The panel consists of an acrylic sheet followed by a polyhedral wall, an air cavity and heavy insulation. In the air cavity, an array of tubes is placed containing a PCM (in this case sodium sulphate decahydrate or Glauber's salt). The panel was used for

heating by absorption of solar irradiation during the day, and retrieval of this heat at night by placing heavy insulation between the panel and the outside atmosphere, and then passing air between the tubes and into the room. This is a good example of early developments in PCM technology, which was focused on inorganic PCMs and therefore required that the PCM was physically separate from the fabric of the building.

- (iii) As the heat transfer medium in a radiant floor heating system. Barrio *et al.* (1991) investigated the use of solid-solid organic PCM neopentylglycol (NPG) for this purpose. This consists of a panel containing the PCM, placed horizontally on top of an electrical resistance heater. Other products are currently on the market comprising encapsulated mineral salt PCM for use beneath the screed layer in an under-floor heating system.
- (iv) By the impregnation of organic PCM into porous construction materials to increase the thermal mass and to develop a direct gain storage element capable of diurnal heat energy storage. Many different building materials have been investigated as potential hosts for PCM including timber, porous gypsum wallboard, wood-particle board, concrete, brick, rock and aggregates.

The focus of this paper has been on this latter application, and as such will be discussed here. It is difficult at present to cite specific examples of the use of PCM-building elements, but it is possible to arrive at a theoretical scenario in which PCM-building materials are used.

Passive architecture can be interpreted as architecture which tempers the external environment, creating a relatively stable environment internally. Therefore, a passively designed office building incorporating such features as exposed ceiling and floor slabs and a facility for night cooling

would maximize the energy-storing capabilities of the PCM-fabric elements. This is achieved firstly by increasing the absorption surface area for during the day and by increasing the thermal storage capacity by mechanical or natural ventilation with cool air at night. The building has large areas of openable windows to all facades. It is located in a moderate climate, with large amounts of sunshine, and is well insulated which enables it to retain absorbed heat and maintain a steady temperature indoors.

The chosen PCM will begin to absorb heat in a latent manner as the resultant temperature in the space exceeds 25 °C. The heat absorbed by the PCM wallboard/ceiling slab/floor slab comes from the occupants, computers and lighting inside. Other heat gains derived from solar gain through glazing are also absorbed, although this is already at a minimum due to appropriate external shading. When the heat gain to the space has reached its peak, say in the afternoon, the PCM has been fully charged, *i.e.* it has completely melted and cannot absorb any more heat through latent means. It will now continue to absorb heat, but as a sensible heat storage medium. In effect, this means that the resultant indoor temperature has not risen significantly above 25 °C despite continuous heat gain.

In the evening, after the building has been vacated and begins to cool down, the PCM-fabric elements will discharge all the heat they had gained during the day. The discharge period is enhanced by natural ventilation during the night via automatic vents. This ensures that, by the following morning, the PCM has completely re-solidified and has fully expelled all the heat energy it had stored both latently and sensibly.

Excessive heat gains during the summer are dealt with using a natural or mixed-mode ventilation

system. In winter, minimal heating will be necessary to maintain a comfortable temperature. Taken a stage further, energy storing building materials could become a feature of autonomous, or “free running” buildings, which require little or no mechanical plant to maintain a comfortable indoor environment.

## THE FUTURE

In the present market situation, an investment in PCM storage in the building fabric may not be economically justified if only energy savings were accounted for. Therefore, the effect of improved thermal comfort should also be taken into consideration. In order that more interest would be shown in the use of PCM building elements, it is obvious that more work should be done on enhancing and improving the economic viability of such an investment. This could be done by further refinement of the PCM-building material combination to improve its thermal characteristics, or by further investigation into building materials which may be used as PCM absorbers. Another area which needs further research is that of the flame propagation and fume generation of energy-storing building materials and the establishment of a fire rating. Finally, it appears that there is a shortfall in the amount and scope of long-term durability testing of these materials, and this is an area which needs attention before the idea fully takes hold.

## APPENDIX A

*Theoretical (i) and measured (m) eutectic points (T) and heats of fusion ( $\Delta H$ ) for selected carboxylic acids and their mixtures*

Mixture (fatty acids)	x (wt.%)	$T_i$ (°C)	$T_m$ (°C)	$T_i - T_m$ (°C)	$\Delta H_m$ (kJ/kg)
Capric-lauric	61.5-38.5	18.5	19.1	-0.6	132

Capric-myristic	73.5-26.5	23.5	21.4	2.1	152
Capric-palmitic	75.2-24.8	24.6	22.1	2.5	153
Capric-stearic	86.6-13.4	27.6	26.8	0.8	160
Capric	100	31.5	30.1	1.4	158
Lauric-myristic	62.6-37.4	31.8	32.6	-0.8	156
Lauric-palmitic	64.0-36.0	33.0	32.8	0.2	165
Lauric-stearic	75.5-24.5	37.0	37.3	-0.3	171
Myristic-palmitic	51.0-49.0	40.0	39.8	0.2	174
Lauric	100	42.0-44.0	41.3	0.7 to 2.7	179
Myristic-stearic	65.7-34.3	45.1	44.0	1.1	181
Palmitic-stearic	64.9-35.1	46.7	50.4	-3.7	179
Myristic	100	54.0	52.1	1.9	190
Palmitic	100	63.0	54.1	8.9	183
Stearic	100	70.0	64.5	5.5	196

Source: Peippo et al. 1991

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