Increasing thermal mass in lightweight dwellings using phase change materials – a literature review

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Abstract

The number of houses of lightweight timber or steel frame construction being built over recent years has increased significantly. These buildings have low thermal mass and may be subject to large temperature fluctuations and particular overheating during the summer and this problem is set to get worse with the changing climate. Researchers have been investigating the use of PCMs (phase change materials) for improving thermal mass in lightweight buildings and found them to be effective. However, until recently, various problems have prevented products from entering the commercial market. In the last few years microencapsulated paraffin PCMs have been developed that are easy to use and building products are now available to buy containing these materials.

Although there is significant academic research relating to PCMs for thermal buffering in lightweight buildings, there is a lack of field trials and case studies of PCMs in buildings in use. There is also a lack of information and guidance for designers and building owners. Recommendations are made for further research to discover the viability of uptake for PCM wallboard technology and the provision of information about the benefits of the products to the public and industry professionals.

Keywords: Phase change material; thermal mass; latent heat storage; microencapsulation; passive cooling; lightweight construction; thermal inertia; energy efficient housing.

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1.0 INTRODUCTION

It is generally accepted that thermal mass contributes to energy efficiency in buildings reducing the requirement for air conditioning in summer and reducing heating fuel consumption in winter. This paper reviews research relating to the use of PCMs (phase change materials) in providing artificial thermal mass to buildings that are of lightweight construction. PCMs can be used for thermal storage due to the latent heat absorbed during melting and emissions during solidification.

1.1 Background

When new housing is being constructed, there has been increasing pressure for the design to include the use of construction materials with low embodied energy and from renewable sources. As a result of this, there has been a significant increase in the quantity of timber framed housing being built in the UK over the past few years. UK Timber Frame Association (UKTFA) figures show that timber frame market share of new build housing has risen from 8.4% in 1998 to 24.9% in 2008 (UKTFA, 2009). Timber frame is considered to be sustainable and environmentally friendly as the structure has a low embodied energy and comes from renewable sources. However, these types of construction are considerably more lightweight than modern traditional built brick and block housing and although newly constructed housing is well insulated, internal temperatures can fluctuate. This can lead to a lack of thermal comfort, particularly in summer; resulting in increased use of electricity for comfort cooling in the form of electric fans or air conditioning.

As a result of climate change, there is considerable and growing interest in methods for reducing carbon emissions in the built environment. Research into the use of PCMs as thermal storage has been ongoing for several decades for applications such as storage of solar thermal energy for power generation, solar water heating and thermal storage for heat pumps among others. Recently there has been a renewed interest in the use of PCMs as thermal buffers to promote energy efficiency and occupier comfort in buildings.

1.2 The significance of thermal mass

Thermal mass is, in simple terms, the ability of a material to store heat; this ability depends on the density, specific heat capacity and thermal conductivity of the material. In buildings, materials such as concrete and masonry are good providers of thermal mass; these materials absorb heat from the air as the ambient temperature rises and release heat into the air as the ambient temperature falls. The thermal mass acts as a buffer so that temperatures inside the building rise and fall more slowly than external temperatures and maximum and minimum temperatures are less extreme. This reduces the amount of heating or cooling required and therefore reduces fuel consumption as well as CO_2 emissions. To be effective the surface of the material must be sufficiently exposed to allow heat transfer. The larger the amount of these materials that are exposed to the internal environment in a building, the greater the benefits in thermal mass. Hence it may be observed that one of the most comfortable places on a hot day is a cathedral with its thick exposed stone walls. Dry lining and suspended ceilings separate the thermal mass from the internal atmosphere of the building considerably reducing the beneficial effect (Braham et al, 2001).

The value of thermal mass in dwellings has been demonstrated by Hacker et al (2008) who carried out a study using computer modelling of a typical two bedroom semi detached house with four levels of thermal mass as follows:

1. Lightweight – timber frame with brickwork external skin.
2. Mediumweight – traditional brick and block exterior wall, with lightweight timber upper floor and partitions and drylining throughout.
3. Medium-heavy – as mediumweight but with blockwork partitions and precast concrete hollow-core upper floor with drylining throughout.

4. Heavy – dense concrete block inner leaf and partitions, with precast concrete hollow-core upper floor and first floor ceiling. Fair faced finish to inner leaf and partitions as well as stone tiles to the solid concrete ground floor.

The most lightweight version of the house is typical modern timber frame construction and the medium weight version is currently the most common form of new-build house construction. The medium-heavy weight house is less common and the heavyweight house is not typical.

The four variants of the house were modelled to be identical apart from the parts of the construction contributing the thermal mass and the model included occupancy of two adults and a small child over a projected lifecycle of 100 years. The climate for the 100 year period was modelled for climate change using data from the UKCIP02 medium-high emissions scenario Tyndall Centre for Climate Change Research at UEA (Hulme et al, 2002; cited by Hacker et al, 2008).

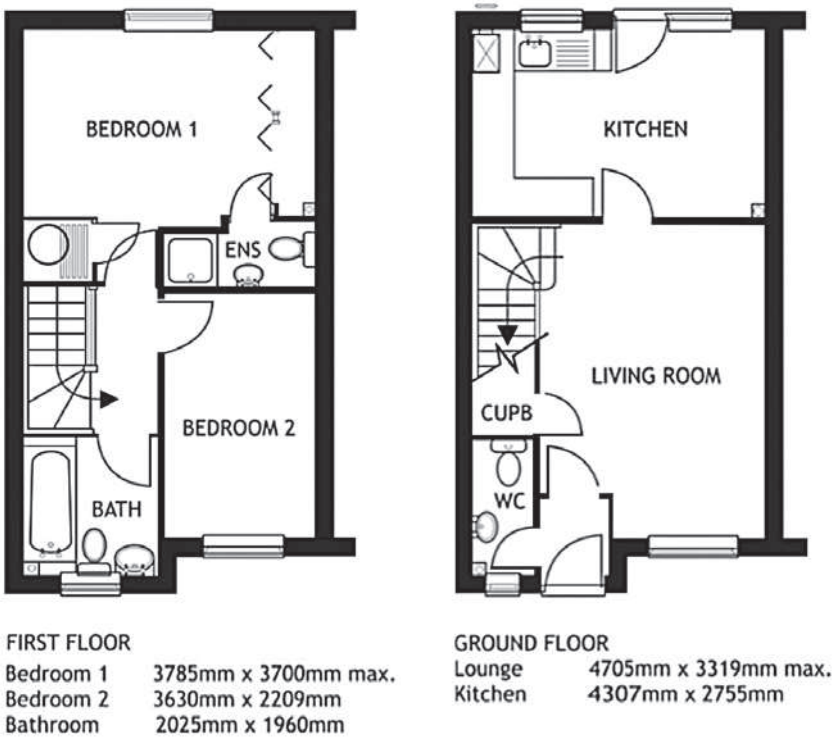

Figure 1: The case study house (Hacker et al, 2008).

The study found that the heavier weight cases all showed reduced operational CO_2 emissions. The largest benefits were found for the heaviest weight considered over the lifetime of the building which included savings in air conditioning which was installed in the model following overheating in 3 consecutive years. The initial carbon emissions (ECO_2) was greater in all the heavier weight cases, but by a relatively small amount in the context of the total lifecycle emissions. No clear "optimum" weight was found, with the heaviest weight case showing best performance over the 100 year lifecycle (Hacker et al, 2008).

A similar exercise was carried out for 13 different building scenarios including offices and schools as well as dwellings in London, Manchester and Edinburgh in research carried out for CIBSE (CIBSE, 2005).

This showed similar benefits of thermal mass, but demonstrated the importance of sufficient ventilation to prevent build up of heat over time in summer causing heavyweight elements to lose their passive cooling potential.

Holford and Wood (2007) also show the benefits of thermal mass in buildings and how it can be exploited in naturally ventilated buildings to achieve energy efficiency. They review other research into the subject including several case studies before assessing the factors that limit thermal buffering and describing their mathematical model for predicting the effects.

Guidance for designers and other professionals is provided by the BRE in digests 454 parts 1 and 2 (2001) on thermal mass in office buildings and also Information Paper IP6/01 *Modelling the performance of thermal mass* (2001). Although these publications are aimed at the design of offices, much of the information is also applicable to dwellings.

1.3 Phase Change Materials (PCMs)

Thermal mass as described above requires dense materials with sufficient specific heat capacity and conductivity to store sensible heat. Clearly, it is not practicable to install large amounts of concrete or masonry into existing lightweight buildings in order to improve their thermal mass; the solution to this problem would need to be unobtrusive and easy to install. Much research has been done in recent years into the possibility of using PCMs to store latent heat and improve the thermal mass of lightweight buildings.

Kuznik et al (2008) give a good explanation of how PCMs store and release latent heat:

> *"An interesting feature is that they can store latent heat energy, as well as sensible energy. As the temperature increases, the material changes phase from a solid to a liquid. As this physical reaction is endothermic, the PCM absorbs heat. Similarly, when the temperature decreases, the material changes from a liquid to a solid. As this reaction is exothermic, the PCM releases heat."*

There is a wide variety of applications that may potentially use PCMs for latent heat storage and as a result, a great amount of research has been carried out over the years. Zalba et al (2003) review research into many applications including solar power plants; thermal protection of food; thermal comfort in vehicles, engine cooling and spacecraft thermal systems.

There is also a variety of materials that can be used as PCMs depending on the application. Sharma et al (2009) classify PCMs into organic, inorganic and eutectic materials. Voelker et al (2008) identify paraffins (organic) and salt hydrates (inorganic) as being suitable for use in building materials for thermal buffering.

2.0 REVIEW OF THE RESEARCH

The scope of this study is recent research carried out from 2000 to 2009 concerning building materials that can be used to upgrade the thermal performance of existing buildings. The research generally falls into three categories – literature reviews, research using theoretical models and research using experimental data. Some of the papers cover at least two categories.

Zalba et al (2003) give an idea of the scale of the available literature on PCMs for thermal energy storage generally, listing over 230 references. Sharma et al (2009) also provide a general review of PCM materials and applications but includes a substantial review of building applications. Khudair and Farid (2004) and Pasupathy et al (2008) limit their review to PCMs used for energy conservation in building applications which include use in concrete blocks, plasters solar and underfloor heating and PCM filled double glazed windows as well as in wallboards.

2.1 Suitable PCM Materials

Khudair and Farid (2004) explain that PCMs suitable for building applications should have a high heat of fusion, good thermal conductivity, high specific heat capacity, small volume change, be non corrosive,

non-toxic, exhibit little or no decomposition or supercooling and have a phase transition close to human comfort temperature. They also list 9 potentially suitable materials including hydrated salts, paraffins and fatty acids. Pasupathy et al (2008) describe the development of PCMs for heating and cooling of buildings explaining that salt hydrates are cheap and abundantly available, but they have several disadvantages and that researchers now label them "limited utility PCMs". Farid et al (2004) state that salt hydrates are "*corrosive to most metals and suffer from decomposition and supercooling, which can effect their phase change* properties". However, despite these problems, there is one product using salt hydrates as PCM that has recently come onto the market, "Delta-cool 24". Paraffin waxes seem to be the PCM of choice for those researching PCM wallboards as although they are more expensive than salt hydrates, they are more stable, non-corrosive and do not have problems with supercooling.

2.2 Encapsulation

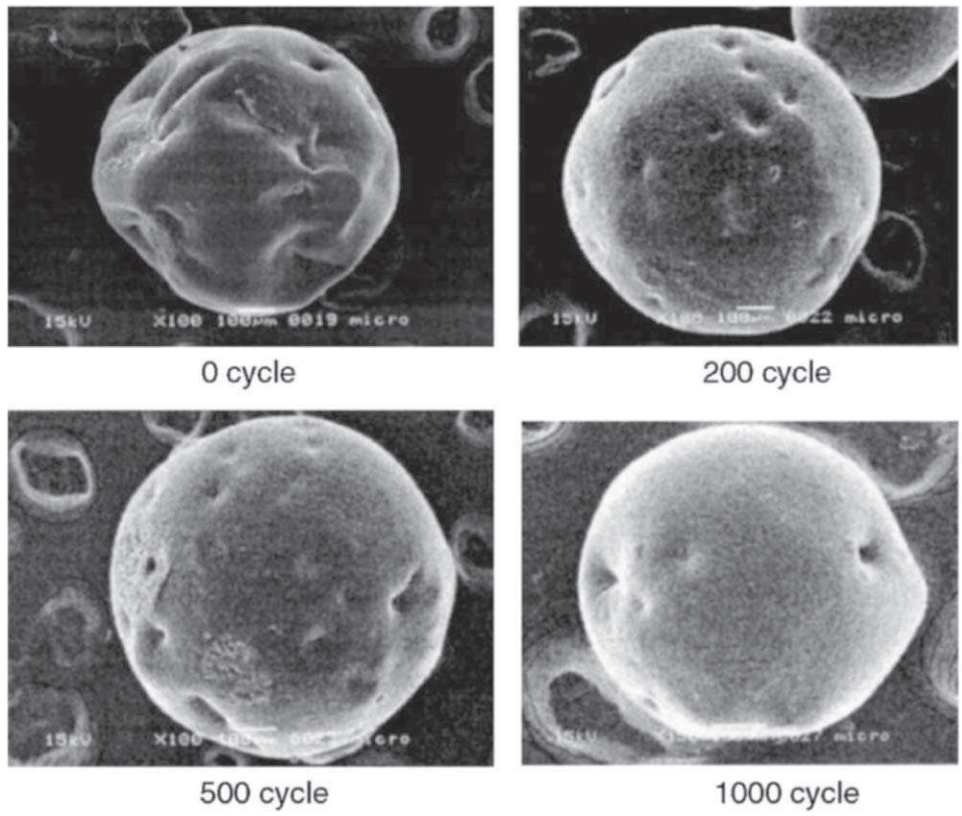

Figure 2: Microencapsulated paraffin profile evaluated by scanning electron microscope at different thermal cycles (Hawlander, Uddin and Zhu, 2002, cited by Khudair and Farid, 2004)

Although the theory of PCMs storing latent heat as temperatures rise and releasing it as temperatures fall is very promising, the research conducted over the years has not resulted in commercially viable products until relatively recently. Schossig et al (2005) explain that since the 1970s several researchers have tried incorporating PCMs into building materials by immersion processes or macro-capsules. Where PCMs

were not encapsulated, there were problems of leakage and interaction between the PCM and the matrix material. Macro-capsules had several disadvantages including the necessity to protect them from damage, the work required on site, the expense of incorporating them into a building and inefficient heat transfer. This last problem is explained well by Pasupathy et al (2008): "*When it was time to regain the heat from the liquid phase, the PCM solidified around the edges and prevented effective heat transfer*".

Khudair et al (2004) and Pasupathy et al (2008) both review research which shows the beneficial effects of micro-encapsulation of paraffin waxes for use in building products. Micro-encapsulation is where small spherical or rod-shaped particles are enclosed in a thin polymeric film. The very small size of these capsules overcomes the problems of inefficient heat transfer. These micro-capsules can be incorporated simply and economically into construction materials (Pasupathy et al, 2008). Khudair and Farid (2004) cite research by Hawlader, Uddin and Zhu (2002) showing the resilience of the microcapsules, as shown in Figure 2, and also research by Hawlader, Uddin and Khin (2002) demonstrating that they have high energy storage and release capacity.

2.3 PCM Plaster and Wallboards

Various researchers have carried out theoretical and experimental analysis of PCMs for use in walls. Darkwa (1999), Neeper (2000) and Richardson and Woods (2008) analyse numerical models that indicate benefits but require experimental validation. Richardson and Woods (2008) conclude that construction materials containing PCMs can be considerably thinner and lighter than the equivalent thermal mass without PCMs. Darkwa and Kim (2005) tested and compared gypsum plasterboard with randomly

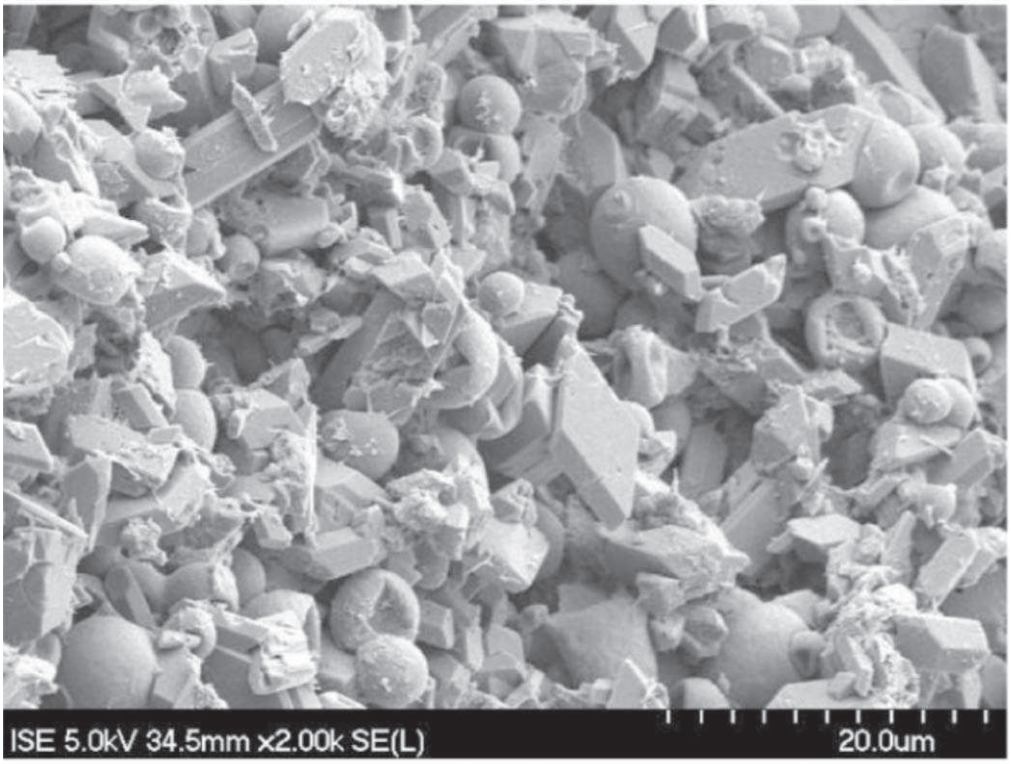

Figure 3: Scanning electron microscope image of the spherical PCM micro-capsules homogenously dispersed between the gypsum plaster crystals (Schossig et al, 2005).

Figure 4: Fraunhofer ISE façade testing facility. The test offices are the two rooms at the left hand end of the building (Schossig et al, 2005).

distributed microencapsulated paraffin PCM with a laminated board and found the laminated board to perform significantly better. Carbonari et al (2006) developed a theoretical model which was then experimentally validated for PCM sandwich panels for use in prefabricated buildings. The PCM used was eutectic salts, sealed into rigid plastic containers and inserted into sandwich panels. They found that their model was accurate and the PCM panels performed well.

Schossig et al (2005) undertook a project over 5 years funded by the German government, which is probably the most comprehensive study undertaken so far. Initially, they simulated the thermal performance of a typical lightweight office using a numerical model with PCM mixed with the interior plaster. Samples of plaster were then tested under various conditions to validate the model.

Then unlike most of the other researchers who have carried out similar work, they tested the material in full sized offices. Unfortunately, when real offices were tested, it was not possible to make adequate comparisons because of the different behaviour of the occupants, so they built 2 full sized test rooms with lightweight construction for test and control as shown in Figure 4. They tested 2 different PCM products each for a period of a year with identical conditions in the PCM and control rooms.

Figure 5 shows that the number of hours above 26°C in the PCM room is significantly reduced. An interesting result is that during one 3 week period during the project, the temperature in the non-PCM test room exceeded 28°C for more than 50 hours, whereas the temperature in the PCM room was only above 28°C for *about 5 hours*.

Schossig et al (2005) found that microencapsulated PCMs have the advantages of easy application, good heat transfer and no need for protection against destruction. The results showed potential for reduced cooling demand and increased thermal comfort in lightweight buildings. However, they stressed the importance of sufficient night ventilation to ensure the stored heat is fully discharged over night. They do not state what the PCM material is, although it implied that it is a paraffin and they do give the melting range of 24 – 26°C.

Voelker et al (2008) carried out an investigation with two test rooms and investigated microencapsulated paraffin PCM incorporated into wall plaster and later the addition of tubes below ceiling level filled with salt hydrate PCM. Both PCMs were found to be effective, however their beneficial effects were negated after a few hot days when the heat was not fully discharged over night. In common with Shossig et al (2005) they contend that this can be avoided by effective night ventilation.

Kuznik, Virgone and Noel (2008) tested a sample of material and using a numerical model and specially adapted software called *CODYMUR*, investigated the optimal thickness of the wallboard material. The wallboard was a flexible sheet containing 60% microencapsulated paraffin PCM and their reference case consisted of a single wall consisting of timber, insulation PCM board and plaster facing. They found that the optimal thickness for this PCM material is 10mm.

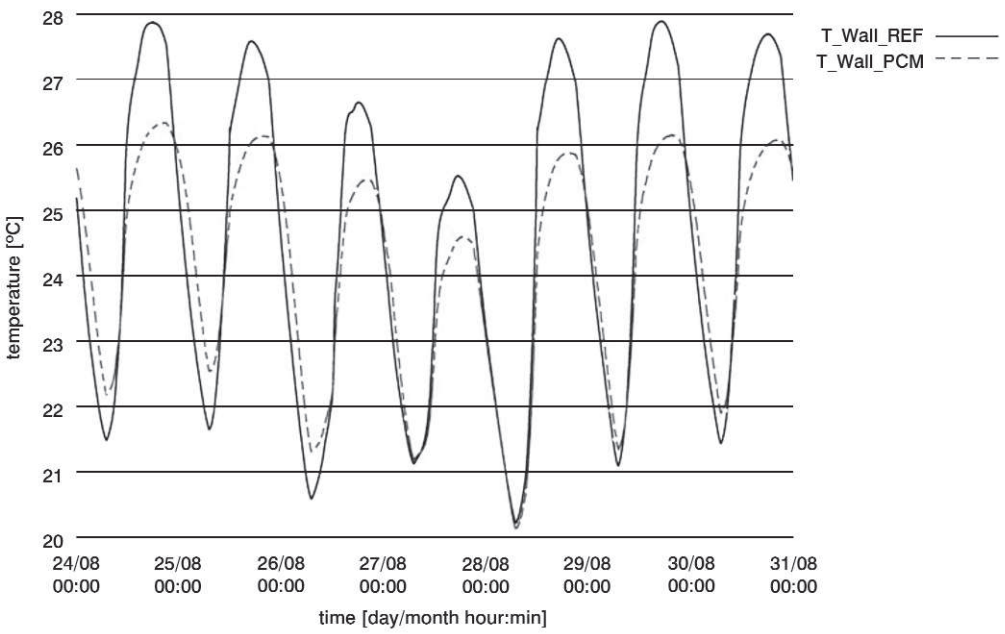

Figure 5: Results from the testing by Schossig et al (2005) show the difference between test room with PCM plaster (dashed line) and with non-PCM plaster (solid line). The lines indicated wall temperatures in the two test rooms with night ventilation and solar shading.

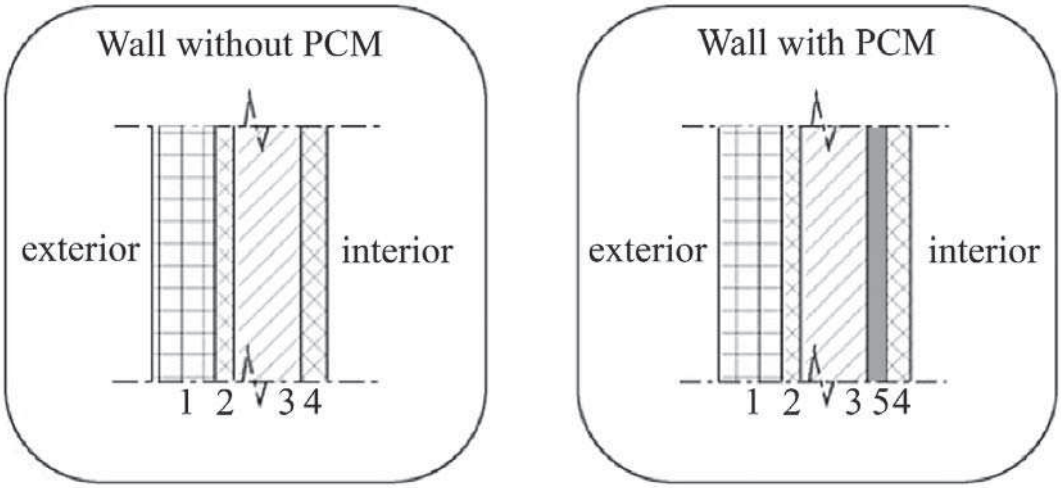

Figure 6: Wall compositions in Kuznik, Virgone and Roux's experimental test rooms. 1 – 50mm wood plate; 2 – 10mm plaster; 3 – 50mm polystyrene; 4 – 13mm plaster and 5 – 5mm PCM

Kuznik, Virgone and Roux (2008) investigated the efficacy of the same wallboard material using an experimental test room with simulated summer conditions including solar simulator consisting of spotlights shining through a glazed façade. The other 3 walls of the room had walls with PCM behind plaster (control without PCM). The construction of the test room walls is shown in Figure 6.

They found that the air temperature fluctuated between 18.9°C and 36.9°C in the control and 19.8°C and 32.8°C in the PCM room. Thus temperature fluctuations were reduced by 4.7°C in the PCM room.

3.0 INDUSTRY ENGAGEMENT

Although research into the performance of PCM wall linings has been ongoing for many years in various countries, the results have not been encouraging enough for products to be produced commercially until recently. BASF Construction Chemicals introduced *Micronal* microcapsules of wax PCM in 2004 for use in the manufacturing of building products such as plasterboards or floor screeds (BASF, 2004) and this product was incorporated into a commercially available plasterboard for the first time in 2005 (BASF, 2005). It is also available in a wet applied gypsum plaster called *Maxit Clima*. BASF claim that "*a 3cm layer of Maxit Clima plaster corresponds approximately to the thermal mass of an 8 cm-thick concrete wall, a 13 cm-thick plasterboard, or a 29 cm-thick lightweight brick wall*". Schossig et al (2005) state that a commercially available product has been installed into two office buildings shown in figure 7 – this is presumed to be Maxit Clima as the pictures are acknowledged to "Maxit".

DuPont launched a board product, *Energain*, in December 2006 also containing paraffin wax (Kucharek, 2007) although this product comes in the form of aluminium laminated panels that are installed behind plasterboard dry lining rather than having PCMs within the plasterboard itself. Both Du Pont *Energain* and BASF *Smartboard* have been used in UK projects reported recently in the media. *Energain* was used in "Crossways" a house designed by the architect Hawkes, reported in Building Magazine and featured in an episode of Channel 4's Grand Designs shown in February 2009 (Kennett, 2009). BASF Smartboard was used at Hamond's High School in Norwich in place of concrete slabs in autumn 2008 and reported in Building Sustainable Design Magazine (Jansen, 2009). These media reports will have raised the profile of the products in the industry.

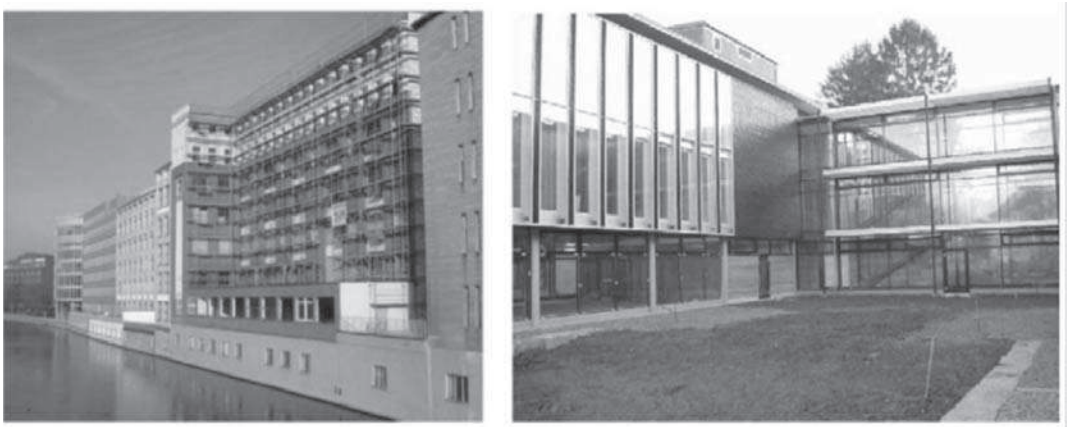

Figure 7: Office buildings in Germany where PCM plaster has been installed (Schossig et al, 2005 "Source: Maxit").

There is also a salt hydrate product available called "Delta-cool 24" which comes in various forms of macroencapsulation including pouches that are designed to sit on top of suspended ceiling tiles and are marketed for use in office or commercial properties.

Figure 8: Delta-cool 24 comes in various forms of encapsulation (Dörken, Delta-Cool 24 brochure, no date).

From the research reviewed here, it is not possible to say whether the development of commercially available products is due to the innovations in technology such as micro-encapsulation of PCMs suitable for incorporating into wallboards or whether it is due to the social and economic influences of carbon emissions and climate change. At the moment there seems to be a lack of data to show the rate of uptake of these products.

3.1 Barriers and Enablers to use of PCM Products

As with many innovative materials, PCM wall and ceiling linings are expensive and this is probably the major barrier to their use at present. Kucharek (2007) quotes Marco Schmidt of BASF admitting that their plasterboard lining is 10 times more expensive than ordinary plasterboard and Jansen (2009) states that DuPont *Energain* costs approximately £50/m^2. Clearly, these would be a significant cost to upgrade a building were they to be retrofitted. However, Jansen (2009) writing in *Building Sustainable Design*, quotes Dr Jonathan Gray of White Young Green explaining that problems of crane access and scheduling made the use of Energain with lightweight construction cheaper than concrete panels for the Hamond's High School project.

Another possible barrier is that despite the wealth of academic research and testing of PCM materials, there have not yet been many buildings that have demonstrably benefitted from it and clients may be averse to taking the risk or being "guinea pigs" for new and apparently untried technology, particularly in the current economic climate. The manufacturers of the materials have persuasive examples on their websites and in their product literature of how thermal mass can be improved and energy costs reduced. However, prospective users would have to look at the websites or access the product literature to see this information. A question remains as to whether potential users of this technology are likely to be directed to the information. As an example, there is no advice on the use of PCM technology to improve thermal mass on the Energy Saving Trust website, including their pages for housing professionals (http://www.energysavingtrust.org.uk/). Clearly, lack of knowledge of the technology would be a barrier to its use and further research is needed to investigate industry knowledge and how to improve dissemination of information.

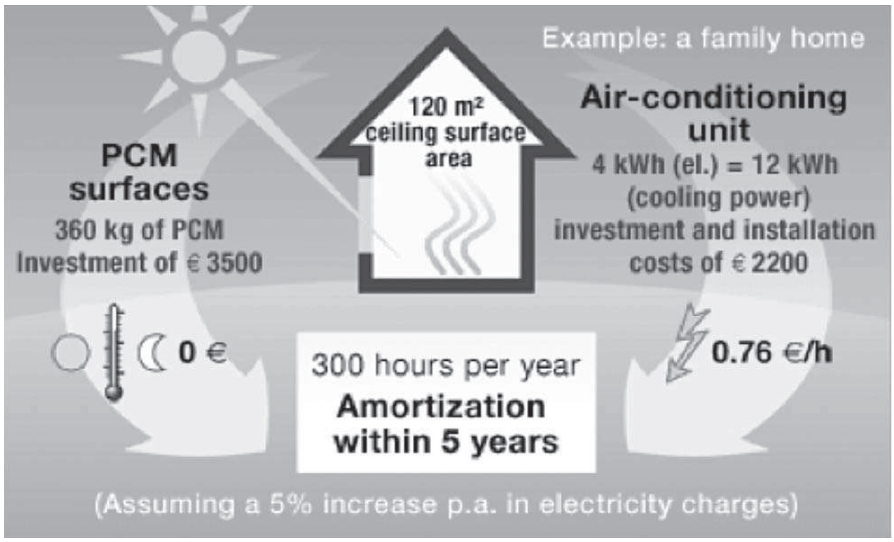

Figure 9: Illustration from Micronal PCM Smartboard product literature and BASF website (with permission from BASF, no date)

DuPont give details of testing of their *Energain* boards on their website (DuPont, 2008). This testing involved two test rooms, one with the product and one without, tested over 3 seasons in France in association with EDF France (Electricité de France). They claim that this was a "*unique real-life test – the longest and most scientific test ever conducted with a phase change material*". However, this claim would be difficult to substantiate as Schossig et al (2005) carried out extensive testing of 2 PCM materials for a full year each as part of a 5 year study in Germany. DuPont's research does not seem to have been published in any academic journals although it does bear some resemblance to the research carried out by Kuznik, Virgone and Roux (2008). The publication of information relating to this research on the website may be helpful in influencing people to install the product in their homes.

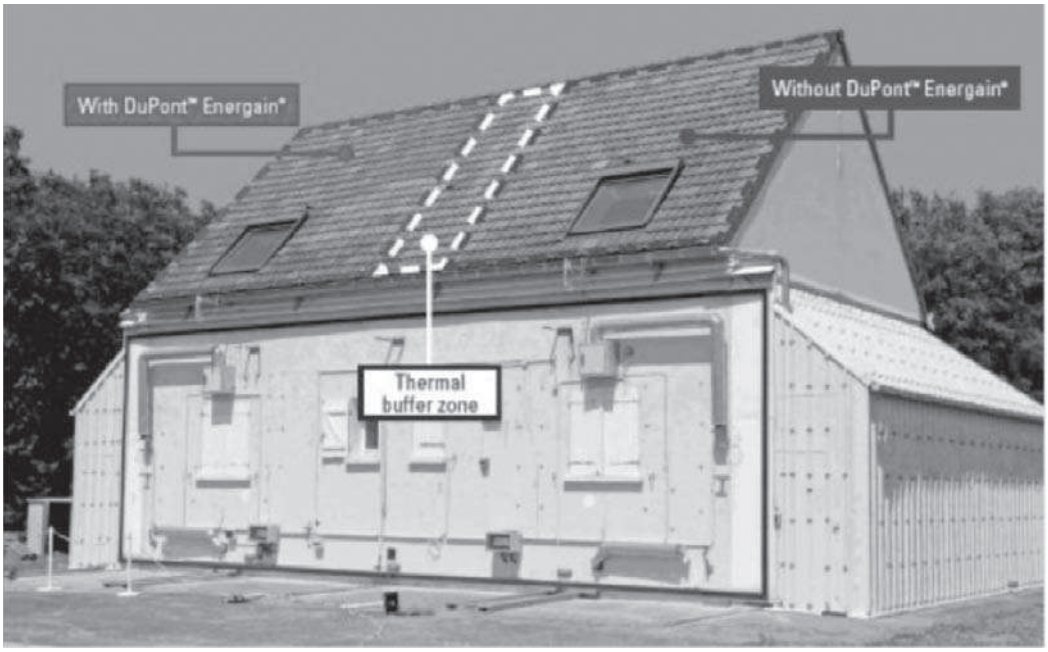

Figure 10: DuPont's test house in France (DuPont, 2008)

The provision of software models to help designers predict the benefits of using PCM materials and the requirements for heating and cooling in a building containing these materials will also encourage their use. Several of the researchers have developed models that have been validated through testing including *CODYMUR* (Kuznic, Virgone and Noel, 2008) and found it to be effective. DuPont are now marketing the software "*CoDyBa*" for use with their *Energain* product.

3.2 Use in existing masonry buildings with retrofit internal insulation.

The Department of Communities and Loocal Government document "Review of the Sustainability of Existing Buildings – the energy efficiency of dwellings – initial analysis" (November 2006) sets out the problem of carbon emissions and the existing housing stock:

> *"With Government's commitment to increase housing supply, around two-thirds of homes standing in 2050 are likely to have been built before 2005. New build represents only approximately 1% of the total stock each year. Building Regulations have raised energy efficiency standards of new homes significantly in recent years – current (April 2006) standards are 40%*

> *higher than for properties built in 2002; 70% more than in 1990. So most of the existing stock, and a significant proportion of those that will still exist in 2050, were constructed to lower, often much lower, standards than new build today. The existing stock, therefore, accounts for the great majority of carbon emissions from dwellings, both in terms of their lower energy efficiency and their numbers."*

There is thus a clear need for measures to improve the carbon emissions from existing dwellings in order to achieve the Government's targets over the coming years. There are various methods of improving the thermal performance of the fabric of a building in order to improve energy efficiency, including retrofit insulation, draught-proofing and replacement of windows with double or triple glazing. Upgrading the thermal performance of walls in older housing with solid walls requires either externally applied insulation systems which cause a significant change in appearance and usually require specially designed replacement windows and doors or internal drylining systems which isolate the thermal mass of the building.

There does however seem to be a lack of research into the effect of internal retrofit insulation on the thermal comfort of occupants, particularly in summer and whether the use of PCM lining would be effective in reducing carbon emissions in these cases.

4.0 CONCLUSION AND RECOMMENDATIONS

Much research has been carried out over the years into the use of PCMs to increase the thermal inertia of lightweight buildings and recently research has shown the potential benefits of PCM wall boards using microencapsulated paraffins. Some research has also shown potential benefits of salt hydrate PCMs. It is clear that these materials can be effective in increasing energy efficiency, particularly by reducing cooling loads in summer, providing sufficient ventilation is afforded at night to allow the heat built up during the day to fully discharge overnight.

Numerical models and software such as *CODYMUR* (Kuznic, Virgone and Noel, 2008) have been developed that can be useful to designers in predicting the performance of the materials in use and these may help to influence their uptake.

Although the aim of these materials is to provide benefits in the form of reduced energy consumption, reduced carbon emissions and improved thermal comfort, it would appear that there is very little guidance to inform people or influence their decisions to use the products, other than marketing by the manufacturers of the products.

The following recommendations would help to address these issues:

- Further research including large scale case studies of buildings in use, their energy consumption and thermal comfort of occupants with and without PCM products.
- Research on existing lightweight domestic buildings and attitudes of their owners towards upgrading thermal mass.
- Improvement in the advice available to homeowners and Registered Social Landlords regarding PCM products available and their benefits.
- The provision of more information to professionals regarding PCM products and their benefits.
- Research should be carried out into the performance of traditional masonry buildings with retrofit internal insulation to discover if the isolation of the thermal mass from the internal atmosphere causes similar temperature fluctuations to those found in lightweight buildings. Experimental data could be gathered to ascertain whether PCM products could be helpful or be economically viable over the life cycle of the buildings.

GLOSSARY

Eutectic – describing a mixture of substances having the lowest freezing point of all possible mixtures of those substances.

Macroencapsulation – encapsulation of PCM material in larger containers more than 1mm in diameter

Microencapsulation – encapsulation of PCM material in small capsules

PCM – Phase Change Material: A material that stores and releases latent heat during change of state between solid – liquid or liquid – gas.

Sensible heat – The heat absorbed or evolved by a substance during a change of temperature that is not accompanied by a change of state.

Supercooling – where a material remains liquid below its freezing point. Some materials require a seed crystal or nucleus around which a crystal structure will form and without this, solidification may fail to take place at freezing point. Supercooling can be avoided by adding nucleating agents.

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