AN INNOVATIVE WALL-LINING FOR BUILDINGS INCORPORATING PHASE CHANGE MATERIALS

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Abstract

The use of thermal energy storage in buildings is well understood but contemporary buildings with highly insulated, lightweight construction have low thermal inertia. This causes them to respond rapidly to external temperature changes, which results in significant internal temperature fluctuations and overheating. This research addresses this problem by developing a thermal interactive wall-lining through the inclusion of phase change materials.

Phase change materials (PCMs) not only absorb sensible heat but also absorb and release latent heat during phase transition. This research set out to determine if it is possible to locate phase change materials on the surface of a room and if they can effectively improve the thermal performance of a room.

Using the scientific method the suitability of different types of PCMs was investigated for inclusion within a vinyl matrix. Experiments evaluated the maximum quantity of PCM loading and thermal analysis identified the largest potential heat storage capacity for the phase change wall-lining. Following successful laboratory experiments a pilot scale prototype phase change wall-lining was manufactured and tested. The test involved an experiment comprising two thermally matched chambers to evaluate the thermal performance of the phase change wall-lining in a controlled environment. The results demonstrated the phase change wall-lining can reduce internal temperatures by more than 2°C and delay the time taken to reach extreme temperatures. The effect of different air flow rates on the ability to charge and discharge the phase change wall-lining have been evaluated to identify the required operating criteria for use in buildings.

This research has developed an innovative phase change wall-lining that reduces internal peak temperatures, minimises diurnal temperature fluctuations by storing excess heat and improves the thermal comfort. The outcomes provide a greater understanding of the interaction between air and PCMs when located on the surface of a room, and indicate that such materials have the potential to improve thermal performance of new and existing buildings.

Statement of Candidates Contribution

This research arose out of a Teaching Company Scheme (TCS), now known as Knowledge Transfer Partnership (KTP) scheme, between the University of Brighton and OMNOVA Wallcoverings (UK) Ltd to develop wallcoverings embedded with phase change materials which began in 2002.

KTP is a government funded scheme that provides up to 67% grant funding to enable companies to engage in knowledge transfer with universities. A KTP is a partnership between a company and a graduate who work together to deliver a strategic project for the business which the company would be unable to do without the knowledge and expertise provided by the university (Brighton, 2014).

The collaborators on the project were:

Allan Marshall	Product Innovations Director, OMNOVA
Dr Terry Corner	Senior Project Leader (Supervisor), OMNOVA
Steve Mitchell	Product Development Manager (colleague), OMNOVA
Prof. Andrew Miller	Professor of Building Sustainability (Supervisor), University of Brighton
Dr Kenneth Ip	Principal Lecturer (Supervisor), University of Brighton

All of the research reported in this thesis was undertaken by the author, with the exception of the development of the phase change wall-lining formulation which was undertaken by Steve Mitchell of OMNOVA, as referenced in Chapter 4. The preliminary lab investigations were undertaken by the author of this thesis, which are reported in Patent WO 2003/085346 A1. Subsequent formulation work was undertaken by Steve Mitchell due to his 25 years' experience developing formulations at OMNOVA. The set-up of the Environmental Chambers was undertaken by the author of this research, with assistance from the technical staff at the University, and all the testing in the chambers was completed by the author.

OMNOVA were involved in the research from 2002 to 2006 inclusive as a funding partner. This was the period of the product development, trial manufacture and testing in the environmental chambers. The subsequent period from 2006 to 2013 was spent undertaking the data analysis and writing up of the PhD thesis (part-time).

During the research a number of research papers were presented at key conferences as shown in Table 1.1.

Publication	***Contribution***
Ip, K., Miller, A., Corner, T., Dyball, D L., (2003) Development of Phase Change Thermal Storage Wallcoverings In Buildings. The CIB 2003 International Conference on Smart and Sustainable Built Environment Brisbane, Australia.	Ip, K., - lead author & presenter of paper at conference Dyball, D.L. – undertook the market research and dynamic thermal modelling reported in the paper
Ip, K., Miller, A., Corner, T., Dyball, D L., (2005) Development of Phase Change Thermal Storage Wallcoverings In Buildings. In: Smart and Sustainable Built Environment. Editors: J. Yang, P. Brandon and A. C. Sidwell, Blackwell Publishers Pages: 95-102.	Ip, K., - lead author & presenter of paper at conference Dyball, D.L. – undertook the market research and dynamic thermal modelling reported in the paper
Dyball, D L., Ip, K., Miller, A., Corner, T., (2005) Development of Phase Change Wall-linings to Enhance Thermal Storage of Buildings. The World Sustainable Buildings Conference (SB05). Tokyo, Japan.	Dyball, D.L. – Lead author & presenter of own research
Ip, K., Dyball, D L., Miller, A., (2008) Thermal behaviour of a wall-lining containing phase change materials. World Sustainable Building Conference Melbourne, Australia.	Ip, K., - presenter of paper at conference Dyball, D.L. – author & all own research

Table 1.1 List of publications and contributions of co-authors

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I would like thank a number of people for their support and guidance throughout my research. Thank you to Dr Terry Corner and Allan Marshall of OMNOVA for starting me on this journey. Special thanks to Dr Kenneth Ip and Professor Andrew Miller who have patiently guided me through my research and have provided valuable support and technical knowledge. Special thanks also to Professor Neil Ravenscroft who has given a lot of time and support to help me tell my story.

I would like to thank Dr David Pope for his technical assistance with setting up the environmental chambers and a special thank you to Pete Mathers for his time, technical expertise and banter when setting up and establishing the environmental chambers.

Thank you to my family for their love and support, especially to my Dad for inspiring my ambition.

Finally, and importantly, a massive thank you to my husband for his tremendous support and to our beautiful daughters for understanding when mummy needs to study.

Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed:

Date:

Nomenclature

Symbol	Designation	Units
a_m	fraction melted	
a_r	fraction reacted	
c	specific heat capacity	kJ/kgK
$\dot{c}_p$	average specific heat capacity	kJ/kgK
c_{pa}	specific heat capacity of air	kJ/kgK
Δh_m	heat of fusion per unit mass	kJ/kg
Δh_r	heat of reaction per unit mass	kJ/kg
m	mass of material	kg
$\dot{m}$	mass flow rate of air	kg/s
Q	quantity of heat transferred	W
t	time	seconds
T	temperature	°C
ΔT	temperature difference	°C
ΔT_s	average surface temperature	°C
U	internal energy	kJ
W	work done	J

Subscripts	
C	control chamber
e	exhaust air
l	liquid
LHC	latent heat capacity
m	melt
s	solid
SHC	specific heat capacity
T	test chamber
v	volume
w-l	wall-lining

1 Background

Buildings are a shelter providing protection from the external climate conditions. Originally buildings were constructed using local materials and considered the local climate. This is known as vernacular architecture, where the governing principle was that the buildings should reflect on and respond to their environment. Vernacular architecture is regionally distinct. For example in the north of England many villages were constructed of stone, as this was their local resource. This stone masonry construction provided protection from the harsh weather and maintained a stable internal temperature throughout the year. Building design in hotter climates would be adapted to suit their conditions. For example Wind Tower houses in the Middle East were constructed using thick adobe construction (high thermal mass) to limit heat transfer through the building envelope. The cooling of the interior is assisted with a wind tower ventilation system that captures the wind and draws it down, distributing it through the house.

The type of materials used in the building fabric affects its thermal performance and can have a profound effect on the energy demand for heating and cooling in a building and also on the temperature of internal surfaces (radiant temperature) which is important for occupant thermal comfort.

Thermal comfort is affected by a number of variables, including air temperature, radiation (radiant temperature), humidity, air flow, the activity being undertaken and the clothing of individual. As thermal comfort is affected by radiant temperature, the surface temperature of materials in a room will affect the radiant temperature.

During the industrial revolution came technological advances, including methods for heating our buildings. In the industrial era there was a focus on economic growth which resulted in the rapid growth of urban populations. Constructing buildings became an economic consideration, selecting materials and method of construction with a lower capital cost, rather than having a long term vision for the building. Therefore the building envelope became a skin separating the indoor space from the external environment and mechanical systems would be used to condition the indoor space. Vernacular architecture was no longer considered as energy to power the technology driven modern buildings was readily available.

The energy crisis in the 1970's made people realise fossil fuel is a finite resource and the rate of consumption could no longer continue. Legislation was introduced in the UK, via the Building Regulations, to make new buildings more energy efficient. In the UK, heating is the largest energy use in buildings. Therefore the UK Building Regulations set standards to limit the heat loss from buildings and these standards are continually improving. To achieve these standards requires high levels of insulation in buildings. Insulation acts as a barrier, preventing heat from escaping from a building through the walls, floor and roof. This is advantageous in winter as it reduces the amount of heating required in a building, however this also prevents heat build-up from escaping during the summer, and therefore mechanical cooling and air-conditioning is becoming more commonplace.

With rising fuel costs and the need to reduce carbon dioxide (CO_2) emissions alternative solutions needs to be found. It is no longer enough to design a building based upon its aesthetics and space requirements. A building should be designed to be capable of reacting to the environment, adjusting with the internal and external environmental conditions. The building fabric should be able to exchange heat with the internal environment providing thermal stability. The heating, ventilation and air-conditioning (HVAC) should be the secondary method of controlling the internal thermal conditions.

The ability for the building fabric to exchange heat with the internal environment to improve the air temperature and thermal comfort is known as the thermal performance of the building. All materials are capable of this in the form of sensible heat storage although materials with high thermal mass such as traditional stone masonry can exchange larger amount of sensible heat.

Phase change materials (PCMs) are a thermal energy technology that can be used in buildings to significantly increase the thermal mass as they are able to store both sensible and latent heat unlike conventional building materials such as concrete. Concrete has a sensible heat storage capacity of 1.0 kJ/kgK, whereas an inorganic phase change material such as calcium chloride hexahydrate can store up to 193 kJ/kg during phase transition.

Significant research has been underway for almost 30 years to develop methods of incorporating phase change materials into traditional building products to increase the thermal storage capacity of buildings. Much of the initial research took place in the United States of America, following the fuel crisis of the early 1970's, with the aim to reduce energy demand for heating and cooling residential buildings. By incorporating phase change materials into buildings it was demonstrated that peak temperatures could be reduced and/or the peak load for a heating or cooling system could be delayed by a number of hours and shifted out of the occupied period of a building or into an off-peak time period. This could reduce the fuel costs for a home owner or business and also reduce the peak demand on the national grid, provide greater stability in energy supply.

The aim of this research is to utilise technology to improve the thermal performance of buildings to facilitate a building to react and respond to its thermal environment, rather than require energy systems to control internal conditions. This will provide thermal energy storage in modern contemporary buildings that is able to thermally respond to the environmental conditions in a similar way to traditional vernacular architecture.

2 Literature Review

Modern, lightweight buildings lack the thermal inertia necessary to be able to exchange heat with the internal environment. This lack of thermal performance causes high peak temperatures and rapid temperature fluctuations to occur within a building resulting in poor thermal comfort conditions and energy systems being required to condition the internal spaces.

Technological advances have facilitated buildings with improved winter thermal performance by minimising heat loss and technology has advanced the energy efficiency of the building services systems that deliver heating, cooling and ventilation to buildings throughout the year which reduces the energy used. Available technology has not been adequately adopted to improve the summertime thermal performance of buildings. Thermally efficient lightweight buildings incur summertime overheating and require energy consuming cooling systems to improve the thermal comfort. Thermal energy storage technology needs to be applied in lightweight buildings to improve their thermal performance and provide thermal comfort conditions for the building occupants during the warmer periods.

2.1 Underpinning Theory

Heat is the thermal form of energy, and heat transfer takes place when a temperature difference exists within a medium or between two different media (Dincer, 2002). Heat always requires a temperature difference and the greater the temperature difference the greater the heat transfer. The units for heat are joules (J) or kilojoules (kJ).

There are essentially three methods of storing thermal energy: sensible, latent and thermochemical heat storage. Each method differs in the heat storage capacity per unit weight or volume of storage medium, in the time-temperature history of the material during heat storage and recovery, and in the relative development of the technology at the given time.

2.1.1 Sensible Heat Storage

Sensible heat storage enables thermal energy to be stored by changing the temperature of the storage medium. The amount of heat stored depends on the specific heat capacity of the medium, the temperature change and the amount of storage material (Lane, 1983).

The sensible heat stored in a material is based on the first law of thermodynamics. The first law of thermodynamics can be defined as the law of conservation of energy and states that in a closed system, energy can be neither created nor destroyed. For a change of state from an initial state (1) to a final state (2), with a constant amount of matter, Dincer and Rosen (2002) have expressed it as:

$$Q_{1\text{-}2} = (U_2 - U_1) + W_{1\text{-}2}$$

Where the internal energy:

$$(U_2 - U_1) = mc_v(T_2 - T_1).$$

Where:

Q = *quantity of heat transferred (kJ)*
U = *internal energy (kJ)*
W = *work done (kJ)*
m = *mass of material (kg)*
c_v = *specific heat capacity of material (kJ/kgK)*
ΔT = *temperature difference (°C)*

An important consequence is that the internal energy change will be independent of the thermodynamic path, e.g. heat transfer and work (Dincer, 2002).

The thermal mass of buildings is commonly used for sensible heat storage to modify internal thermal comfort conditions. The most common material for substantial sensible heat storage is concrete which has a sensible heat storage capacity of 1.0 kJ/kgK. A cathedral is a classic example of a building that utilises sensible heat storage as the interior always remains cool during summer months.

2.1.2 Latent Heat Storage

As a solid material melts it changes phase from a solid to liquid. As this phase change takes place the material absorbs a certain amount of heat, referred to as melt enthalpy. Despite the amount of heat being absorbed by the material, the temperature of the material remains relatively constant, whilst the phase change takes place. The heat that has been absorbed by the material is called ‘latent heat’. When the phase change process is reversed, from liquid to solid, the latent heat is released, again at an almost constant temperature. Figure 2.1 illustrates this process.

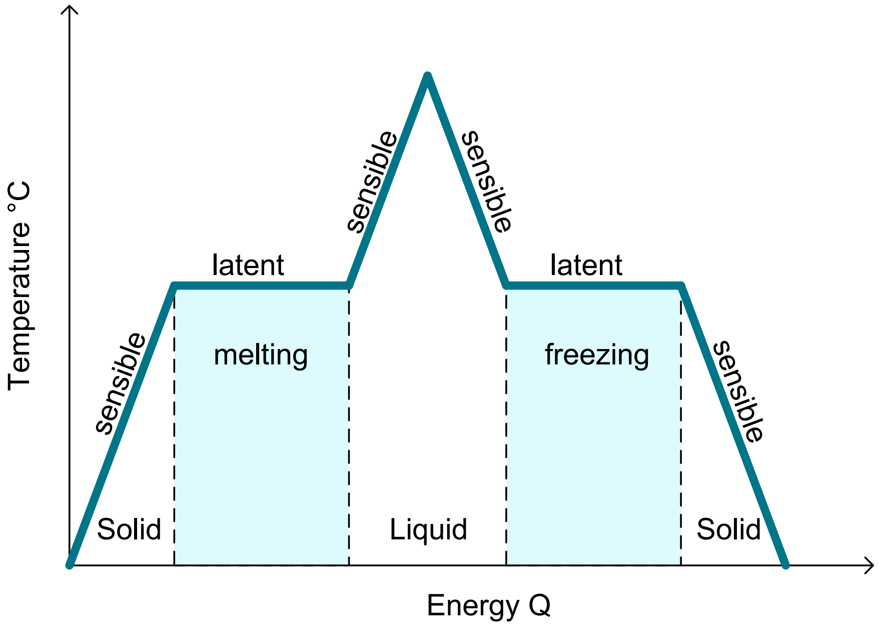

Figure 2.1 Latent heat storage process

As illustrated in Figure 2.1 the latent heat storage process also makes some use of sensible heat capacity. The equation given by Lane (1983) that represents this process is:

$$Q = m\,[a_m \Delta h_m + \dot{c}_{ps}\,(T_m - T_i) + \dot{c}_{pl}\,(T_2 - T_m)]$$

Where:

Q = *quantity of heat transferred (kJ)*
m = *mass of material (kg)*
a_m = *fraction melted*
Δh_m = *heat of fusion per unit mass (kJ/kg)*
$\dot{c}_{ps}$ = *average specific heat capacity of material when solid (kJ/kgK)*
$\dot{c}_{pl}$ = *average specific heat capacity of material when liquid (kJ/kgK)*

T_m = *melt temperature (°C)*
T_i = *initial temperature (°C)*
T_2 = *final temperature (°C)*

Phase change materials (PCMs) are materials that absorb and release latent heat during phase transition and could be used for an energy storage application in buildings. Phase change materials can store up to two hundred times more heat during the phase transition than concrete, the typical solution for thermal energy storage in buildings.

2.1.3 Thermochemical Heat Storage

Thermochemical heat storage systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. For this the heat storage capacity is dependent upon the amount of storage material, the endothermic heat or reaction and the extent of conversion. According to Lane (1983) this is represented by the following formula:

$$Q = a_r m \Delta h_r$$

Where:

Q = *quantity of heat transferred (kJ)*
a_r = *fraction reacted*
m = *mass of material (kg)*
Δh_r = *heat of reaction per unit mass (kJ/kg)*

This type of heat storage is not suitable for a building application due to the requirement for physical intervention to break the molecular bonds.

2.2 Using Thermal Mass for Thermal Energy Storage in Buildings

Traditional vernacular building methods used construction materials that contain high thermal mass and are referred to as having a 'heavyweight construction'. Buildings containing higher thermal mass have a higher thermal admittance value which is a measure of their ability to store and exchange heat with the environment, measured in W/m^2K. Lightweight buildings have a low admittance value and are unable to store heat – the heat either transmits through the lightweight material or the insulation prevents the heat transfer, trapping the heat within the building causing internal temperatures to increase.

Table 2.1 gives examples of typical building constructions and their associated thermal admittance values. The table demonstrates that concrete has a high thermal mass compared with a timber frame construction, whilst having high levels of insulation (140mm) the lack of thermal mass will prevent the building fabric absorbing internal heat gains.

Thermal mass can be used to stabilise internal temperatures from external heat gains and provide a high admittance for absorbing internal heat derived from people, equipment and artificial lighting. Typically buildings utilising thermal mass can reduce peak temperatures by 3°C as they perform like a heat sink, soaking up the internal heat gains.

Examples of how thermal mass can be utilised for passive (no energy input required) and active (requires fan assistance) thermal storage are presented in the following pages.

Wall Construction	***Admittance W/m²K***
Precast concrete sandwich panel: *19mm render, 80mm dense concrete, 50mm EPS insulation, 100mm dense concrete, 13mm dense plaster*	5.48
Brick/dense concrete block cavity walls: *105mm brick, EPS insulation, 100mm dense concrete, 13mm dense plaster*	5.75
Brick & block cavity wall: *105mm brick, 25mm airspace, 25mm EPS insulation, 100mm lightweight aggregate concrete block, 13mm dense plaster*	2.95
Timber frame wall: *105mm brick, 50mm airspace, 19mm plywood sheathing, 140mm stud with 140mm mineral fibre wool insulation, 13mm plasterboard*	0.86
Internal Partitions	
Block partition: *13mm lightweight plaster, 100mm lightweight concrete block, 13mm lightweight plaster*	2.09
Timber studding: *12mm plasterboard, timber studs, 12mm plasterboard*	0.69
Internal Floor/Ceiling Constructions	
Dense cast concrete: *100mm dense cast concrete*	6.57
Cast concrete: 50mm screed, *150mm cast concrete, 13mm dense plaster*	5.09
Timber flooring: *19mm timber flooring or chipboard on 100mm joists, 12mm plasterboard ceiling*	1.89

Table 2.1 Examples of admittance values for different building constructions (Sualles, 2005)

2.2.1 Thermal Mass with Night-cooling

Thermal mass of a building can be utilised using exposed concrete soffits, natural ventilation and night-cooling. The exposed concrete soffits absorb internal heat gains during the day and cool night air is brought into the building to remove the stored heat from the structure, see Figure 2.2. This provides a cooler, fresher building for the following day and importantly enables the thermal mass to once again absorb internal heat gains.

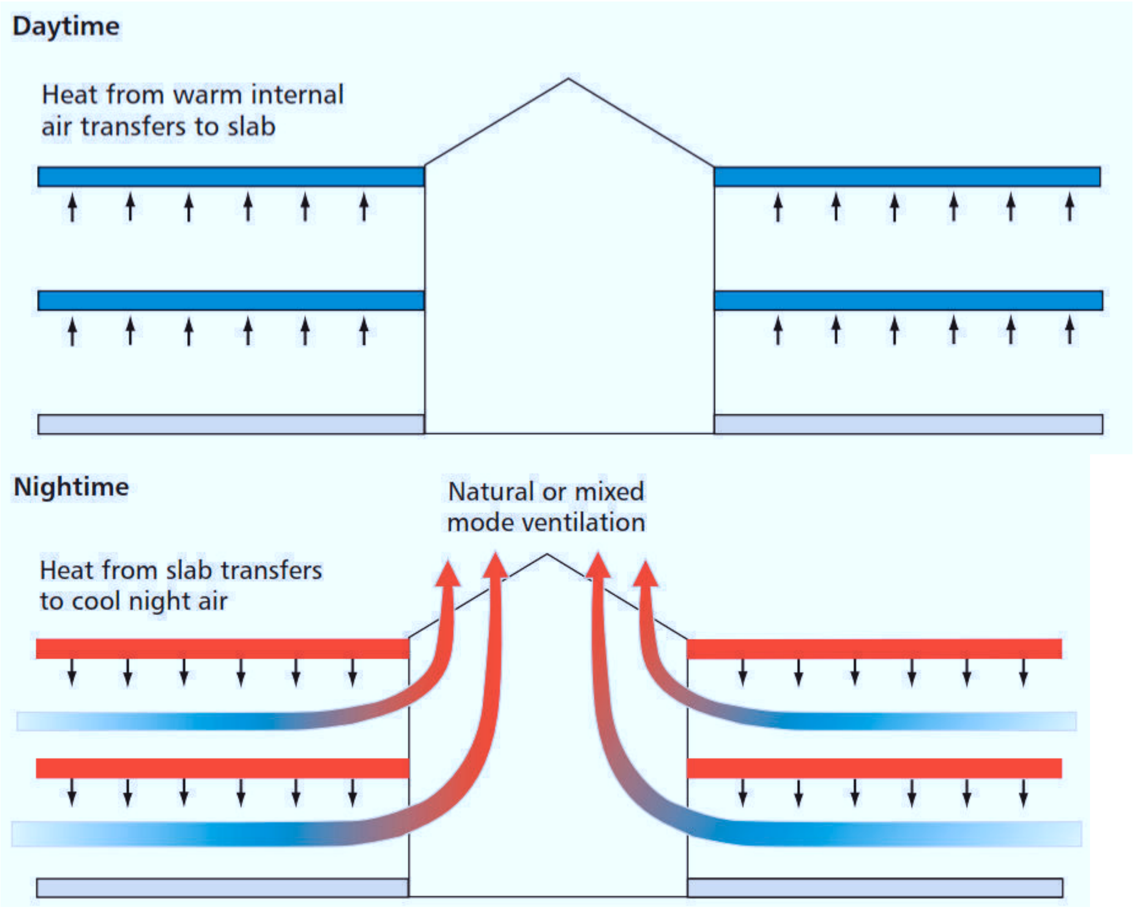

Figure 2.2 **Illustration of principle of utilising thermal mass with natural ventilation and night-cooling (CIBSE, 2005)**

2.2.2 <u>TermoDeck</u>

TermoDeck is a simple ventilation system that provides passive heating and cooling by utilising the thermal mass of the building, as shown in Figure 2.3. The air passes through hollow core slabs which heat or cool the air due to passive heat exchange with the concrete. The concrete slabs are able to absorb over 85% of the heat or ‘coolness’ in the supply air and the heat transfer from the slab to room is mainly via radiant effect with the remainder supplied by the air into the rooms (Braham et al., 2001). The advantage of the radiant heat transfer is this directly heats/cool the occupants rather than the air around them, increasing their thermal comfort. The system is able to supply 100% fresh air during occupied periods keeping the building fresh and occupants alert (Tarmac, 2006).

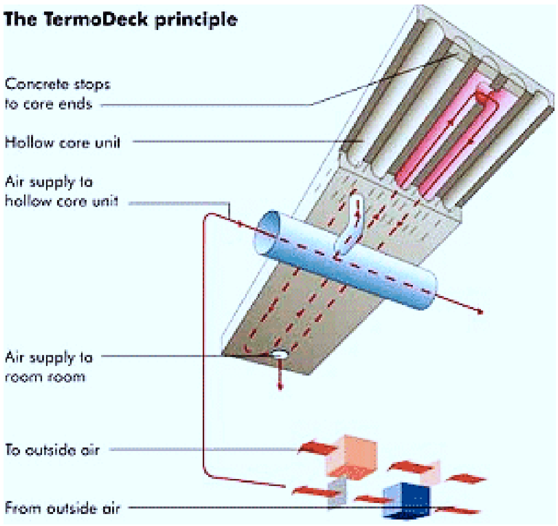

Figure 2.3 Schematic of hollow-core TermoDeck system (Tarmac, 2003)

The TermoDeck system was installed in the Elizabeth Fry Building at University of East Anglia, a successful low energy building. The TermoDeck system maintained comfort temperatures of around 22°C all year round and the energy consumption attributable to the fans, pumps and controls used in the TermoDeck system was just 18 kWh/m^2/yr, considerably less than a traditional mechanical cooling system (PROBE, 1998).

2.2.3 CoolDeck

The CoolDeck system developed by Oscar Faber (now AECOM) utilises the thermal capacity of concrete ceiling and floor voids. Utilising thermal mass in buildings is often difficult due to the poor rates of heat transfer from the air to the mass. The CoolDeck concept is to attach narrow sheeting elements to the slab surface in a void and circulate air, using a low energy fan, through the narrow paths between the slab and sheeting, Figure 2.4. The turbulent airflow created through the paths enhances the heat transfer between the slab surface and the circulating air.

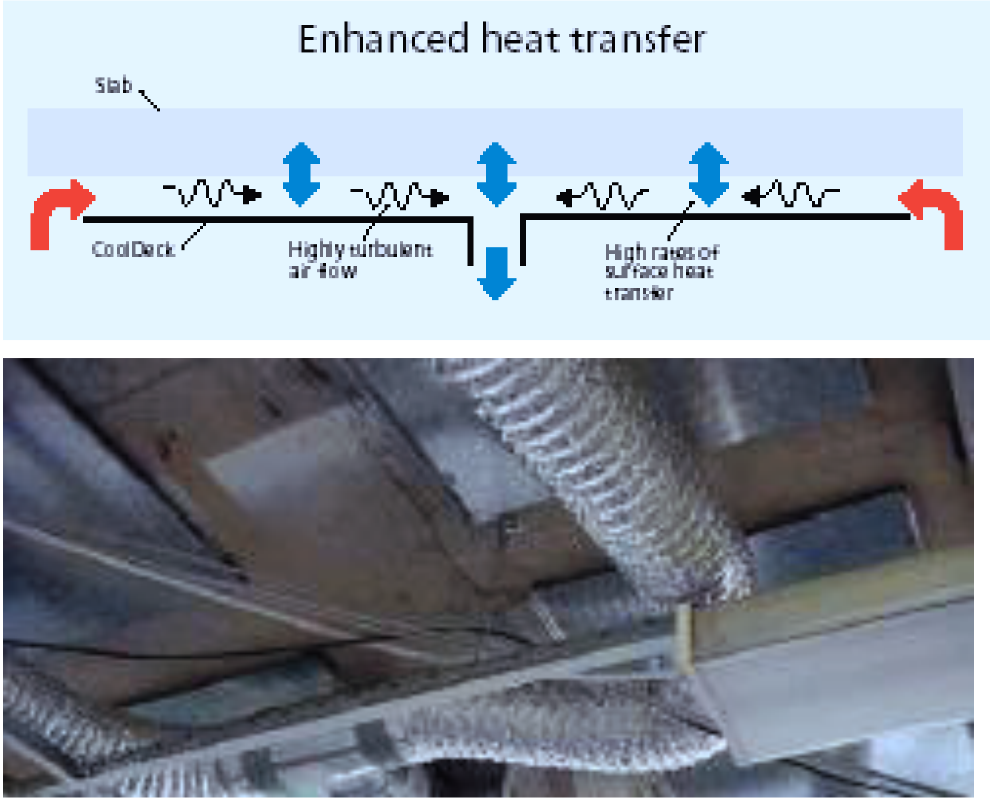

Figure 2.4 **Schematic of heat transfer concept of CoolDeck (upper) and photo of installation with ductwork in ceiling void of Stevenage Borough Council offices (lower) (FaberMaunsell, 2003)**

CoolDeck was installed in the offices of Stevenage Borough Council as a solution for summertime overheating. The design target set was to increase the surface convection heat transfer coefficient of the concrete soffit to 15 W/m^2K (approximately 5 times the typical un-enhanced value) to provide effective storage of night-cooling introduced at normal ventilation rates. The system, in conjunction with solar blinds and reduced internal gains, successfully reduced internal temperatures by 3-4°C (Barnard, 2003).

2.2.4 Lightweight Construction

Currently lightweight construction is often chosen over traditional heavyweight construction for new buildings often because concrete buildings have a higher structural loading which requires thicker walls to support the concrete and results in either a larger building footprint or a smaller floor area. Lightweight construction can maximise the available floor area in a building, can often be erected quicker which saves time and money, and produces less waste. This trend has resulted from the increase in factory mass produced building products, known as off-site construction, and commercial timescales.

These modern lightweight buildings have improved insulation levels which reduce heat loss but lack the heat storage capacity of thermal mass to absorb internal heat gains. Therefore the internal temperature rises and the lightweight buildings respond quickly to outside temperature changes due to the lack of thermal mass. The common solution to overheating is to install air-conditioning.

Modern contemporary buildings need to have the thermal storage capacity of thermal mass without the volume and weight of the traditional construction materials. A method of thermal energy storage introduced in Section 2.1 is latent heat storage. Utilising the technology of latent heat storage in phase change materials provides an opportunity to increase the thermal capacity of lightweight buildings without the weight associated with traditional materials that only use sensible heat storage.

2.3 Phase Change Materials

Phase change materials (PCMs) are materials that absorb and release latent heat during phase transition. Phase change materials have a high latent heat of fusion and high energy densities. If the thermal energy storage capacity of phase change materials could be incorporated into buildings, the opportunity to improve the thermal performance of lightweight buildings could be realised.

Figure 2.5 shows phase change materials can be classified as organic or inorganic materials, both as compounds and eutectics. Inorganic PCMs include salt hydrates, salts, metals and alloys. Organic compounds consist of paraffins, non-paraffins and polyalcohols.

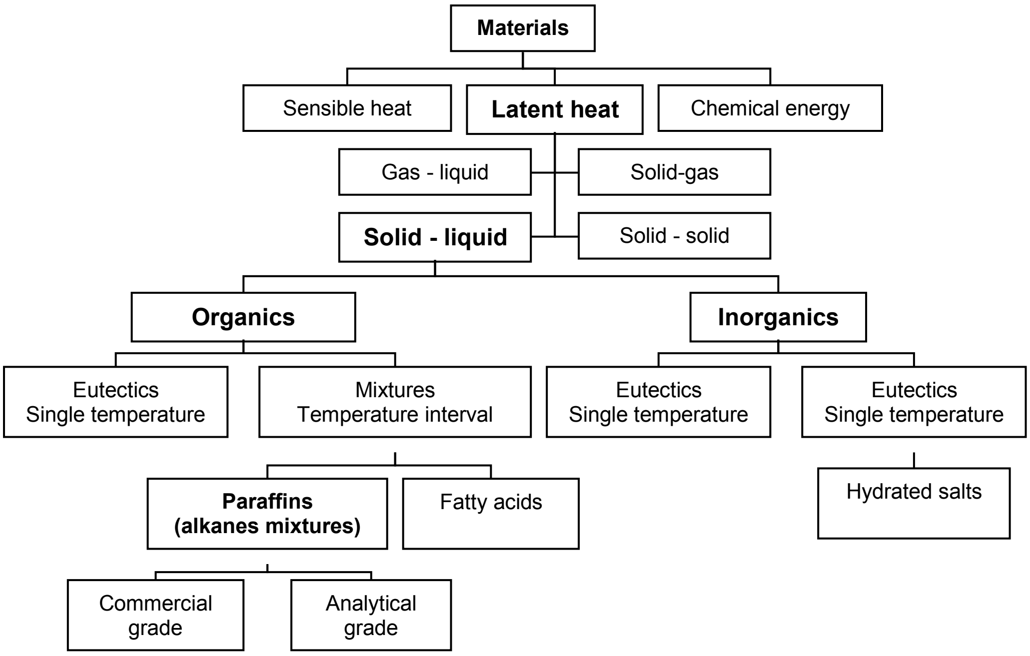

Figure 2.5 Classification of Latent Heat Energy Storage Materials (Abhat, 1983)

Sari (2003) explained the for use in a building a phase change material must have an appropriate phase change temperature, high latent heat capacity, be low in cost, readily available, non-toxic, non-flammable, have long term thermal stability and uniform phase change characteristics i.e. no super-cooling or phase separation. Supercooling is the process of lowering the temperature of a liquid below its freezing point without becoming a solid. Supercooling can be prevented by adding a nucleating agent, phase segregation can be prevented by adding thickening agents, or rotating the storage devices or alternatively direct contact heat transfer can be used (Hasnain, 1998).

To be able to utilise a phase change material as a thermal mass solution in buildings it must be able to operate within a temperature range acceptable for thermal comfort of the occupants. CIBSE (1999) recommends summer operative temperature range of 21°C to 25°C for most building types where air-conditioned. For naturally and mechanically ventilated building it recommends 25°C should not be exceeded for more than 5% of the occupied period. Based on these criterion it is established that a phase change material should be selected with a phase change temperature that enables thermal comfort to be maintained at approximately 25°C.

2.4 Methods of Analysing PCM Properties

To select a phase change material appropriate to its application, its thermal properties need to be determined. These include the phase change onset temperature, peak phase change temperature and the latent heat of fusion.

The phase change onset temperature is the temperature at which the phase transition starts and begins to either absorb or release latent heat. The onset temperature is generally the same for both the melt and freeze transitions, particularly if the phase change material is pure and not a blend.

The peak phase change temperature is often referred to as the peak melt point and the peak solidification or freeze point. This is the temperature at which the peak amount of latent heat has been absorbed or released.

The latent heat of fusion is the amount of latent heat that is absorbed or released by the phase change materials during the phase transition. This is commonly referred to as the latent heat storage capacity. Phase change materials do make use of sensible heat storage also but this a significantly lesser proportion of their heat storage capacity.

The two main methods of analysing phase change materials are differential scanning calorimetry (DSC) and the T-history method, which are described in the following sections.

2.4.1 Differential Scanning Calorimetry

A common method used to analyse the thermal properties of materials is differential scanning calorimetry (DSC). DSC measures the temperatures and heat flows associated with transitions in materials as a function of time and temperature in a controlled atmosphere (Lungren, 2002). These measurements provide quantitative and qualitative information about physical and chemical changes that involve endothermic and exothermic reactions or changes in heat capacity. Information that can be obtained from a DSC include glass transition points, melting and boiling points, specific heat capacity, latent heat capacity, percent crystalline, purity of a material. The DSC is often used for optimising formulations, materials selection and analysing finished products.

The thermal properties of phase change materials and materials containing PCMs can be analysed using DSC. The DSC machine used for analysing PCMs in this research uses a technique called heat flux DSC. A heat flux DSC detects the difference in heat flow that is supplied to the sample and reference pans uniformly in the DSC cell, see Figure 2.6.

The heat flow difference between the sample and reference pan is proportional to the temperature difference between the sample and reference. The heat flow difference is quantitative and it is used to make calculations about thermal properties of the sample material (TA-Instruments, 2003b). This enables the melting and solidifying temperatures and the latent heat capacity of PCMs to be easily identified as shown in Figure 2.7.

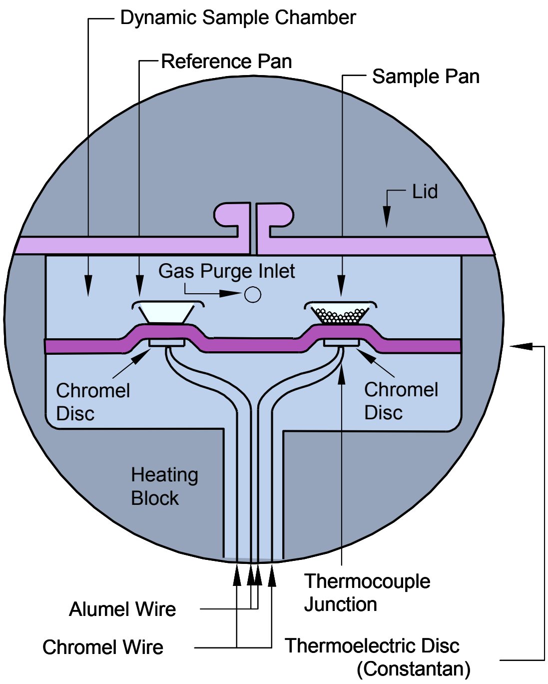

Figure 2.6 Illustration of a DSC cell (TA-Instruments, 2003b)

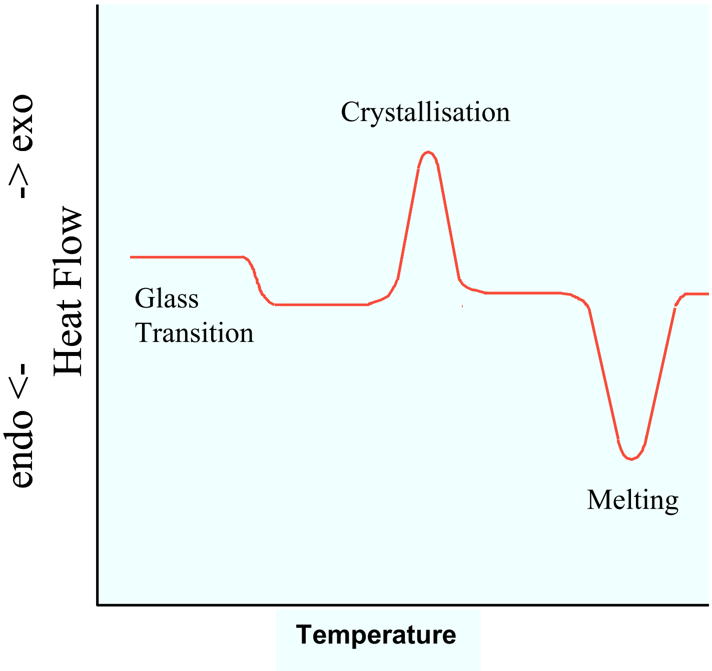

Figure 2.7 Example of melting & solidification curves obtained using a DSC (TA-Instruments, 2003a)

Mehling and Schossig (2005) have found there are several criteria that need to be considered when using DSC to determine the properties of materials. The higher the heating rate (therefore the faster the temperature rise) the better the peak, but this does lead to a broader peak, hence a loss in the resolution and a change in the onset temperature. The sample mass also affects the results obtained. The larger the sample the lower and broader the peak. This reduces the resolution and accuracy of the enthalpy temperatures which are calculated using the area under the curve. These occurrences are illustrated in Figure 2.8.

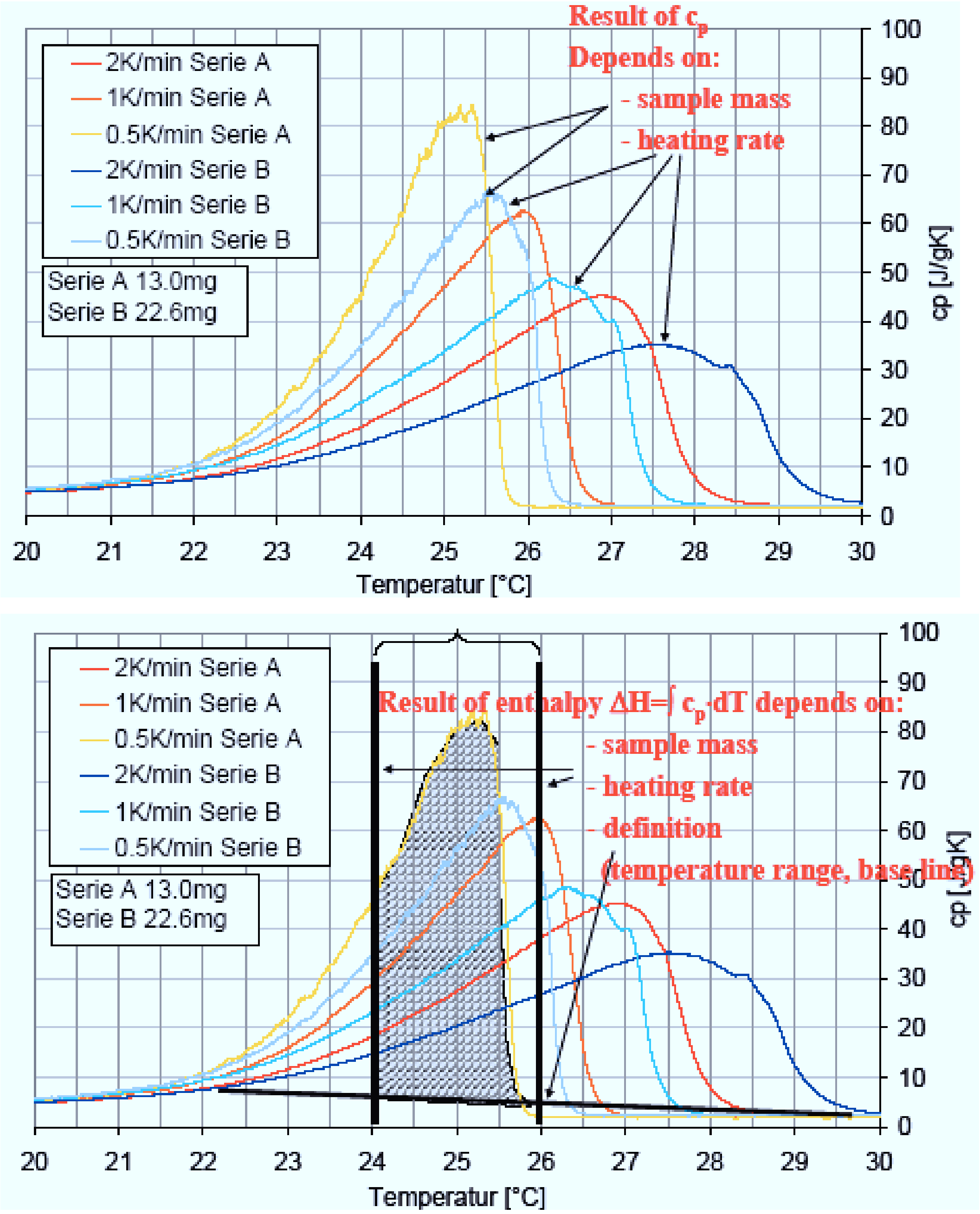

Figure 2.8 Results of DSC testing using different sample sizes and heating rates (Mehling and Schossig, 2005).

2.4.2 T-History Method

Whilst DSC is an accurate method of determining the phase transition temperatures and heat of fusion of phase change materials it is only measuring a very small quantity, usually maximum of 10mg. This does not give an accurate representation of the thermophysical properties of bulk materials and how they would perform in practical systems. Yinping et al (1999) proposed the temperature history (T-history) method of determining the phase change temperature, heat of fusion, degree of supercooling, specific heat capacity and thermal conductivity of several samples simultaneously.

In the method proposed by Yinping et al (1999) a PCM sample and a sample with known thermal properties are heated then allowed to cool in ambient air or a water bath can be used, as shown in Figure 2.9 (Hong et al., 2004). The temperature history during cooling is recorded and the results of both the samples compared graphically using a temperature versus time curve, a T-history curve. The comparison of the curves using heat transfer calculations determines the thermophysical properties of the PCM sample from the known reference sample.

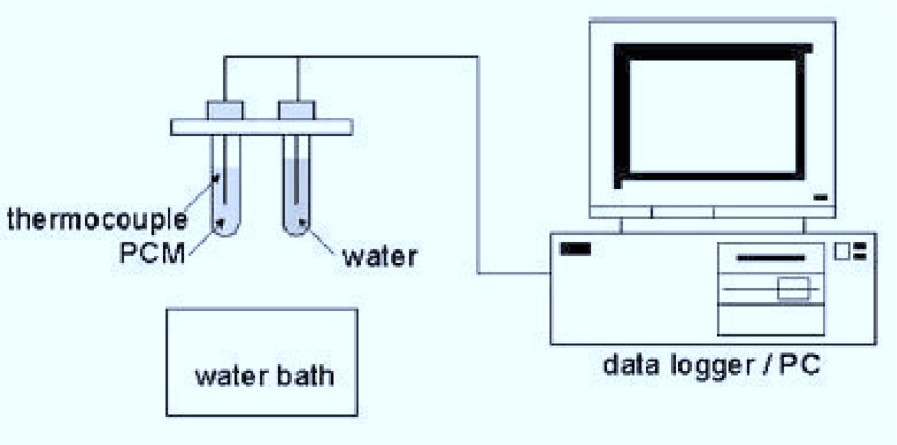

Figure 2.9 Schematic of T-history method equipment (Hong et al., 2004)

2.5 Encapsulation of Phase Change Materials

Once a suitable phase change material has been selected for application in a building it needs to be contained. There are a number of critical factors that need to be considered when designing a containment system: containment, protection, heat transfer, and handling. A phase change materials system is typically required to last for 20 years, hence the encapsulant must also have a long-life. The requirements needed for a PCM encapsulant have been outlined by Lane (1983) and are shown in Table 2.2.

Physical Properties of Encapsulant	***Compatibility of the PCM-Encapsulant Pair***
Strength	Not corrosive
Flexibility	No migration of PCM into encapsulant
Thermal stability	No reaction between PCM and encapsulant
Barrier to moisture and air	
Stable to UV exposure	
Stable to environmental conditions	
Capable of being used safely	
Heat transfer	

Table 2.2 Requirements of a PCM encapsulant (Lane, 1983)

There are three types of phase change material containment systems that are of a scale applicable for a thermal mass solution: macroencapsulation in metals, plastics, films and other materials, absorbed within a matrix and microencapsulation. These encapsulation methods are discussed in the following sections.

2.5.1 Macroencapsulation

This is the most common type of containment system available at present. This system encapsulates a significant quantity of PCM, from grams to kilograms, into a discrete unit. These units usually have a large surface to volume ratio to maximise the availability for heat transfer. Macroencapsulated PCMs in buildings are usually used in systems that have forced air heat transfer and have also been used in liquid heat transfer systems, where the heat transfer fluid flows in the spaces between the PCM units.

A disadvantage to using macroencapsulated PCMs in buildings is the decreasing heat transfer rate during solidification process which occurs when the PCM solidifies around the edges and limits the heat transfer. A key concern with encapsulating salt hydrates is supercooling and phase segregation.

Examples of different commercially available macroencapsulated phase change materials are shown in Figure 2.10 and their thermal properties summarised in Table 2.3.

Figure 2.10 Examples of macroencapsulated phase change materials

Left to right: Climsel pouches (Climator, 2006), K-Panel (PCP, 2006), PlusICE beam (EPS, 2001) and STL nodules supplied by Cristopia.

Trade name	PCM Type	Containment system	T_{melt} range (°C)	Heat storage capacity (kJ/kg)	Supplier
ClimSel C **	Salt hydrate	Pouches, bulk containers, batteries	+7 to +58	162 - 364	Climator
PC **	Salt hydrate	Trays (K-Panel) & custom made containers	-30 to +94	165 - 355	PCP Ltd
PlusICE A** or E**	Eutectic solution	Large tubes, radiators, beams, heat exchangers, custom-made containers	-114 to +164	169 – 180	EPS Ltd
S** or SN**	Eutectic solution	Plastic spheres	-33 to +27	207 - 328	Cristopia

Table 2.3 Commercially available macroencapsulated PCMs

2.5.2 Microencapsulation

Microencapsulation is the packaging of micron-sized materials (both liquids and solids) in the form of capsules, ranging from less than 1μm to more than 300μm. The encapsulation process was first discovered and developed by Barrett K Green of the National Cash Register Corporation (NRC) in the 1940s 1950s respectively, as a method of encapsulating ink for carbonless copy paper. The shell of the capsule can be formulated by using a wide variety of materials including natural and synthetic polymers (Hawlader et al., 2003). There are a number of different methods for microencapsulation, including spray-drying, coacervation, centrifugal and fluidised bed processes, and coating.

Microencapsulating phase change materials has been identified as a method of introducing high thermal storage capacity into materials that can replace conventional building materials. The need for this ‘dual function’ increases the difficulty in developing suitable products, as the system needs to meet the requirements of an encapsulated PCM, as outlined above, and those of the building material it is meant to be replacing.

The disadvantage of microencapsulated phase change materials is the high ratio of encapsulant to PCM. This reduces heat storage density and can often be expensive. The encapsulating matrix can often reduce the convective heat transfer, slowing the charging rate (Lane, 1983).

Currently there is only one manufacturer with commercially available microencapsulated phase change materials. BASF brought to market Micronal®, a microencapsulated paraffin wax as illustrated in Figure 2.11, which is available as a dry powder or within a liquid slurry. The thermal properties of Micronal are given in Table 2.4.

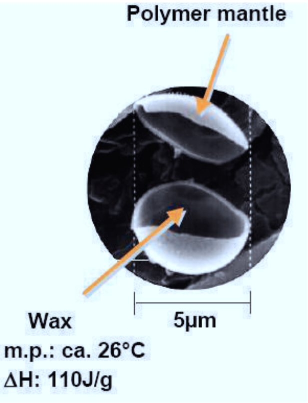

Figure 2.11 Schematic of microencapsulated paraffin illustrating the polymer shell (BASF, 2004)

When this research began there was an alternative commercially available microencapsulated phase change material called Thermasorb manufactured by Frisby Technologies Inc however this company filed for bankruptcy in 2003.

Trade name	PCM Type	Shell Type	T_{melt} range (°C)	Latent heat storage capacity (kJ/kg)	Capsule diameter (μm)	Source
Micronal – liquid	Paraffin wax	PMMA	23 & 26	46	6-10	BASF
Micronal – powder	Paraffin wax	PMMA	23 & 26	110	6-10	BASF

Table 2.4 Commercially available microencapsulated PCMs

2.5.3 Absorbed Within a Matrix

Phase change materials are available that have been absorbed into another medium, for example into a powder or granules, as illustrated in Figure 2.12, and the phase change materials do not become removed when phase change takes place. Table 2.5 lists some of the available matrix systems containing phase change materials. The materials could be utilised in building materials to increase the thermal energy storage capacity of the building fabric.

Figure 2.12 Examples of materials with phase change materials absorbed within the matrix

Trade name	PCM Type	Containment system	T_{melt} range (°C)	Heat Storage Capacity kJ/kg	Source
PX **	Paraffin wax	Silica	28 - 79	96 - 112	RUBITHERM GmbH
GR **	Paraffin wax	Diatomaceous earth	28 - 79	63 - 72	RUBITHERM GmbH
FB 80	Paraffin wax	Fibre boards	79	132	RUBITHERM GmbH
PlusICE **	Eutectic solution	Granules, powders, rubbers			EPS Ltd

Table 2.5 Commercially available PCMs within a matrix system

2.5.4 Shape Stabilised Phase Change Materials

Shape stabilised phase change materials (SS-PCMs) are a novel compound material of phase change material and supporting material. They are formed by a liquid mixture of phase change materials and supporting material which is cooled below the glass transition point of the supporting material until it becomes solid (Memon, 2014). The most common supporting material used is high density polyethylene (HDPE) and up to 80% by weight PCM content can be achieved. As long as the operating temperature for the SS-PCMs remains below the melt temperature of the supporting material it keeps its shape.

SS-PCMs have a good specific heat capacity but can have low thermal conductivity, which can be improved with the addition of graphite (Zhang et al., 2006).

2.6 Use of Phase Change Materials in Construction Materials

Using the latent heat storage properties of phase change materials is not a new concept with the first practical application undertaken by Dr Maria Telkes in 1948. Dr Telkes utilised inorganic phase change material sodium sulphate decahydrate, known as Glaubers salt, to develop the first PCM heated solar house called The Dover House (Lane, 1983).

Following the fuel crisis in the early 1970s efforts to utilise the thermal energy storage capacity of phase change materials became an active field of research as the need to conserve fuel and develop alternative energy sources was realised (Farouk and Güçeri, 1978, Collier and Grimmer, 1979, Chandra et al., 1985, Shapiro et al., 1987, Salyer and Sircar, 1989, Neeper, 1990, Feldman et al., 1991, Kedl, 1991, George and Shepard, 1993). A number of research programs for solar heating and heat storage technology were funded in the United States by the Energy and Research Development Authority (ERDA) and later the Department for Energy (DOE) which focussed on PCM research and development as part of the solar energy research program (Lane, 1983).

In more recent years the research to utilise phase change materials has a wider spectrum of applications. The potential for phase change materials to improve thermal inertia of lightweight buildings and reduce peak temperatures has attracted significant research interest (Hed, 2005, Voelker et al., 2008, Ahmad et al., 2006b, Fraisse et al., 2006, Schossig et al., 2005b).

Investigations have also evaluated using phase change materials to prevent heat transmission in a building in warmer climates (Cabeza et al., 2007, Chi et al., 2005, Lai and Chaing, 2006) and to improve the insulating properties of buildings in cooler climates (Kosny et al., 2008, Métivaud et al., 2004).

The ability of phase change materials to assist with load management of building services is an active area of research. The energy saving potential of using phase change materials to reduce peak demands for heating and cooling or shifting the peak demand into off-peak times to lower fuel bills, has been assessed (Halford and Boehm, 2007, He et al., 2004, Nagano et al., 2006, Osterman et al., 2012, Pasupathy et al., 2008, Turnpenny et al., 2000).

Many researchers have calculated the effectiveness of incorporating phase change materials into buildings to improve energy efficiency and thermal comfort based on numerical simulations (Stovall and Tomlinson, 1992, Feustal, 1995, Kang et al., 1997, Costa et al., 1998, Darkwa, 2000, Neeper, 2000, Vakilaltojjar and Saman, 2001, Ghiabaklou, 2003, Kim and Darkwa, 2003, Ip et al., 2003, Cabeza and Ibañez, 2004, Heim and Clarke, 2004, Van Dorp, 2004, Halawa et al., 2005, Xu et al., 2005, Carbonari et al., 2006, Darkwa and O'Callaghan, 2006).

The numerical simulations have shown that the required melting point of the chosen phase change material is dependent on the application. Different melt points should be selected based on whether the aim is to reduce overheating - a summer application, or save heating energy - a winter application (Schossig et al., 2005b).

Many of the thermal simulations undertaken have been developed from mathematical models using the finite difference approach, including (Stetiu and Feustal, 1998). They simulated the thermal performance of a PCM wallboard in an office building. They determined that using PCM wallboard coupled with mechanical night ventilation enabled a smaller mechanical system to be installed, but only in areas where the outside air temperature at night is below 18°C.

Much of the research, both academic and commercial, to include PCMs in buildings has focussed on integrating them into traditional building materials and products. Therefore this literature review is structured according to the types of building products.

2.6.1 PCM Wallboard

One of the most researched construction materials is wallboard (commonly referred to as plasterboard in the UK) as approximately 41% of the wallboard is air voids. According to Feldman et al (1991) incorporating phase change materials into standard gypsum wallboard can increase its thermal storage capacity by ten times

Some of the many researchers have undertaken theoretical and practical investigations into impregnating gypsum wallboard with PCMs (Shapiro et al., 1988, Salyer and Sircar, 1989, Kedl, 1991, Athienitis et al., 1997, Heim and Clarke, 2003, Khudhair et al., 2003). Scalat et al. (1996) tested a PCM wallboard in a full scale test room which demonstrated it can function efficiently as a thermal storage medium.

A common method to produce a PCM wallboard was to soak the gypsum wallboard in a bath of liquid PCM to soak up the phase change materials into the internal air voids. This process is known as imbibing and it was realised a maximum loading of approximately 25% by weight of PCM could be used as higher loadings resulted in the PCM exuding from the wallboard (Rudd, 1993).

Neeper (2000) determined that to utilise PCM wallboard for a 24hr charge and discharge cycle (diurnal cycle) the storage capacity may be limited to 300-400kJ/m^2 even if the wallboard has a greater latent heat storage capacity. This has not been evaluated any further by other researchers.

Athienitis et al. (1997) soaked gypsum board in butyl stearate and achieved 25% by weight PCM content with a phase change temperature range of 16-20.8°C and a latent heat storage capacity of 126 kJ/kg. The PCM wallboard was installed in an outdoor test room and the results showed that surface of the PCM wallboard remained 6°C lower than standard gypsum board. This reduction of mean radiant temperature by the PCM improves thermal comfort of the room. During the PCM discharge stage, which took 7-11 hours, the surface of the PCM wallboard remained 1-1.5°C higher than the standard board it was adjacent to. Unfortunately this was a single test room therefore there are no definitive comparative results for air temperature reductions, changes of temperature fluctuations, amount of energy stored and released or potential energy savings that could be achieved by the PCM board.

Inherent problems associated with the imbibing technique include an offensive odour due to the volatile organic compounds (VOCs) and corrosion of metal surfaces within a room due to the impurities from the fatty acid phase change materials. As the imbibing process requires organic compounds as the phase change material therefore flammability is an issue. Additional fire retardants would be required to enable the PCM wallboard to be suitable for use in buildings, but this would lower the thermal capacity of the wallboard as less PCM would be able to be used (Rudd, 1993). Fire retardants mixed with organic PCMs has been shown to downshift the phase transition temperatures (Shapiro et al., 1988).

Feldman et al. (1991) proposed an alternative method of direct incorporation, by mixing an organic PCM into the gypsum slurry the manufacturing process. The PCM had a tendency to migrate to the surface of the paste which caused instability. Therefore dispersion agents are required to ensure good distribution of the PCM into the slurry mix.

PCM wallboard containing 30% by weight paraffin wax was simulated by Stovall and Tomlinson (1995) using TRNSYS. The results showed the PCM wallboard was capable of improving thermal comfort conditions by minimising the diurnal air temperature swings and maintaining the temperature closer to the desired thermal comfort temperature for longer. The PCM wallboard could also affect radiative exchange between occupants and the walls by holding the walls at a more constant and comfortable temperature, thus improving thermal comfort for occupants. No practical experimentation was undertaken to validate the simulation results.

Simulation program RADCOOL, based on finite difference approach, was used by Stetiu and Feustal (1998) to numerically evaluate the thermal performance of PCM wallboard in an office building environment to reduce energy loads. The output results showed the proposed PCM wallboard was effective at absorbing internal heat gains which minimised the cooling loads, so was effective at reducing size of cooling systems in climates where outside air temperature drops below 18°C at night and mechanical ventilation is used. If the air temperature remains above 18°C at night other methods to discharge the stored heat would be required.

Much of the research into PCM wallboard is based upon the wallboard containing PCMs randomly distributed throughout the gypsum. According to Kim and Darkwa (2003) this method of developing PCM wallboards provides insufficient heat transfer during the discharge period and a reduction in overall thermal conductivities due to the solidification of PCMs closer to the surface of the wallboard limiting heat transfer. They investigated a laminated wallboard, which included a thin laminated sheet of PCMs adhered to wallboard, containing an increased density of PCMs per unit area to enhance heat transfer and limit multi-dimensional effects. Numerical evaluations showed the laminated wallboard improved thermal response through rapid transfer of latent heat (Darkwa and Kim, 2004, Darkwa and Kim, 2005a, Darkwa and Kim, 2005b). This research has continued to develop and a composite laminated aluminium/hexadecane PCM for wallboard was tested using a heat flux test rig

(Darkwa and Zhou, 2011). The testing showed a latent heat capacity of 167 kJ/kg was achieved and the inclusion of aluminium provided a higher thermal conductivity value of 1.25 W/mK than without 0.15W/mK. The heat flux test rig results demonstrated the laminated PCM wallboard had a faster thermal response and enhanced heat transfer rate. The research concluded further investigation of a suitable adhesive was required as the thermophysical properties of the PVA may have affected the thermal performance of the samples.

Ahmad et al. (2006a, 2006b) have developed and tested a prototype wallboard system. The system uses a rigid 25mm PVC panel (Figure 2.13) containing PCM coupled with a vacuum insulation panel to create a lightweight structure that reduces heat loss from the building and improves thermal efficiency. The PCM panels has a melting temperature range of 21°C – 25°C and a latent heat storage capacity of 148 kJ/kg.

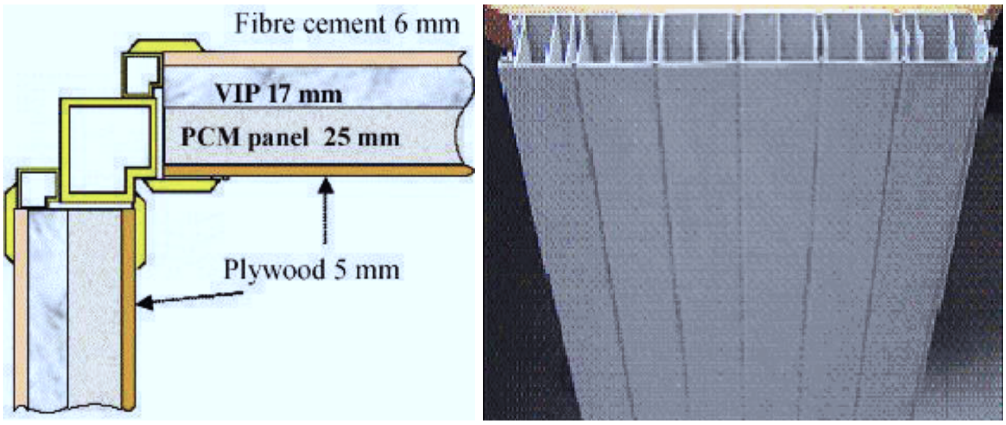

Figure 2.13 View of wall configuration with VIP (left) and PVC panel (right) filled with PCM (Ahmad et al., 2006b)

The panel system was installed in a test cell, along with a second test cell with without PCM, with heat flux sensors and thermocouples, and was located outside. The PCM panel reduced the peak temperature by 20°C (from 60°C to 40°C) during the day and at night, the cell remained at 23°C when the external temperature was 12°C. Therefore the PCM panel successfully reduced peak temperature, prevented heat loss and improved the thermal inertia of the test cells. The results were used to validate a TRNSYS simulation model that utilised a modified PCM module, referred to as Type 101, and determined the optimum thickness for a PCM panel was 20mm. When the thickness is greater than this the peak temperature reduction is not significant and the PCM panel does not function as efficiently.

Whilst the test cell data was used to validate a simulation model, the thermal conditions of the experiments, heating to 60°C, are unrealistic boundary conditions for a building.

A practical full scale test installation was undertaken by Kuznik et al. (2008b) using two identical test chambers of dimensions 3.1m x 3.1m x 2.5m, located within a controlled climatic chamber. A 5mm flexible sheet containing 60% PCM from DuPont was tested to review its performance during a summer season, using realistic temperature boundary conditions of 15-30°C. The results showed the peak indoor air temperature was reduced by 3.8°C and the temperature fluctuations decreased by 4.7°C. Interestingly Kuznik et al show the PCM material stores and releases about 352kJ/m^2 but they do not state what the latent heat capacity of the PCM material is nor do they publish the phase change temperature in this or any other research paper published around this time (Kuznik et al., 2008a).

DuPont have launched a PCM wallboard to market called Energain®. They describe it as a thermal mass panel which is an aluminium laminated panel with a finely mixed core of ethylene based DuPont polymer (40%) and paraffin wax (60%). The 5.2mm thick panel has a melt point of 21.7°C and has a latent heat capacity of 70 kJ/kg (DuPont, 2011). From a review of Kuznik's publications it can be deduced that the 5mm PCM material tested in the chambers is the Energain® panel without the aluminium panel. This is confirmed in later research papers (Kuznik et al., 2011, David et al., 2011) and states the thickness of the PCM is the result of a commercial compromise and allows 77% of the optimal efficiency that would be obtained with 10mm thickness that was identified by simulation and would double the thermal inertia of a wall (Kuznik et al., 2008a).

Although the technical datasheet published by DuPont states the phase change temperature is 21.7°C, the DSC data presented by Kuznik et al. (2011) shows the phase change onset temperature is 13.6°C for the heating cycle with peak temperature of 22.2°C and during the cooling cycle the solidification of the PCM begins at 23.5°C and peaks at 17.8°C, illustrated in Figure 2.14. This is a very wide phase change temperature range and in practical applications a building would not be unlikely to utilise the full 72 kJ/kg latent heat storage capacity.

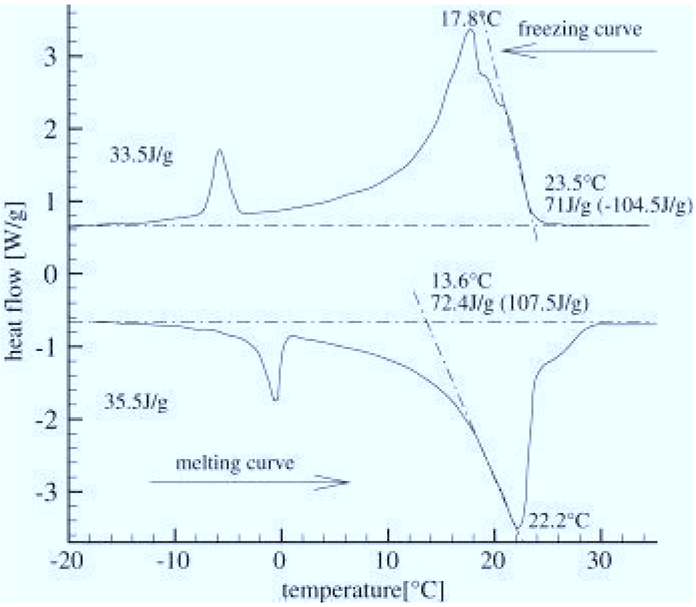

Figure 2.14 DSC curves of Energain® panel (Kuznik et al., 2011)

The Energain panel was installed in a lightweight office building named HELIOS in the south of France. Two identical offices were fitted out with monitoring equipment and the Energain panels were installed on the walls behind the plasterboard and in the false ceiling of one office. The Energain reduced the peak temperature by 2.2°C, reduced the surface temperatures in the room which meant the globe temperature (indicator of thermal comfort) was 3°C lower than the air temperature and the peak globe temperature was reached 1 hour later in the PCM room. Analysing the number of hours the globe temperature is above 29°C for the period of analysis February to December, the difference between the room with PCM and the room without PCM is about 98 hours. An independent study was also undertaken by EDF in France installing Energain in the attic of a fully equipped test house demonstrated temperature reductions of 7°C (DuPont, 2007).

None of the publications for the real test installations provide quantitative data as to the amount of PCM utilised during the experiments. Many of the research papers talk about the heat exchange between the room air and the phase change materials, yet Energain is installed behind gypsum wallboard which has a low thermal conductivity of 0.16 W/mK. Furthermore the product literature states the Energain panel is for use in walls and ceilings together with a mechanical ventilation system and 5m^2 of Energain can provide 1 kWh of additional cooling each day (DuPont, 2007). This concurs with Stetiu and Feustal (1998) that mechanical ventilation is required to discharge the PCM if night air is not below 18°C. As the freeze point of Energain's PCM is 17.8°C it is critical sufficient cool night air discharges the stored heat.

Knauf have launched a PCM wallboard onto market, PCM Smartboard™, containing Micronal, the microencapsulated PCM from BASF. The Smartboard™ contains 3kg/m^2 of Micronal (26% by weight) and the literature states that two layers of 15mm Smartboard™ provides the same thermal capacity as 140mm concrete, see Figure 2.15 and that 10m^2 of Smartboard can absorb 1kWh of energy (Knauf, 2008).

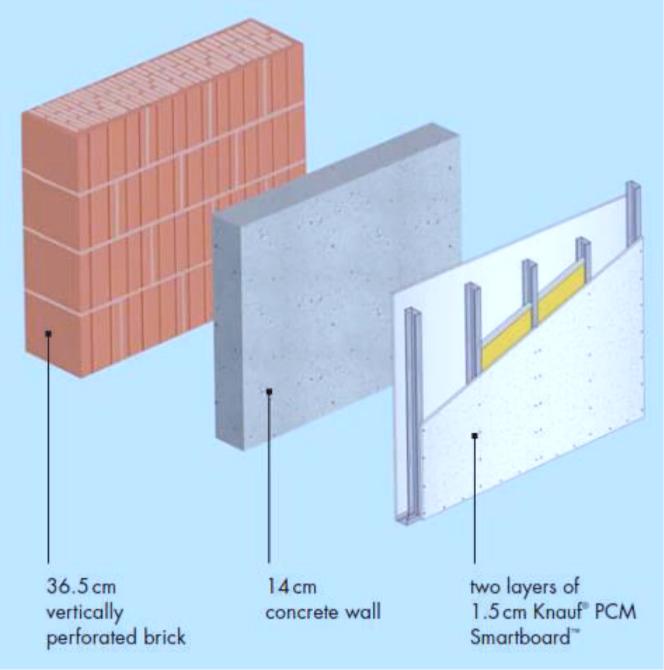

Figure 2.15 Thermal capacity comparison of Knauf PCM Smartboard™ (Knauf, 2008)

The Smartboard has been installed in the following:

- Haus Der Gegenwart (House of the Present), Munich – winning design of an architecture competition, completed in 2005
- Hölderlin Grammar School, Lauffen am Neckar – new lightweight classroom extension
- "Sodastrasse 40" pilot project, Ludwigshafen – refurbishment of 2 semi-detached houses on the BASF estate, installed Smartboard in attic space
- Hammonds High School, Norwich – used instead of concrete slabs

In the United States National Gypsum have developed ThermalCORE™ panel, a PCM gypsum wallboard containing BASF's Micronal. ThermalCORE is not yet commercially available as field tests are ongoing.

2.6.2 PCM Plaster

Following a successful research project funded by German government Maxit have successfully developed a gypsum plaster containing phase change materials, known commercially as Maxit Clima (Schossig et al., 2005a). The plaster contains 20% (by weight) microencapsulated paraffin and has a melting range of 24-26°C with a latent heat capacity of 18kJ/kg. The plaster is spray applied, 2-3cm thick, and can be used in conjunction with a capillary mat ceiling to enable active discharging of stored heat. The system is capable of reducing internal temperature peaks by up to 4°C.

As the PCM being used is a paraffin wax, there is a fire risk associated with the PCM plaster, therefore an additional fire-resistant coating is necessary to meet the building fire requirements. No research results have been given to identify the effect on the thermal performance of the PCM plaster when the fire-resistant layer is added. The layer could act as an insulating layer, inhibiting the heat transfer into the PCM plaster.

Figure 2.16 Maxit Clima PCM plaster applied over capillary cooling mats to produce an actively chilled ceiling (Fisch and Kühl, 2006)

PCM gypsum has been used in the development of a thermally activated ceiling panel (Koschenz and Lehmann, 2004, Koschenz et al., 2005). The panel is a 5cm deep, steel case containing PCM gypsum (25% by weight of microencapsulated paraffin, melt point 22°C) over a capillary water tube system and contains metal fins to increase the thermal conductivity of the PCM gypsum as illustrated in Figure 2.17. The panel successfully reduces internal temperatures by 4°C and has been installed in a new-build administrative facility in Germany. The steel casing and water capillaries assist with improving the fire performance of the paraffin containing gypsum, and the capillaries also discharge stored heat.

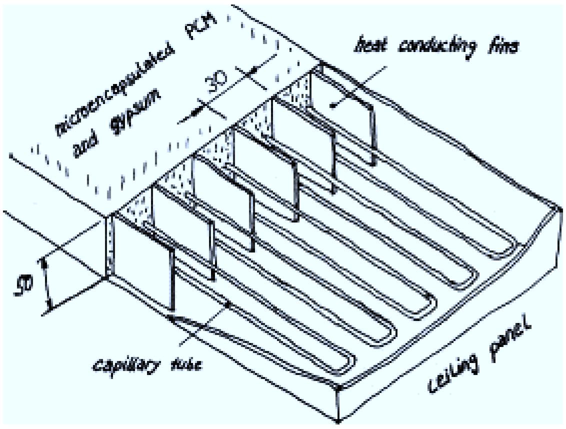

Figure 2.17 Schematic of thermally activated ceiling panel containing PCM (Koschenz and Lehmann, 2004)

2.6.3 PCM Concrete

Concrete is a conventional building material with high thermal mass and the inclusion of phase change materials can further increase the thermal storage properties. Olaya et al (2003) stated the storage capacity of concrete could be improved by 300% with the inclusion of phase change materials and it would be effective in reducing temperature fluctuations in buildings.

There are three common methods of incorporating PCMs into concrete:

1. Immersion - as concrete is porous, it can be immersed in liquid PCM
2. Impregnation – vacuum impregnation of PCM into porous aggregates
3. Direct – the direct mixing of encapsulated PCMs into the mix during manufacture

Investigations by Lee et al (2000) found that butyl stearate and paraffin impregnated into concrete blocks could improve their thermal capacity and shift peak demand for cooling and heating to off-peak demand times, resulting in lower fuel bills. Although only up to 8% PCM loading was achieved the PCM concrete took longer to reach 25°C than standard concrete blocks. The researchers investigated the effect of the air velocity on the charge and discharge time of the heat from the concrete blocks. They concluded for the desirable times of 8 hours to charge and 16 hours to discharge that air velocities of 4-5m/s and 1.5m/s, respectively, must be used.

Kissock and Limas (2006) added 10% paraffin wax to concrete to determine the thermal properties. The results were used to simulate the diurnal load reduction achievable using the PCM concrete. Results indicated the peak cooling load could be reduced by 19% and annual load reduced by 13% more than traditional concrete mass.

Cabeza et al (2005, 2006) developed a PCM concrete containing 5% microencapsulated paraffin wax. Test boxes were built with the PCM concrete to improve the thermal inertia of a structure and the initial results showed the surface temperature of the PCM concrete walls remained up to 3°C lower during peak conditions and took 2 hours longer to reach peak temperature than the standard concrete walls. Thus the thermal inertia and comfort is improved.

Direct incorporation of encapsulated phase change materials into cementitious materials has been found to reduce some of its properties. Hunger et al. (2009) found that increasing the PCM quantity reduced the compressive strength and density of self-compacting concrete although the insulating properties improved as a low thermal conductivity was achieved. Experimental studies undertaken by Mihashi et al. (2002) also found compressive strength to be low in early stages due to reduced hydration peaks. However later stage compressive strength was found to be much higher than normal concrete.

The inclusion of PCMs has been found by Bentz and Turpin (2007), Sakulich and Bentz (2012) and Hunger et al. (2009) to significantly delay the time taken to reach peak temperature (retard) and reduce the peak temperature, suppressing the hydration of cement mortars. Therefore the PCMs change the curing conditions of the concrete.

Microencapsulated PCMs must be able to withstand the shear stress created during the mechanical processing necessary to produce concrete. Shells need to be robust to prevent leakage of paraffin which could result in the paraffin sweating from the cured concrete when undergoing a phase change. Hunger et al. (2009) attributed the loss of compressive strength to the broken PCM shells.

The life expectancy of PCM concrete is significantly less than traditional concrete. Phase change materials typically function for 15-20 years whereas concrete in a building is required for at least 50 years (Lamberg et al., 2000).

‘H + H’ have developed a product called Celbloc Plus® which is an aerated concrete block containing BASF’s Micronal phase change materials. The purpose of the block is to reduce heat penetration from outside in warmer climates.

2.7 Synthesis

There has been significant research over the years to utilise the latent heat storage capacity of phase change materials in buildings by incorporating them into traditional building products. Much of the research has focussed on developing a PCM product that would be located within a construction element. To utilise phase change materials to increase the thermal mass of a building it is important to locate a PCM product on the surface of a room where it is directly exposed to internal heat gains. This would maximise the heat exchange between a room and the phase change materials to be able to utilise their sensible and latent thermal energy storage capacity.

There is minimal research on installing PCM products in test chambers with realistic temperature boundary conditions for a building. Many researchers report only on the peak temperature reduction achieved using a PCM product, but do not analyse the proportion of the latent heat capacity used. Therefore the performance of the PCM products in real world situations is unconfirmed. It is important to understand the different factors that affect the thermal behaviour of phase change materials in a building application. The effect of different air temperatures and velocities on the performance of PCM products needs further research to understand their thermal behaviour and their ability to improve the thermal performance of a building. Until these factors are identified and understood the performance of a PCM product in a building cannot be reasonably predicted and accurate thermal modelling methods cannot be developed.

2.8 Research Question

Is it possible to locate phase change materials on the surfaces of a room and can they effectively improve the thermal performance of a room?

3 Research Method

The programme of work reported in this thesis follows the classic Scientific Method. It is a method, used for centuries, using an iterative process of experiment and analysis to address a hypothesis.

The research question "*Is it possible to locate phase change materials on the surfaces of a room and can they effectively improve the thermal performance of a room?"* requires a series of smaller hypotheses, experimentation, measurement and analysis. Each shall follow on from the last to progress the research forward to address the research question.

Materials or products that are located on the surface of a room are often decorative wallcoverings. This research has been undertaken in collaboration with OMNOVA Wallcoverings (UK) Ltd, a company that manufactures decorative PVC wallcoverings. Experiment 1 involves using an existing method of producing a vinyl wallcovering and the hypothesis considers if phase change materials are included into an existing vinyl formulation a phase change wall-lining could be produced that could be located on the surface of a room.

Experiment 2 evaluates if using large microencapsulated phase change materials results in a phase change wall-lining with a high latent heat capacity. During this experiment the specially developed microencapsulated phase change materials ruptured during the experiment. The supplier modified their formulation and changed the method of manufacture to provide microencapsulated phase change materials with more robust shells. Therefore Experiment 3 investigates if the robustness of the microencapsulated phase change materials provided are improved then a phase change wall-lining with a high latent heat capacity could be produced. Following on, Experiment 4 investigates if the plastisol formulation developed in Experiment 3 can be scaled up and if a trial production run would be successful. Lastly Experiment 5 evaluates the thermal performance of a room lined with the manufactured phase change wall-lining using environmental chambers. The impact of different supply air temperatures and velocities on the quantity of heat that can be stored and released from the phase change wall-lining is assessed and the resulting thermal comfort conditions of the room evaluated.

Table 3.1 shows the hypothesis for each experiment, clearly showing the research development to address the research question.

	Hypothesis
Experiment 1	If PCMs are included in the existing formulations for a decorative vinyl wallcovering then a phase change wall-lining would be viable that could be located on the surface of a wall and/or ceiling of a room
Experiment 2	If large microencapsulated PCMs can be incorporated into vinyl, the phase change wall-lining will have a high latent heat storage capacity.
Experiment 3	If the robustness of the Outlast XXL Thermocules were improved to withstand the mechanical processing of a plastisol formulation, then a phase change wall-lining with high latent heat capacity could be produced.
Experiment 4	If the vinyl plastisol formulation containing microencapsulated PCMs can be up-scaled then a pilot scale production run could manufacture a large quantity of phase change wall-lining.
Experiment 5	If the phase change wall-lining is located on the surface of a room and exposed to different supply air temperatures and velocities then the phase change wall-lining will store and release different quantities of heat which will improve the thermal performance of the room.

Table 3.1 Experimental hypotheses to address the research question

3.1 Layout of Thesis

The background to the research of modern buildings lacking thermal mass and being unable to react to and moderate internal and external temperature fluctuations is introduced in **Chapter 1**. An overview of the methods of thermal energy storage is presented in **Chapter 2** and phase change materials are introduced. A critical appraisal of previous research to include phase change materials into construction materials is given and the limitations defined.

Chapters 4-8 inclusive, report on the series of experiments, following the scientific method to address the research question "*Is it possible to locate phase change materials on the surfaces of a room and can they effectively improve the thermal performance of a room?*" **Chapter 4** investigates the viability of incorporating different types of phase change materials into a standard vinyl wallcovering that could be located on the surface of a room. The successful outcome of Experiment 1 which was the inclusion of microencapsulated phase change materials into a plastisol formulation were detailed in a patent application which was granted in 2003.

Following the realisation in Chapter 4 that microencapsulated phase change materials would result in the highest loading of PCMs in a vinyl wallcovering, **Chapter 5** investigates if larger microencapsulated PCMs than those used in Experiment 1 would provide a higher latent heat storage capacity in a phase change wall-lining. This experiment includes analysis of particle size using scanning electron microscopy (SEM) and thermal analysis using differential scanning calorimetry. The outcome of Experiment 2 was that larger particles of microencapsulated PCMs had a higher latent heat capacity and a greater quantity could be included in a phase change wall-lining. As a result larger microencapsulated phase change materials do produce a phase change wall-lining with a greater latent heat storage capacity.

Further work was required by the microencapsulated phase change materials supplier to provide more robust particles that would not fracture during mechanical processing of a plastisol formulation, which was in identified Experiment 2**.** Experiment 3 investigates if the improved microencapsulated phase change materials could withstand the processing to produce a phase change wall-lining with high latent heat capacity and is presented in **Chapter 6**. This successful formulation is then scaled up in Experiment 4, **Chapter 7,** and the successful pilot scale production run manufactures 50m of 0.7m wide, 6mm thick, phase change wall-lining that can be fitted on the surface of a room.

To evaluate if locating the phase change wall-lining on the surface of a room would affect the thermal performance of the room, an experiment with environmental chambers is described in **Chapter 8.** The experiment exposes the phase change wall-lining to different supply air temperatures and velocities and the reduction of air and globe temperatures, the amount of energy stored and released by the phase change wall-lining, the time taken to charge and discharge the phase change wall-lining and the effect of the air change rate is measured.

The key findings of the research are presented in **Chapter 9** and the technical issues discussed. The implications of this research are examined and the future work needed to continue to move this research forward is outlined.

4 Experiment 1: Preliminary Investigations of including PCMs in Vinyl

4.1 Hypothesis

If PCMs are included in the existing formulations for a decorative vinyl wallcovering then a phase change wall-lining would be viable that could be located on the surface of a wall and/or ceiling of a room.

4.2 Experimental Setup

Preliminary investigations were undertaken to determine the viability of incorporating PCMs into standard PVC wallcoverings. Polyvinyl chloride (PVC) wallcoverings are usually manufactured using one of two processes, plastisol or calendaring, and the plastisol route is more commonly used. Both of these processes typically use chalk to fill out the formulation, therefore theoretically this could be replaced with phase change materials.

A plastisol formulation describes a suspension of finely divided PVC polymer made by micro-suspension polymerisation, in a plasticiser. Plasticisers are responsible for the flexibility of a PVC wallcovering; the more plasticiser used the more flexible the PVC. Typically plastisols are modified by the addition of stabilisers, inert fillers, pigments and rheology control agents. Each of these components are mixed together at high speed to create a liquid paste.

The paste is then coated out onto a substrate e.g. paper, fabric to form a wallcovering. Coating the plastisol can be done a number of different ways but direct coating of a substrate with a knife-over-roll coater is the most common.

Once the plastisol is coated out onto the substrate at the required thickness, usually between 100-500μm, the coating is passed through a high temperature oven for a few minutes. As the temperature of the plastisol rises, the plasticiser penetrates the polymer particles and they begin to swell. The plasticized particles then begin to coalesce to produce homogenous plasticised PVC and a tough plastic coating is formed when the vinyl is pressed by a chilled smoothing roll. Once cooled the solid PVC can be printed to produce a decorative PVC wallcovering.

Calendering, the second most common route of manufacture, begins with a dry blend. Porous PVC granules made by suspension polymerisation are also mixed with plasticiser, stabilisers, fillers and rheology control agents in a blender to produce a dry powder, PVC compound. The reason the powder is dry is because the PVC granules absorb the plasticiser. The PVC compound is fed into a melt-compounder or extruder to convert the powder into a plastic material that can be fed into hot rollers, the calender. The plastic compound is fed through successive sets of heated rollers where it is converted into a hot, homogeneous sheet of plasticised PVC. This sheet can be used to coat continuous substrates e.g. paper or fabric, or can be laminated with other materials by hot rolling them together. The thickness of PVC sheets manufactured using the calendaring route is usually 100-800μm, but thicknesses up to 1.5mm can be achieved. The finished product can be embossed and printed to become a decorative wallcovering.

A range of phase change materials were trialled including:

- Micronal from BASF[1]
- Thermasorb 83 from Frisby Technologies Inc (no longer commercially available)
- GR27 from Rubitherm
- PX27 from Rubitherm
- RT27 from Rubitherm
- Calcium chloride hexahydrate

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[1] During the development process of the phase change wall-lining BASF changed the trade name of their microencapsulated phase change materials from Ceracap to Micronal. To eliminate confusion the microencapsulated PCMs will be referred to as Micronal throughout this thesis.

The plastisol route was attempted first using a standard plastisol formulation and mix procedure already in use at OMNOVA. The plasticisers, polymers, stabilisers and fire retarding additives were combined to produce a paste and the PCMs were mixed in during the final stages. The pastes were coated out onto a paper substrate and cured in an oven heated at 160°C to produce a vinyl sheet. This method enabled all the types of PCMs to be easily included in the plastisol mix and coating process.

Secondly the calendaring process was attempted but proved unsuccessful. The rollers which knead the PVC compound were unable to maintain contact with the plastic once the PCMs were added. This resulted in the plastic slipping through the rollers and not being compounded. It was concluded that the wax from the PCM particles was escaping and lubricating the rollers, preventing any friction building up to form a compound.

4.3 Measurement

The results of the experiments are discussed in the following sections and presented in Table 4.1. The table describes the process used, type phase change materials, quantity achieved, thickness of the wall-lining produced and thermal storage capacity.

4.3.1 BASF Micronal

The first set of investigations used Micronal, a microencapsulated paraffin wax from BASF that has a melt point of 26°C and a latent heat capacity of 110 J/g.

The aim was maximise the amount of PCM that could be included in the vinyl paste to achieve the highest possible heat storage capacity of the produced wall-lining. Whilst high loadings into the paste could be achieved, the paste viscosity became too high which prevented it coating out to produce a vinyl sheet. Modifications to the formulations were made to optimise the PCM content without compromising the viscosity and the pastes were coated out and cured at different thicknesses with different cure times. By producing a thicker wall-lining it would achieve a higher heat storage capacity per unit area.

The produced samples had a PCM content of 25-27% by weight. The thicker samples had curled edges which is due to the surface curing faster than the middle of the sample. Therefore to produce thick samples it is necessary to undertake two passes, i.e. coat the substrate twice to build up the thickness.

When the Micronal wall-linings were produced and left out overnight, the surfaces became greasy. Visually it appeared the Micronal was exhibiting an incompatibility problem with the plasticisers as the plasticiser seemed to be exuding out of the vinyl over time. The formulation was repeated using different plasticisers but the same plasticiser migration occurred. The formulation was repeated using an inert chalk filler to replace the Micronal to determine if the Micronal was the cause of the incompatibility. This wall-lining showed no exuding problems confirming the importance of selecting the correct plasticiser for use with Micronal.

Thermal analysis of Micronal particles and the Micronal wall-linings were undertaken to determine if the phase change materials were still functioning in the wall-lining. The thermal analysis was undertaken using differential scanning calorimetry (described in Section 2.4.1) and the results showed that the thermal characteristics of Micronal had changed during the formulation process. The results of the Micronal wall-lining showed the melt point had shifted and the curves showing the latent heat capacity had become very broad. This was not consistent with the DSC (differential scanning calorimetry) profile of Micronal so it can be concluded the plasticiser incompatibility was having a detrimental effect on the Micronal, potentially damaging the particles shells and penetrating through into the wax core.

Sample vials were prepared containing Micronal and a range of different plasticisers, at a ratio of 30:70 respectively, to monitor their compatibility. The plasticisers analysed were:

- Reofos 50 (Triaryl Phosphates Isopropylated)

- DOP (Di-octyl phthalate)
- Cereclor S45 (C14-17 chlorinated paraffin)
- DINP (Di-isononyl phthalate)

These were studied over a period of time to identify suitable plasticisers for use in the formulation developments. During the visual studies it was observed that DINP did not penetrate the microcapsules. A formulation was developed using the DINP plasticiser and Micronal. This formulation was successful containing 27% PCM content and the resulting sample wall-lining had an estimated 29 J/g latent heat storage capacity.

4.3.2 Thermasorb 83

Thermasorb from Frisby Technologies Inc is a microencapsulated paraffin wax phase change material with a melt point of 23°C and latent heat capacity of 179 J/g. The initial wall-linings containing Thermasorb produced a very bubbly surface and after several experiments it was concluded that water in the PCM shells was the cause. The water was unable to escape the thick vinyl coating during curing in the high temperature oven so blistering was occurring. The problem was overcome by drying the Thermasorb in an oven prior to inclusion in a plastisol.

The sample wall-lining contained 26% by weight PCM content and had a latent heat capacity of 20 J/g. The thermal analysis results undertaken showed the Thermasorb phase change material functioned in the same way after inclusion in the vinyl wall-lining.

4.3.3 Rubitherm GR30

The Rubitherm GR30 PCMs (wax absorbed into a matrix of diatomaceous earth) were incorporated into a wall-lining but this is not an ideal solution as the particles are very large in size and give the wall-lining a gritty appearance. Also during the coating process the particles would catch under the blade, creating drag lines through the coating.

Although a high content of PCM was achieved (48% by weight) this had a detrimental effect on the strength of the wall-lining. The vinyl was brittle and broke easily due to insufficient PVC in the wall-lining to support the PCMs. It is also important to point out that although a high loading of PCM was included in the wall-lining, this did not equate to a particularly high latent heat storage capacity. Rubitherm GR phase change materials only contain ~67 J/g of latent heat, therefore the latent heat capacity of the resulting 48% content wall-lining would be only 32 J/g.

4.3.4 Rubitherm PX27

Rubitherm PX is hydrophilic silica containing wax phase change materials that have been absorbed into the silica, with a latent heat capacity of 104 J/g.

When the plastisol paste was mixed with a PCM content of 25-28%, the silica powder was still visible. The wall-lining sample produced had a rough surface due to the PCM granules and when the sample was cut some PCM particles fell out. The estimated latent heat storage capacity, based on PCM content is 26 J/g.

An alternative formulation was produced with lower PX27 content to enable sufficient PVC to hold the particles in the sample wall-lining. This contained 15% by weight of phase change materials and had an estimated latent heat capacity of 15 J/g.

4.3.5 Calcium Chloride Hexahydrate & Rubitherm RT27

Bulk phase change materials, calcium chloride hexahydrate (inorganic) and Rubitherm RT27 (organic), were each melted and included in plastisol formulations.

This method was not expected to be successful as there was no way to prevent the PCMs from exuding out of the wall-linings. Also, as calcium chloride hexahydrate is an inorganic PCM it is crucial to maintain the water content as any change will destroy the phase changing ability of the compound, as discussed in Chapter 2.3.

As predicted this was unsuccessful. The PCMs would crystallise on the surface of the vinyl and then undergo a phase change and liquefy on the surface. When this was wiped away, each time the PCMs underwent a melting phase the liquid would leach out onto the surface. This confirmed that PCMs within a matrix or microencapsulated are the only method of successful incorporation into a plastisol formulation.

4.3.6 Thermal Analysis of Initial Lab Phase Change Wall-lining Samples

Each of the phase change wall-lining lab samples produced were tested using differential scanning calorimetry (DSC) at a laboratory at University of Kent at Canterbury. Following detailed analysis of all the results it was realised the DSC machine was faulty. Therefore there is limited thermal analysis data for many of the preliminary experiments discussed in this section.

A number of samples were re-tested by DSC manufacturers to obtain robust, accurate data. The samples selected ensured a lab developed PCM wall-lining with a range of the PCMs were tested. These were samples containing Micronal, Thermasorb and Rubitherm PX27 phase change materials. The results, see Table 4.1, showed that the PCMs still functioned when incorporated into a vinyl wall-lining. The results showed that using the microencapsulated phase change materials gave the highest latent heat storage capacity for the phase change wall-lining. This is because both Micronal and Thermasorb (sample 019) have a higher latent heat capacity than the PX27 sample (037).

Table 4.1 **Summary of laboratory produced vinyl wall-linings containing phase change materials**

	Process	PCM	PCM Content % (by weight)	Plasticiser	Thickness µm	Heat Storage Capacity kJ/kg	Notes
002	Plastisol	Micronal	27.41	R50/CS45			
003	Plastisol	Micronal	26.3	R50/CS45	1600		Surface of samples became greasy
004	Plastisol	Micronal	26.6	R50	1800 2280		Surfaces became greasy
005	Plastisol	Micronal	25.7	R50	1712		Surface became greasy
007	Plastisol	Micronal	27	DOP/CS45	1930		No surface grease occurred
008	Plastisol	Micronal	27.6	DOP	1940		No surface greasing – R50 must be incompatible with Micronal
009	Plastisol	Thermasorb	26.3	R50/CS45	1900		Blistered surface
010	Plastisol	Thermasorb	27	DOP/CS45	1980		Blistered surface
011	Plastisol	Thermasorb	31.9	DOP/CS45	1120 1048		Blistered surface on both samples – moisture content in shells of PCM
013	Plastisol	Rubitherm GR30	47.5	DOP/CS45	2200		Brittle coating – too high PCM loading, gritty surface, poor cure with solvent leaching into paper
014	Plastisol	Rubitherm GR30	30.1	DOP/CS45	2250 1980		Cured for longer in oven which improved cure. Still very brittle
015	Plastisol	Calcium chloride hexahydrate	30.1	DOP/CS45	2250		Calcium chloride hexahydrate was immiscible with the paste. Coated sample had PCM crystals on surface.
016	Plastisol	Thermasorb (dried in oven)	31.9	DOP/CS45	2250		Smooth coating.

	Process	PCM	PCM Content % (by weight)	Plasticiser	Thickness µm	Heat Storage Capacity kJ/kg	Notes
017	Plastisol	Micronal	26.6	DINP	2320		Surface cured quicker than middle of sample so edges curling
019	Plastisol	Thermasorb	25.8	DINP	1207 1426 1180	19.67	Slight bubbles in surface as Thermasorb not dried prior to use
020	Plastisol	Rubitherm PX27	25.8	DINP	1329 1482 1490		See the PCM granules in the coating. When sample cut some PCM falls out.
021	Plastisol	Rubitherm PX27	25.0	R50	1310		See the PCM granules in the coating. When sample cut some PCM falls out.
022	Plastisol	Rubitherm RT27	26.6	DINP	1360		Wax leached out onto surface of sample
025	Plastisol	Rubitherm PX27	28.0	DOP	550		
026	Plastisol	Micronal	26.3	DOP	585 699 1160		Sample curling – surface cured quickly than middle
027	Calendering	Micronal	26.3	R50/CS45/DOP	-		Dry blend would not form a plastic compound. No friction with rollers. Graphical output typical of an over-lubricated formulation
028	Calendering	Rubitherm PX27	7.2	R50/CS45/DOP	-		Produced a plastic sample
029	Calendering	Rubitherm PX27	14.5	R50/CS45/DDOP	-		Dry blend would not form a plastic compound. No friction with rollers. Graphical output typical of an over-lubricated formulation

	Process	PCM	PCM Content % (by weight)	Plasticiser	Thickness μm	Heat Storage Capacity kJ/kg	Notes
030	Calendering	Micronal	14.5	R50/CS45/DOP	-		Would not compound to form a plastic. PCM acting as a lubricant.
031	Calendering	Thermasorb	14.5	R50/CS45/DOP	-		Would not compound to form a plastic. PCM acting as a lubricant.
032	Calendering	Rubitherm PX 27	20	DINP	-		Would not form a compound
033	Calendering	Thermasorb		R50/CS45/DOP	-		Would not form a compound
036	Plastisol	Micronal	14.8	Diolpate	-		
037	Plastisol	Rubitherm PX27	14.8	Diolpate	-	8	

4.4 Analysis

The initial lab developments established it was not possible to include bulk phase change materials, in any form, into a vinyl wall-lining using either the plastisol or calendaring manufacturing method.

The trials to include microencapsulated and ‘absorbed within a matrix’ PCMs into a conventional plastisol formulation were successful however the calendaring method was not as the wax from the capsules lubricated the rollers preventing any contact with the rollers which is required to knead the compound.

The microencapsulated PCMs mixed well into the plastisol paste and were not visible in the coated vinyl samples. The ‘absorbed within a matrix’ phase change materials resulted in a gritty surface in the vinyl samples and when the vinyl was cut, the phase change materials would fall out.

Although higher loadings of the matrix PCMs could be achieved, they have a low latent heat capacity. Therefore to maximise the latent heat storage capacity of a phase change wall-lining microencapsulated phase change materials should be used as they have a higher latent heat capacity.

The experimental work showed that to achieve a thicker wall-lining the paste must be coated out in two passes. This enables the vinyl to cure evenly. When a single thick wall-lining was attempted the wall-lining sample would curl as the surface had cured quicker than the centre.

Monitoring of the coated samples revealed there was some incompatibility between the BASF Micronal microencapsulated PCM and some of the plasticisers used to develop wall-lining samples. Investigations were undertaken to resolve this by mixing the Micronal with a range of plasticisers and monitoring them visually over a long period of time to identify which plasticisers were compatible with Micronal. Of the samples tested Di-isononyl phthalate (DINP) would be the most appropriate.

4.5 Outcome

Due to the success of the preliminary investigations a patent (PCT) application was filed based on the concept of incorporating microencapsulated phase change materials into a flexible wall-lining as illustrated in Figure 4.1. Six of the preliminary experiments undertaken were included as examples in the patent application. The novelty of this patent over other PCMs in building materials is the flexibility of the wall-lining. Other patents have always had a rigid matrix.

The patent was granted in 2003, reference WO 03/085346 A1 and is included in Appendix A.

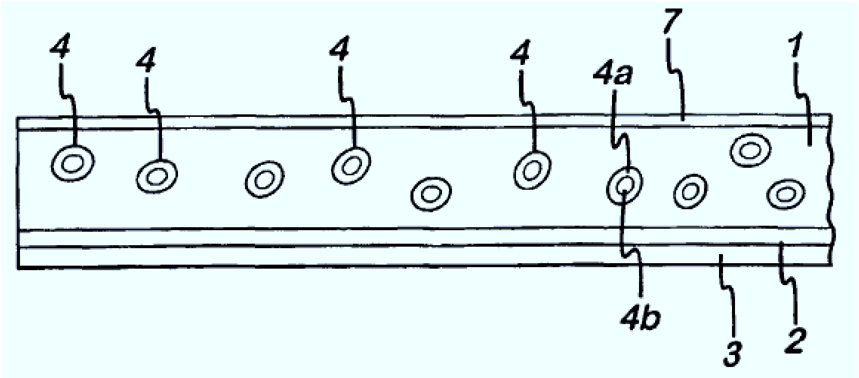


Figure 4.1 Drawing of PCM wall-lining included in patent WO 03/085346 A1

1. body layer, 2. adhesive layer, 3. removable backing, 4. phase change materials, 4a. impermeable coating, 4b. core, 7. pigmented layer

The preliminary lab experiments showed it is viable to include PCMs within a vinyl wall-lining and that to achieve the highest heat storage capacity possible, it is necessary to use microencapsulated phase change materials within a plastisol formulation. This is the best method for achieving the highest loading of PCMs with the maximum heat storage capacity in a vinyl wall-lining.

This contributes to the research question by demonstrating it is possible to locate phase change materials on the surface of a room by including microencapsulated phase change materials into vinyl wall-linings. The next stage of work is to determine which microencapsulated phase change materials is best suited for this application.

5 Experiment 2: Inclusion of Microencapsulated PCMs within Vinyl wall-linings

During the preliminary laboratory investigations, Experiment 1, it was realised that using microencapsulated phase change materials would result in the highest possible loading of PCMs and achieve the highest latent heat storage capacity of a phase change wall-lining.

5.1 Hypothesis

If large microencapsulated PCMs can be incorporated into vinyl, the phase change wall-lining will have a high latent heat storage capacity.

5.2 Experimental Setup

To determine if larger microencapsulated phase change materials could be incorporated into a phase change wall-lining, firstly the size and latent heat capacity of a range of microencapsulated PCMs had to be evaluated and secondly include the larger microencapsulated PCMs within a plastisol formulation, as successfully achieved in Chapter 4.

Scanning electron microscopy (SEM) was used to determine the capsule size which uses a beam of highly charged electrons to examine very small objects. The electron beam, produced by an electron gun is passed through a number of apertures and lenses to produce an image, as illustrated in Figure 5.1. The SEM images the surface (topography), shape, size and arrangement of particles that make up the image (morphology); the composition and crystal structure of the sample.

The SEM that was used in this research was capable of producing magnifications from 20 times to more than 50,000 times the original size. The SEM was used to enable the particle size of PCMs to be estimated from the images.

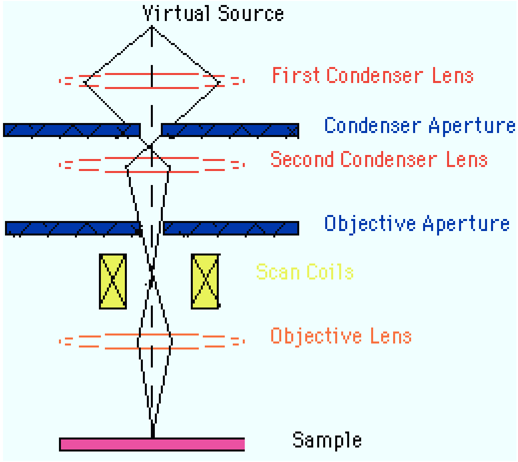


Figure 5.1 **Schematic of SEM image process (Webmaster, 2005)**

Thermal analysis data was critical to determining the phase transition temperatures and latent heat storage capacity of the microencapsulated PCMs and this was determined using differential scanning calorimetry (DSC) as introduced in Section 2.4.1. To ensure the DSC data obtained would be accurate and consistent a DSC machine, model DSC2920 from TA Instruments, was purchased and set up in the lab to aid the development of the phase change wall-lining.

The microencapsulated PCMs to be analysed are the Micronal from BASF, used in the preliminary investigations, and Thermocules® from Outlast Technologies Inc. Outlast manufacture fibres, fabrics and foams containing PCMs known as Thermocules® and were approached to develop materials specifically for this research. They supplied four variants of the Thermocules with different particle sizes, designated XXL, XL, L and S.

The preliminary lab investigations also used Thermasorb from Frisby Technologies Inc. Following the initial experiments Frisby filed for bankruptcy in 2003 therefore the Thermasorb PCMs were no longer available.

Each of the microencapsulated PCMs were analysed using SEM and DSC and when the larger particles with the greater latent heat storage capacity were identified they were included within plastisol formulations to produce lab scale phase change wall-linings. The formulation development was undertaken by

Steve Mitchell, Product Development Manager at OMNOVA, with over 25 years' experience developing formulations.

The resulting phase change wall-linings were analysed using DSC to determine their latent heat capacity and if the microencapsulated PCMs were still operating in the same manner as they had prior to the experiment.

5.3 Measurement

5.3.1 BASF Micronal

The microencapsulated phase change materials manufactured by BASF contain organic wax within a PMMA (polymethylmethacrylate) shell, as introduced in Chapter 4.3.1 and illustrated in Figure 5.2. The microencapsulated PCMs are available both as water based dispersion and in dry powder form.

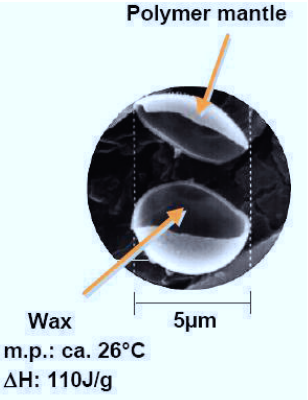


Figure 5.2 Illustration showing a Micronal capsule comprising a wax core within a polymer shell (BASF, 2004)

The SEM image shows that the average particle sizes of the Micronal are 5μm. In Figure 5.3 it does look as though there are much larger particles in the sample but these are in fact agglomerations of the capsules, see Figure 5.4.

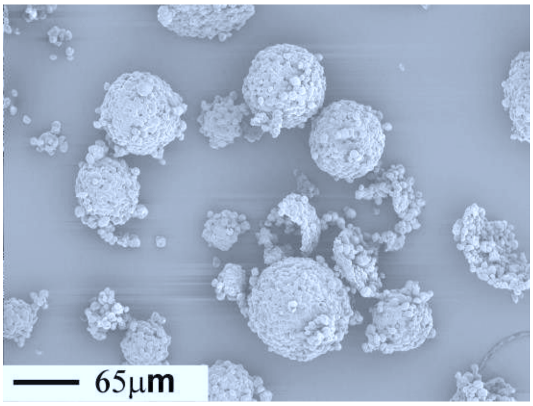


Figure 5.3 Micronal magnified 250 times

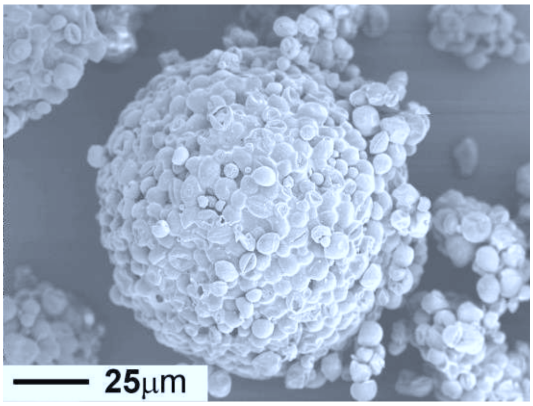
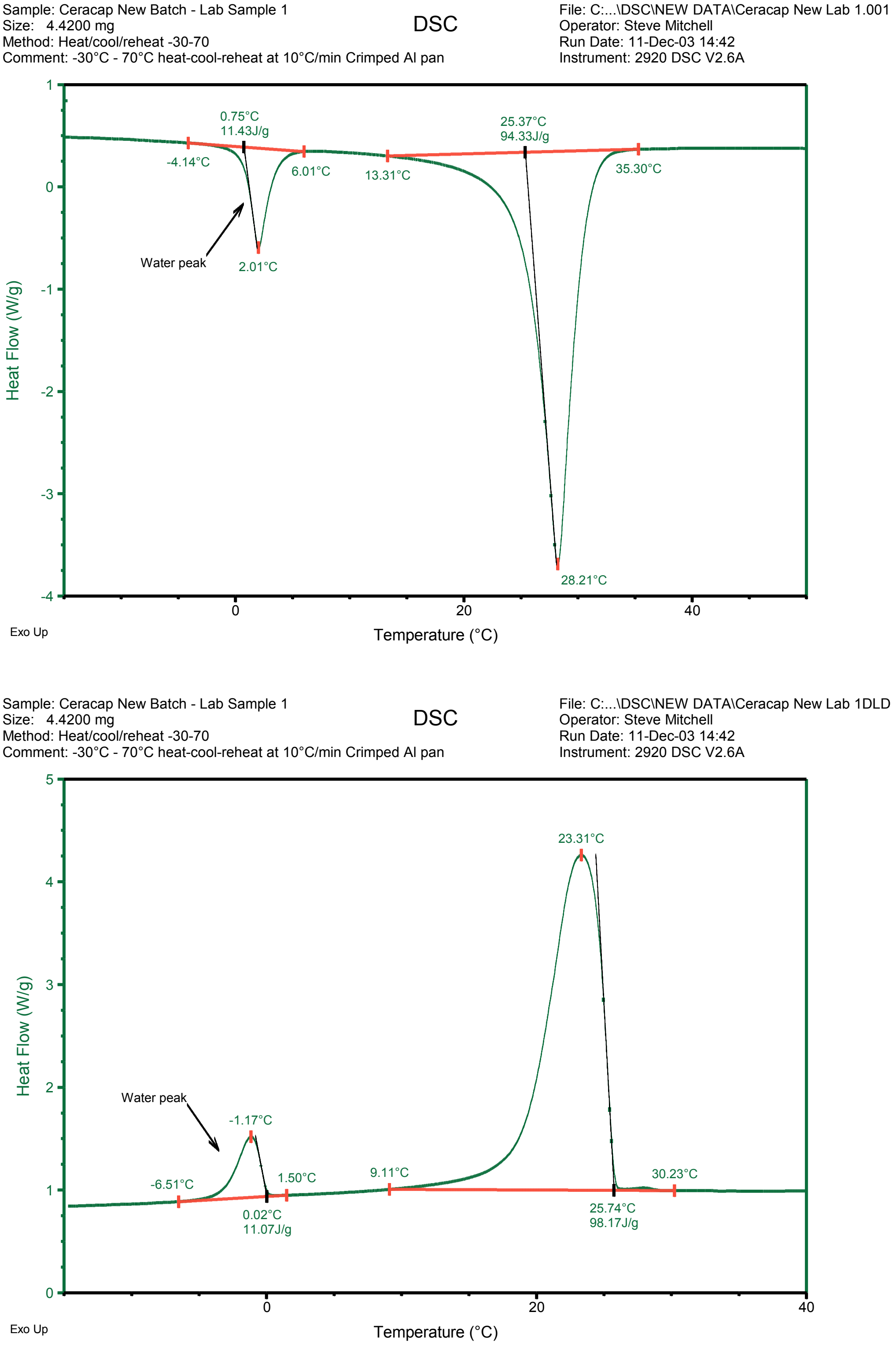


Figure 5.4 Conglomeration of Micronal PCMs, 750 magnifications

The DSC results, shown in Figure 5.5, of the thermal analysis of Micronal show that the phase change temperature is 25°C and the latent heat storage capacity is 96 J/g.

It is important to highlight that the literature showing the DSC data for Micronal received from BASF state the phase change temperature is 28°C and the latent heat storage capacity is 118 J/g. The variation in phase change temperature looks to be a result of differing opinions on the definition of 'phase change temperature'. The described analysis of Figure 5.5 in this research uses the onset temperature to be the phase change temperature, whereas BASF use the peak melt temperature, which is different to the peak freeze temperature. Therefore according to BASF the 'phase change temperature' would be different for the heat cycle and the cool cycle. Using the onset temperature as the phase change temperature would give the same temperature for both the heat and cool cycle. It is important to note this variation in understanding and be aware to check that both the supplier and customer are referring to the same temperature set-point when selecting a phase change material.



Sample: Ceracap New Batch - Lab Sample 1
Size: 4.4200 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\NEW DATA\Ceracap New Lab 1.001
Operator: Steve Mitchell
Run Date: 11-Dec-03 14:42
Instrument: 2920 DSC V2.6A

Sample: Ceracap New Batch - Lab Sample 1
Size: 4.4200 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\NEW DATA\Ceracap New Lab 1DLD
Operator: Steve Mitchell
Run Date: 11-Dec-03 14:42
Instrument: 2920 DSC V2.6A

Figure 5.5 DSC curves showing the phase change temperatures and latent heat storage capacity of Micronal during the heat (left) and cool (right) cycles

The lower latent heat storage capacity results obtained in the DSC results compared to the literature from BASF could be due to the heating rate used when analysing the samples as changes in heat flow affect the sensitivity and resolution of the readings. Another explanation is that DSC data provided by BASF refers to lab developed samples, whereas they are supplying samples from a pilot-scale manufacturing plant which may produce particles with a lower heat storage capacity due to larger scale production methods.

It is also possible that BASF are including the latent heat storage capacity across the temperature range from 0°C to 35°C, therefore the 11 J/g of the water peak is included in the total latent heat capacity. This would then align the difference in the latent heat capacity obtained during this experiment.

5.3.2 Outlast Grade 41 Thermocules

Outlast® Technologies Inc are a manufacturer of thermally adaptive textiles that incorporates microencapsulated phase change materials called Thermocules™. They are constructed using phase change material 1-dodecanol as the core and microencapsulated within a melamine/formaldehyde shell, Figure 5.6.

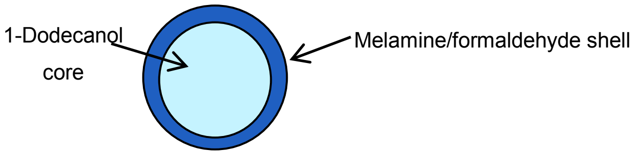


Figure 5.6 Schematic of Outlast microencapsulated PCM Thermocules™

Outlast supplied OMNOVA with four variants of the Thermocules with different particle sizes, designated XXL, XL, L and S, to conduct joint development work. These Thermocules have each been analysed using Differential Scanning Calorimetry (DSC) and Scanning Electron Microscopy (SEM) and the results show that the bigger the particle size the larger the heat storage capacity due to the greater content of phase change materials.

Outlast XXL

The scanning electron microscopy images shown in Figure 5.7 and Figure 5.8 indicate the particle size of Outlast XXL ranges from 40-120μm.

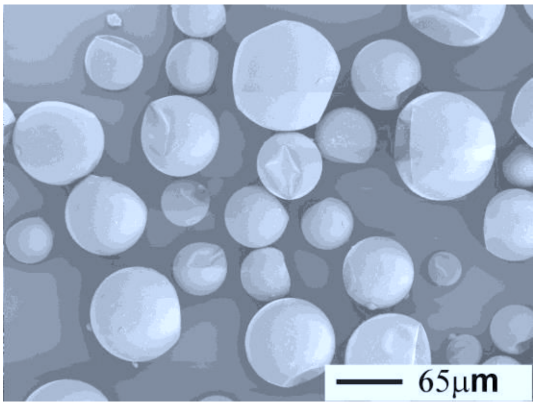


Figure 5.7 SEM of Outlast XXL, magnified 250 times

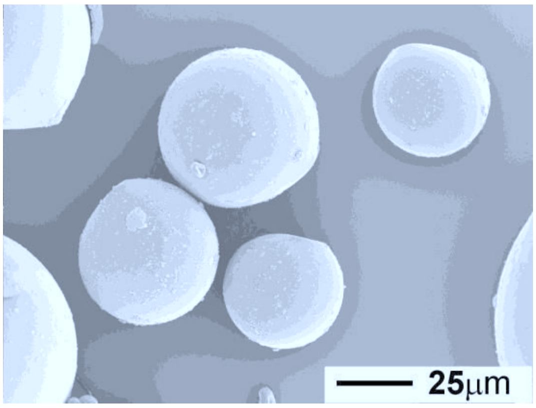


Figure 5.8 SEM image of Outlast XXL magnified 750 times

The DSC results of Outlast XXL, Figure 5.9, show the phase change onset temperature is 23°C and the latent heat storage capacity is 208 J/g. It is important to note the double peak during the phase transition from liquid to solid in the freeze cycle. This could indicate the microencapsulated PCM is a blend of two different PCMs. If this is the case the melt point of the two PCMs appears to be the same but the freeze temperatures are slightly different. Using a slower heating rate would provide greater resolution and the heat cycle may reveal two PCM melt peaks. This further analysis is unnecessary at this stage of the development work as it is more important to identify the heat storage capacity and size of the Thermocules. Furthermore, an agreement is in place with Outlast stating that no analysis of the chemical composition of the PCM core would take place.

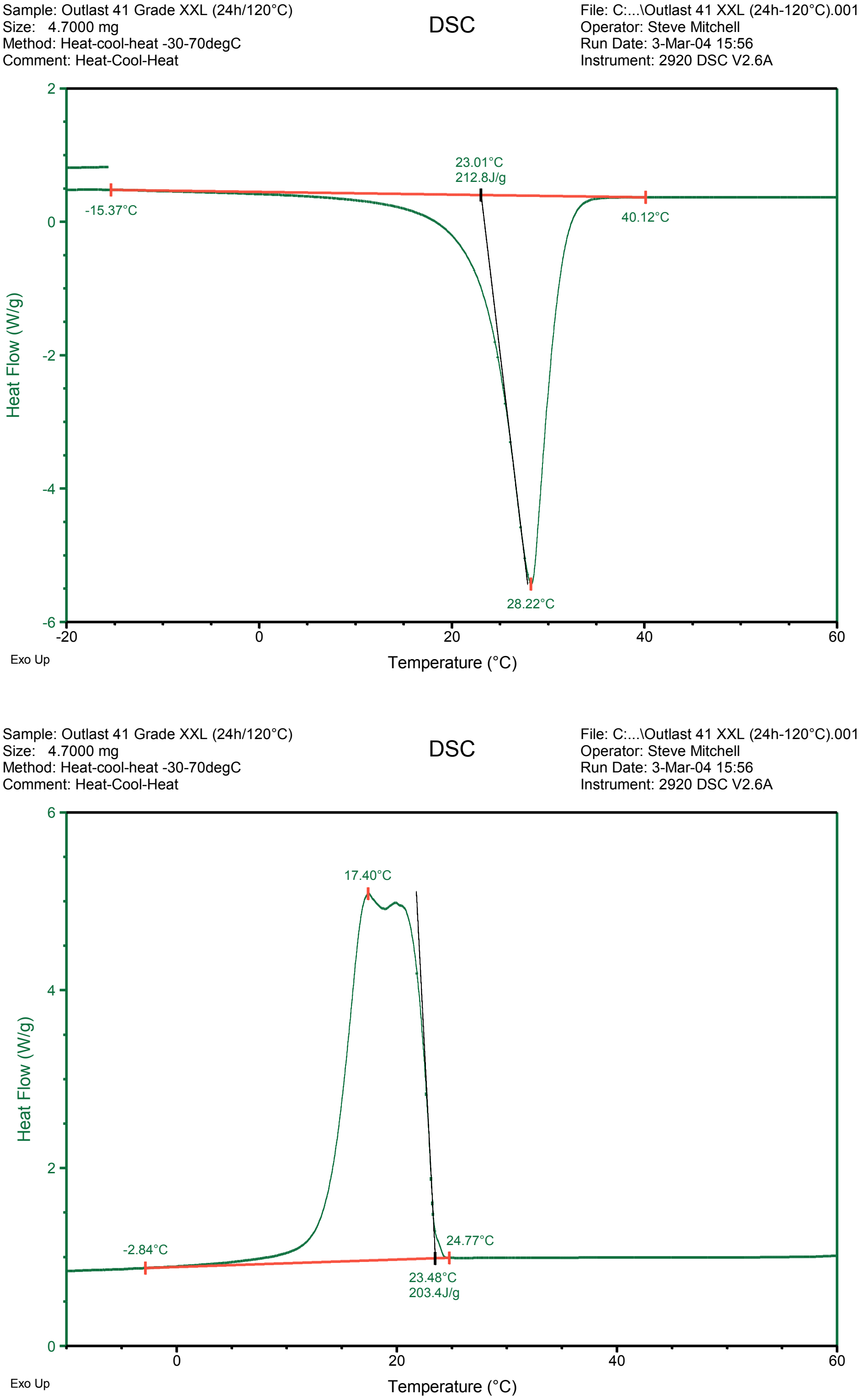


Figure 5.9 DSC results of Outlast XXL during heat (upper) and cool (lower) cycles

Outlast XL

The SEM image in Figure 5.10 shows the Outlast XL particles range in size from 3-100μm, by observation the average particle size is 20μm. In Figure 5.11, as the magnification has increased, you can see the 11-150nm sized particles that form the shell.

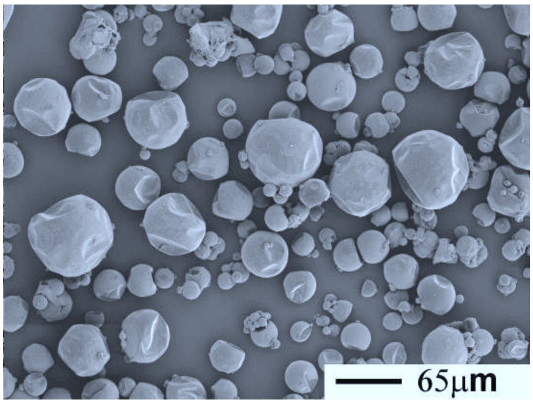


Figure 5.10 Outlast XL PCM magnified 250 times

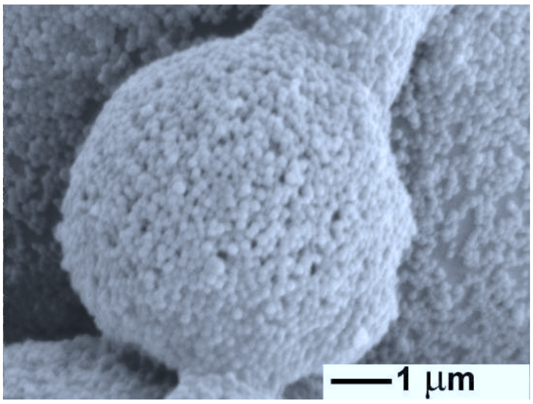
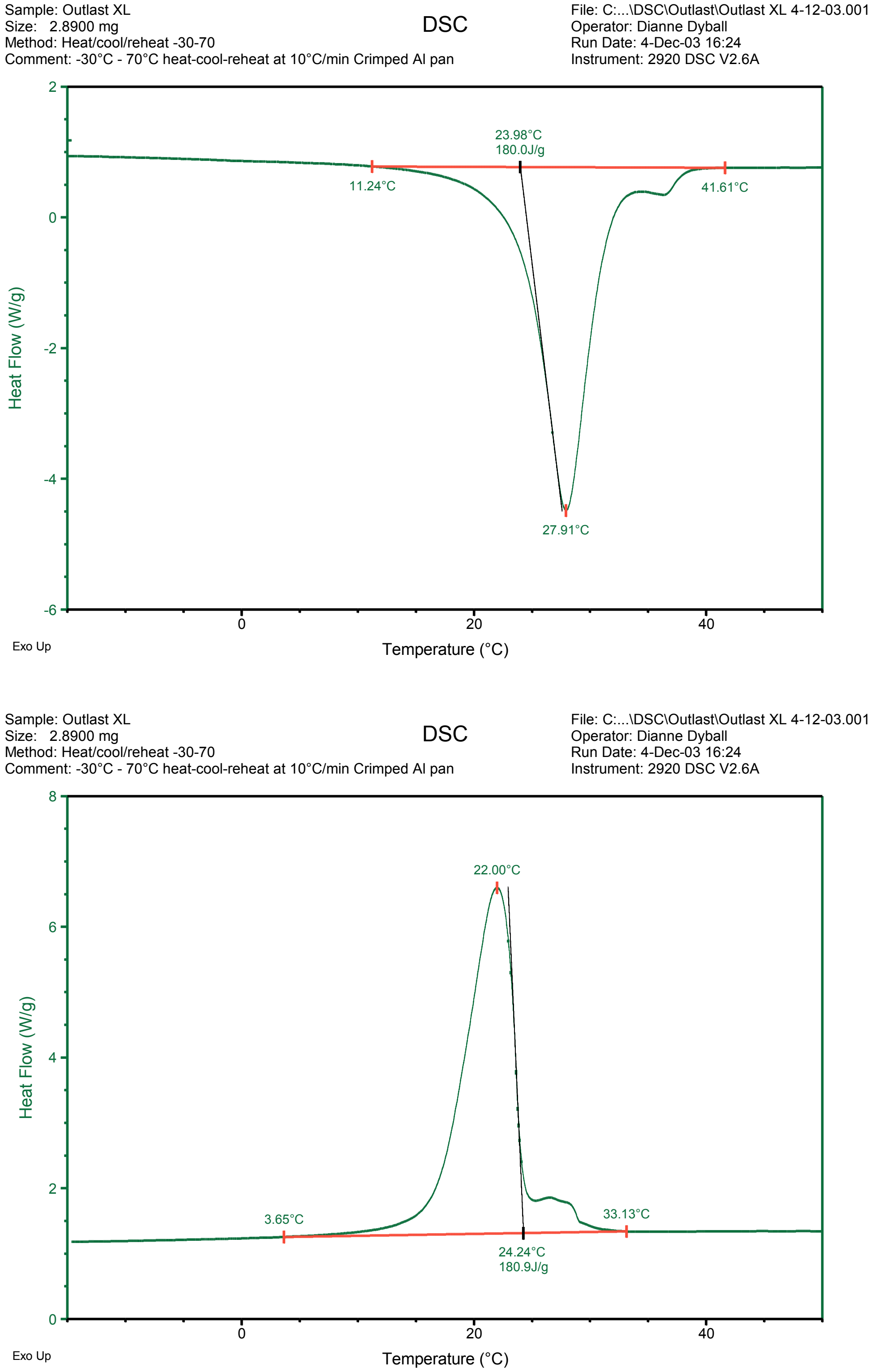


Figure 5.11 Outlast XL PCM magnified 15,000 times

Figure 5.12 shows the latent heat storage capacity of Outlast XL is 180 J/g. The phase change temperature is 24°C with the peak temperatures being 28°C and 22°C during the melt and freeze cycles, respectively. The phase transitions show a small ‘shoulder’ in the curve which may be an additive in the phase change material with a slightly higher melt point than the PCM itself. Due to the different characteristics of the peaks to the Outlast XXL samples it looks as though the PCM used to produce the microencapsulated PCM Outlast XL may be different to the PCM used to produce Outlast XXL.



Sample: Outlast XL
Size: 2.8900 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\Outlast\Outlast XL 4-12-03.001
Operator: Dianne Dyball
Run Date: 4-Dec-03 16:24
Instrument: 2920 DSC V2.6A

Sample: Outlast XL
Size: 2.8900 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\Outlast\Outlast XL 4-12-03.001
Operator: Dianne Dyball
Run Date: 4-Dec-03 16:24
Instrument: 2920 DSC V2.6A

Figure 5.12 DSC results of Outlast XL during heat cycle (left) and cool cycle (right)

Outlast L

The SEM images of Outlast L (Figure 5.13) reveal that the particle sizes are over a narrower range than the XXL and XL samples, just 10-20μm.

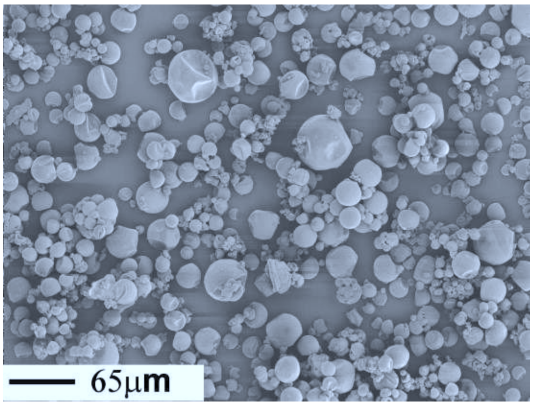
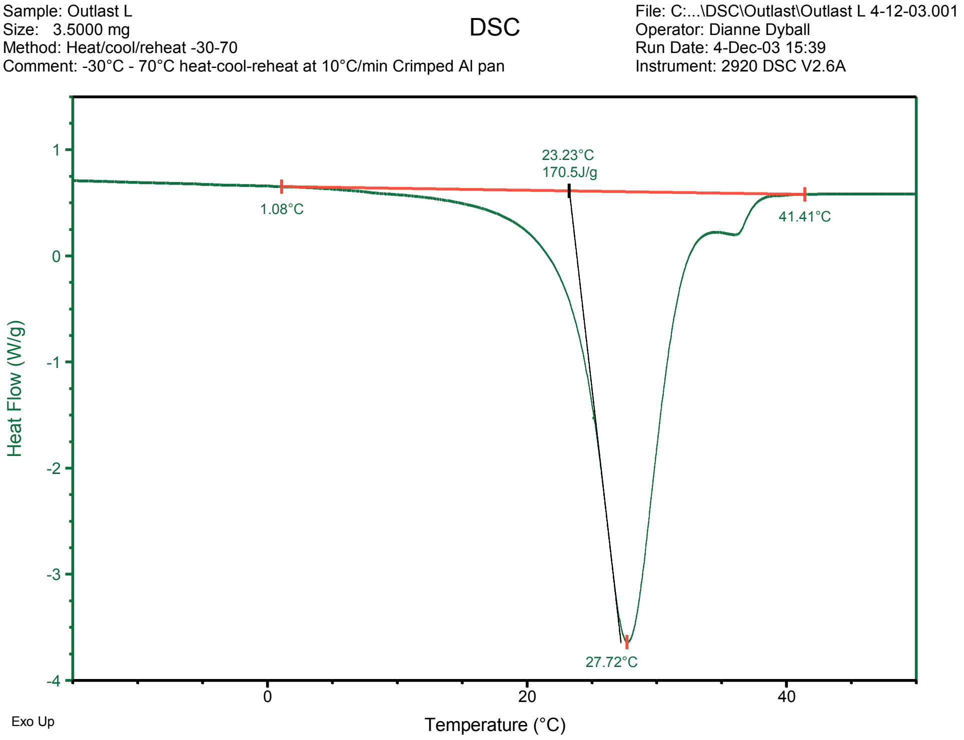


Figure 5.13 Outlast L magnified 250 times

The DSC analysis of Outlast L reveal the phase change temperature is 23°C and the latent heat capacity of this particle size is on average 168 J/g. (See Figure 5.14) It is worth noting the shapes of the peaks in Figure 5.14 are almost identical to the thermal peaks of Outlast XL shown in Figure 5.12.



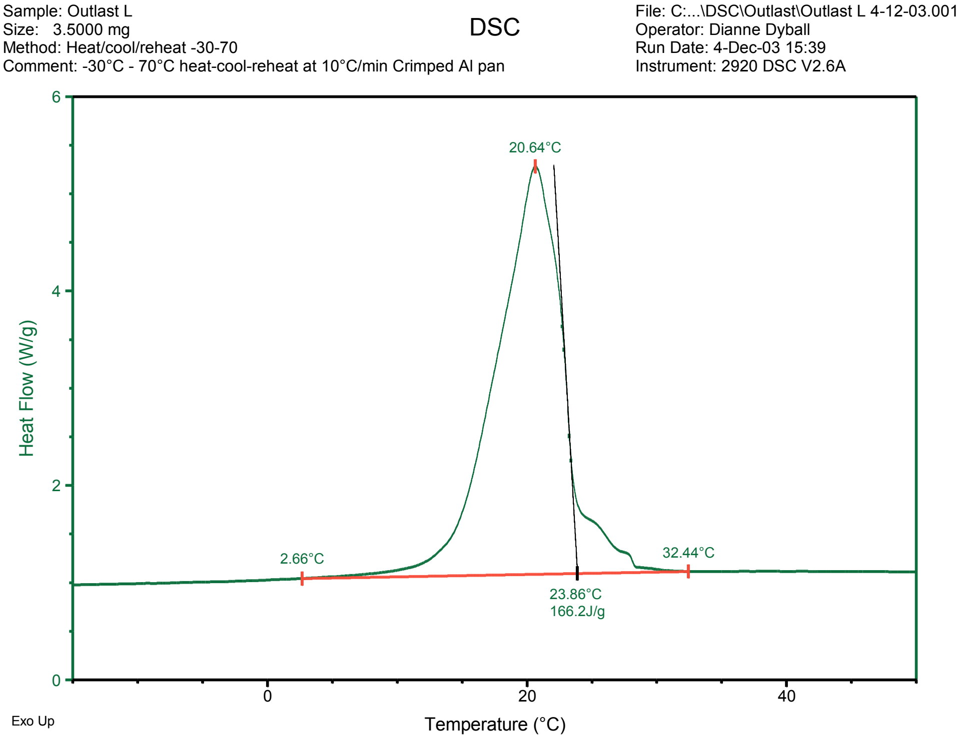


Figure 5.14 Results of DSC of Outlast L during a heat (left) and cool (right) cycle

Outlast S

The particle size distribution in this grade of Outlast PCM is much more consistent at 5μm. Due to such a small particle size the particles appear to be forming conglomerations, giving an appearance of larger particle sizes, as shown in Figure 5.16.

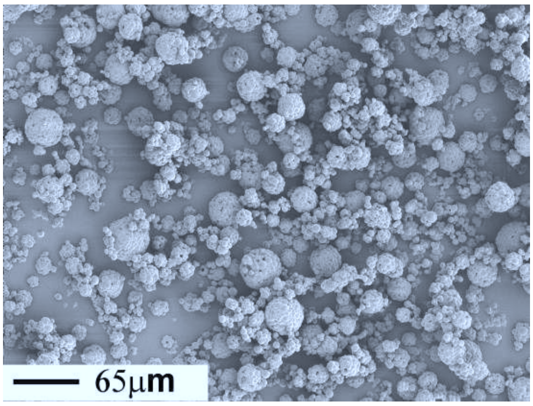


Figure 5.15 Outlast S magnified 250 times

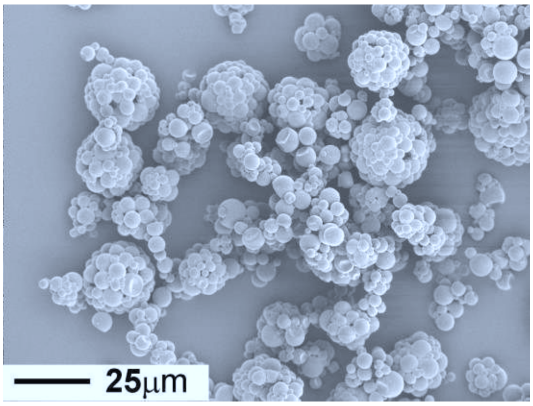
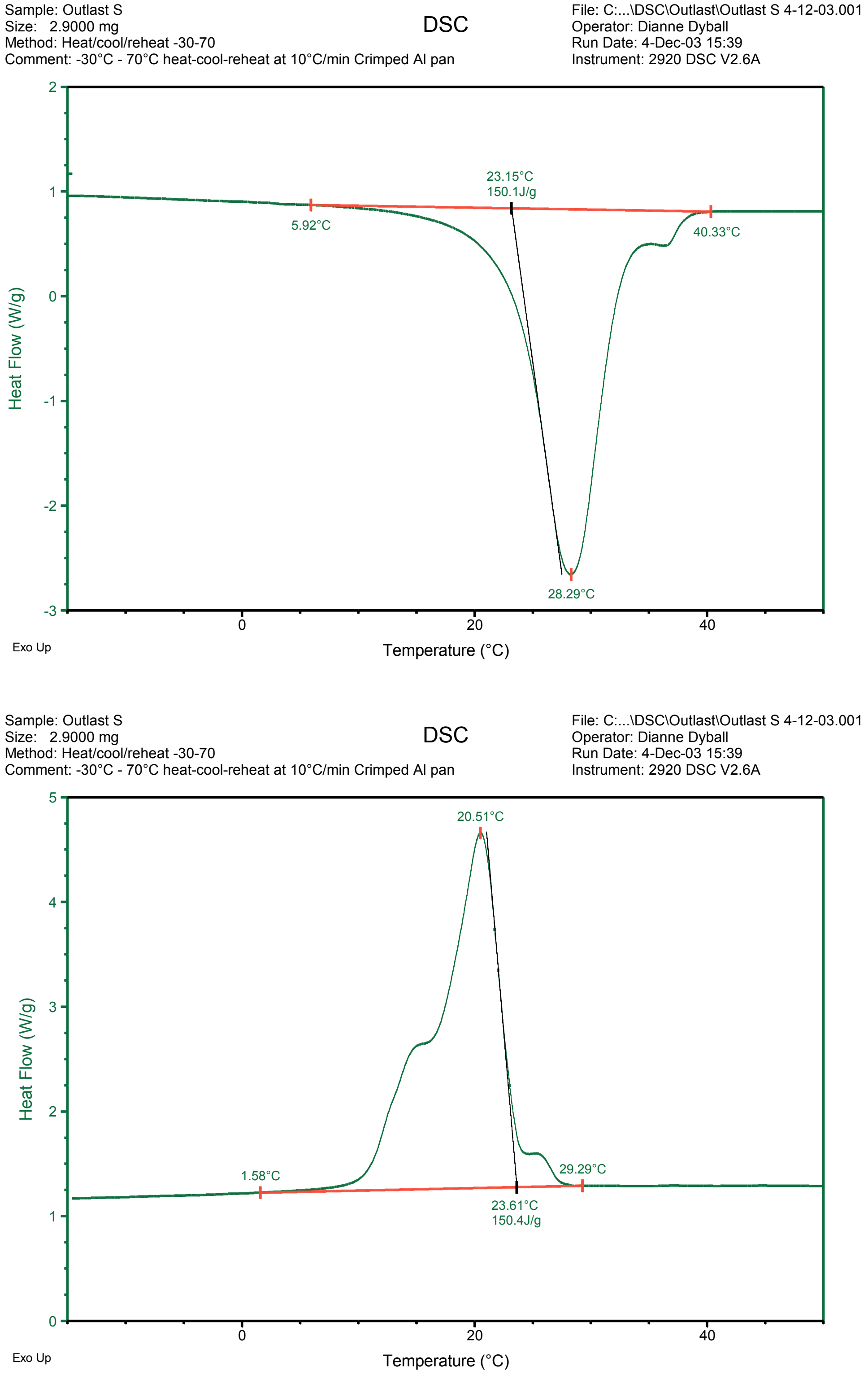


Figure 5.16 Outlast S magnified 750 times

The DSC graphs of Outlast S in Figure 5.17 show the phase change temperature is 23°C during heating and cooling. The latent heat storage capacity is 150 J/g. The step change in the shape of the thermal peak during the freeze cycle suggests some phase separation of the PCM may have occurred. Alternatively this could be a blend of PCMs and is indicating two separate materials. Despite this difference in peak shape, the phase change and peak temperatures of the Outlast L and Outlast S are the same. This would indicate the PCM used is exactly the same in both samples and different particle sizes produce different latent heat capacities. This further confuses the reasons why the peak shape during the freeze process is a different shape. Is it due to the encapsulant? Again no conclusions can be made without detailed chemical analysis of the composition of the PCM and the encapsulant which is not permitted due to the development agreement.


Sample: Outlast S
Size: 2.9000 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\Outlast\Outlast S 4-12-03.001
Operator: Dianne Dyball
Run Date: 4-Dec-03 15:39
Instrument: 2920 DSC V2.6A

Sample: Outlast S
Size: 2.9000 mg
Method: Heat/cool/reheat -30-70
Comment: -30°C - 70°C heat-cool-reheat at 10°C/min Crimped Al pan

File: C:...\DSC\Outlast\Outlast S 4-12-03.001
Operator: Dianne Dyball
Run Date: 4-Dec-03 15:39
Instrument: 2920 DSC V2.6A

Figure 5.17 DSC results of Outlast S during heating (upper) and cooling (lower)

5.3.3 Summary of Microencapsulated PCM Measurements

The particle size and thermal analysis results of the microencapsulated PCMs examined are summarised in Table 5.1. The results show when the particle sizes are 5μm the particles tend to form agglomerations and the larger particle sizes have a higher latent heat capacity.

Supplier	PCM	Particle Size μm	Agglomeration	Phase Change Temp.	Latent Heat Capacity
BASF	Micronal	5μm	Yes 50/100μm	25°C	96 J/g
Outlast	Thermocules XXL	40-120μm	No	23°C	208 J/g
Outlast	Thermocules XL	3-100μm	No	24°C	180 J/g
Outlast	Thermocules L	10-20μm	Some	23°C	168 J/g
Outlast	Thermocules S	5μm	Yes	23°C	150 J/g

Table 5.1 Summary of particle size and thermal properties of microencapsulated PCMs analysed

The measurements show that the Outlast XXL have the largest particle sizes, although there is a range of particle sizes within all the Outlast samples tested. The Outlast XXL has the higher latent heat capacity of 208 J/g, therefore these microencapsulated phase change materials were included in a plastisol formulation.

5.3.4 Phase change wall-lining sample containing Outlast XXL Thermocules™

Laboratory scale experiments have been undertaken to develop a PVC plastisol formulation containing the maximum amount of Outlast XXL achievable to maximise the latent heat storage capacity of the phase change wall-lining. A successful formulation was developed and a phase change wall-lining sample was produced. The DSC results of the sample, referenced Magpie 27, are shown in Figure 5.18.

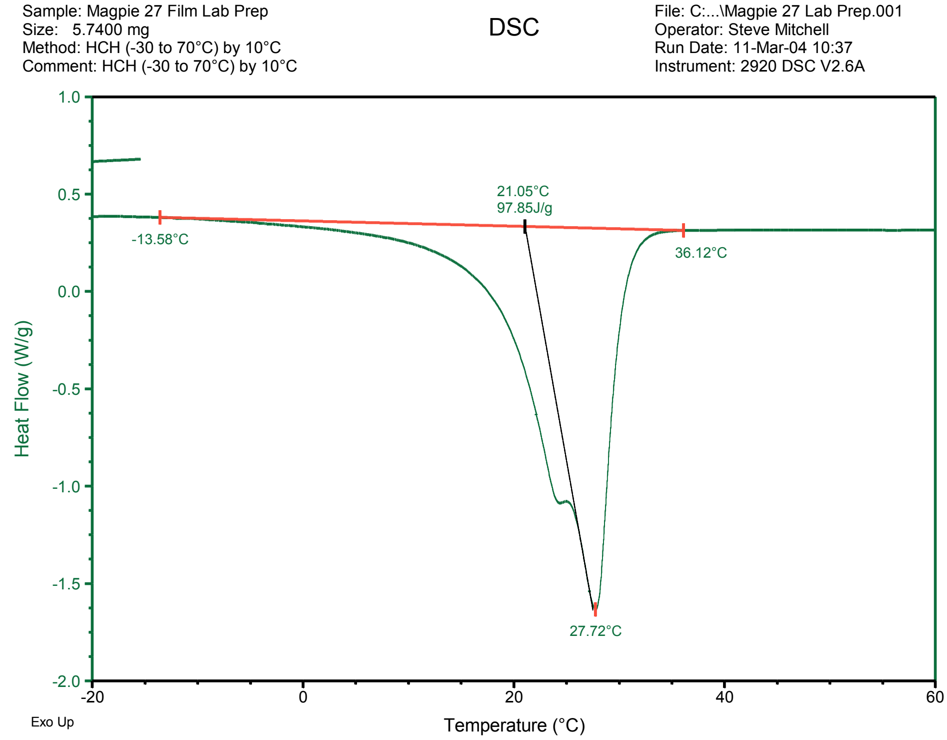
The DSC results indicate the active PCM content is 45% as the latent heat storage capacity of the phase change wall-lining is 94 J/g. The phase transition temperatures are more difficult to define in this sample. The Outlast XXL had a phase transition temperature of 23°C during both the heat and cool cycles, see

Figure 5.9. The DSC results of the phase change wall-lining in Figure 5.18 show the phase change temperature to be 21°C during heating cycle and 19°C during cooling cycle.

The double peak phenomena of the PCM has become more complex following the manufacture into the PVC matrix. The Outlast XXL only exhibited a double peak during the cool cycle. Following the inclusion in the PVC wall-lining there is now a double peak occurring during both the heating and cooling cycles. Figure 5.18 shows the initial peak in the cool cycles has reduced in magnitude. The reason for the change in magnitude of the initial peak could be due to:

- plasticiser migration into the PCM capsule affecting the composition of the PCM
- the PCMs may not all be fully microencapsulated and the PCM wax has become dispersed within the PVC during formulation
- the capsules shells may not be fully cured and are rupturing during formulation

Again no further analysis work can be conducted on the PCMs, but the Thermocules™ can be oven dried to improve the cure and the plastisol formulation needs to be optimised to try and eliminate the problem.



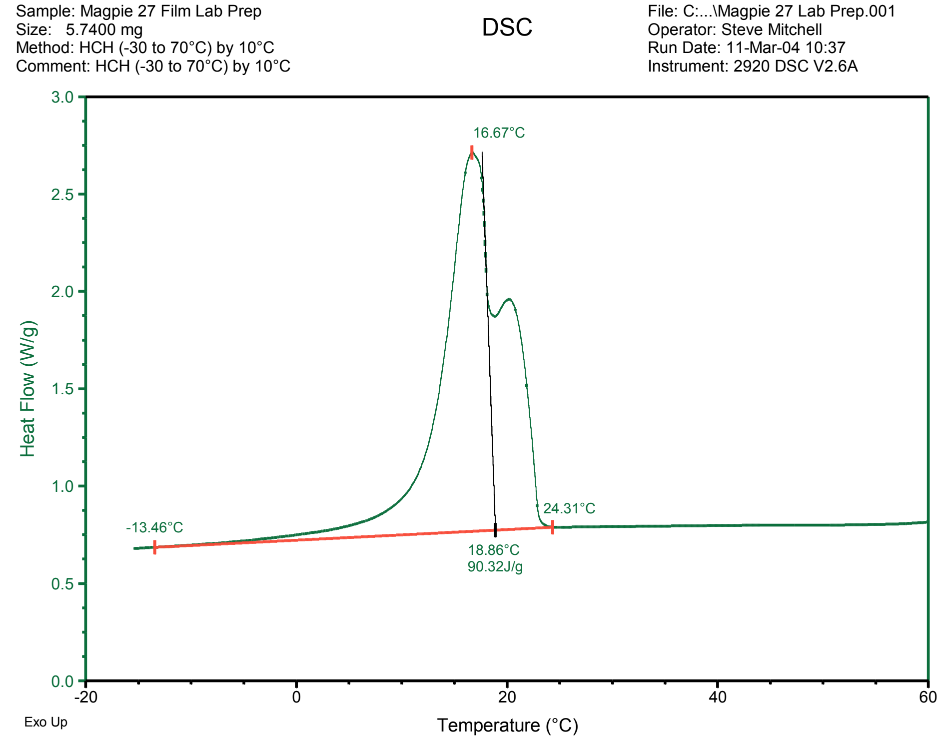


Figure 5.18 DSC results of Outlast XXL in a PVC wall-lining during thermal cycles

5.4 Analysis

When selecting a microencapsulated phase change material it is important to realise which temperature is considered to be the phase change temperature. In Section 5.3 it was clearly identified that there is a difference in opinion as to what the phase change temperature is. In this research it was decided the phase change temperature was the onset temperature i.e. when the material begins to ‘change phase’. This is likely to be a temperature that is similar during both melt and freeze cycles. Choosing the peak melt and/or freeze temperatures gives two different temperature readings and could be misleading when selecting a PCM for an application requiring a specific temperature to be maintained.

The importance of the particle size of the microencapsulated PCM has been demonstrated. The larger the particle size the greater the latent heat storage capacity. Also, greater PCM content of phase change wall-linings can be achieved using the larger particle sizes, hence wall-linings with much larger latent heat storage capacities can be produced.

5.5 Outcome

The microencapsulated phase change materials from Outlast, the XXL Thermocules, had the largest particle sizes ranging from 40-120μm and resulted in the largest latent heat capacity of 208 J/g. This is over double the latent heat capacity of the commercially available BASF Micronal.

A greater quantity of the Outlast XXL Thermocules could be incorporated into a plastisol formulation, achieving 45% by weight compared to 27% with the Micronal. This resulted in a sample phase change wall-lining with latent heat capacity of 94 J/g.

Further work is needed to improve the robustness of the Outlast XXL Thermocules to prevent the shells rupturing and then include them within vinyl to achieve a phase change wall-lining with high latent heat capacity.

6 Experiment 3: Development of Phase Change Wall-lining Formulation

In Chapter 5, Experiment 2, it was determined that larger capsules of microencapsulated phase change materials had a higher latent heat storage capacity and a greater quantity could be included into a vinyl wall-lining. This resulted in the phase change wall-lining having a greater latent heat storage capacity. However, the large microencapsulated phase change materials from Outlast® Technologies Inc, XXL Thermocules™, were fracturing during the formulation process and wax was escaping from the phase change wall-lining.

6.1 Hypothesis

If the robustness of the Outlast XXL Thermocules were improved to withstand the mechanical processing of a plastisol formulation, then a phase change wall-lining with high latent heat capacity could be produced.

6.2 Experimental Setup

Following the success of achieving high loading of XXL Thermocules into a PVC wall-lining, Outlast agreed to lab manufacture a small batch of large microencapsulated phase change materials using a different manufacturing method. The new manufacturing method was a non-agglomeration method and the particles were fully dried to ensure a full cure of the shells. This would ensure the microcapsules were a dry, free-flowing powder containing no free-wax that could escape during manufacture and the shells were robust enough to withstand the mixing process. These particles were supplied and are referred to as Outlast XXL(2) Thermocules.

The XXL(2) particles were analysed using firstly the visual method of scanning electron microscopy and secondly a more detailed assessment using a Mastersizer 2000 particle size analyser. The Mastersizer 2000 can measure the particle size of materials in the range of 0.02μm to 2000μm with an accuracy of

±1%. The analyser detects every particle and produces a graphically display illustrating the size distribution of the capsules.

Differential scanning calorimetry was undertaken to determine the phase change temperature and latent heat capacity of the XXL(2) microencapsulated PCMs.

Extensive formulation developments were carried out to optimise a formulation containing the XXL(2) microcapsules and the resulting phase change wall-lining analysed using DSC to ensure the microencapsulated PCMs still functioned correctly.

6.3 Measurements

6.3.1 Outlast XXL(2)

Scanning Electron Microscopy was used, as described in Chapter 5, to visually determine the particles sizes of the Outlast XXL(2) Thermocules. The SEM images, Figure 6.1, showed the particles sizes ranged from 22-185μm.

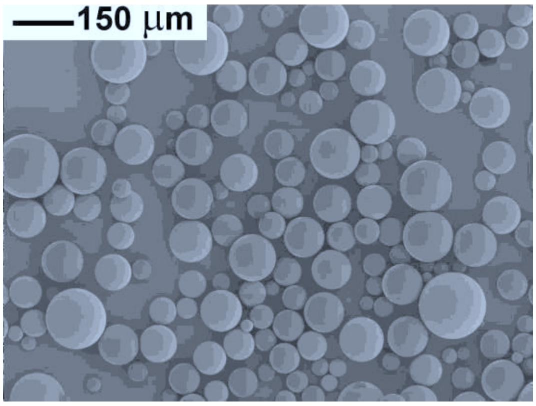


Figure 6.1 SEM image of Outlast XXL(2) showing the size distribution of the microencapsulated PCMs

Due to the broad range of the particle sizes and the greater importance of the development stage a detailed particle size analysis was undertaken. The results of the particle size analysis of Outlast XXL(2) is shown in Figure 6.2. The graph shows the microcapsules are in the size range of 6-195μm, with the average size being 109μm.

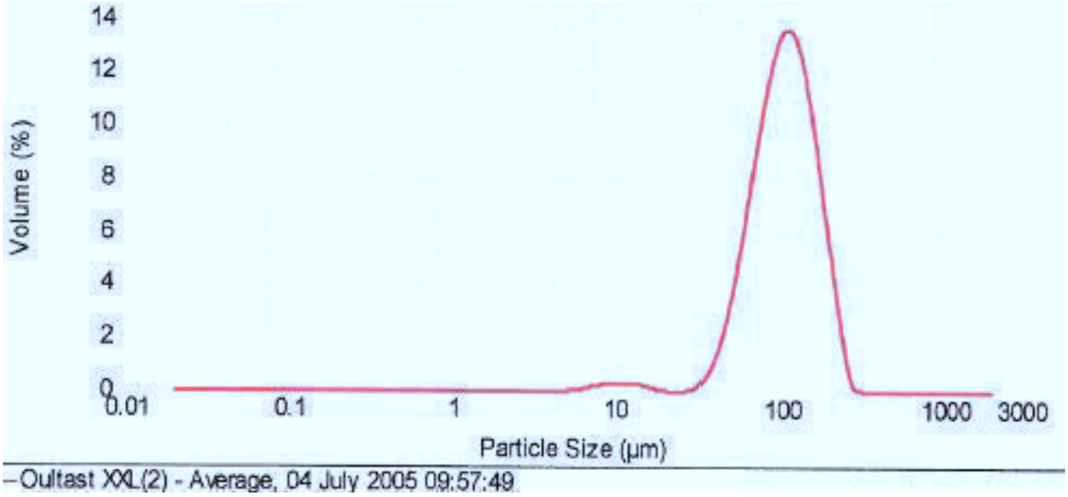


Figure 6.2 Particle size distribution results of Outlast XXL(2)

A sample of XXL(2) was thermally analysed by differential scanning calorimetry. The results, Figure 6.3, showed the phase change temperature of the XXL(2) Thermocules is ~24°C and the latent heat storage capacity is 199 J/g.

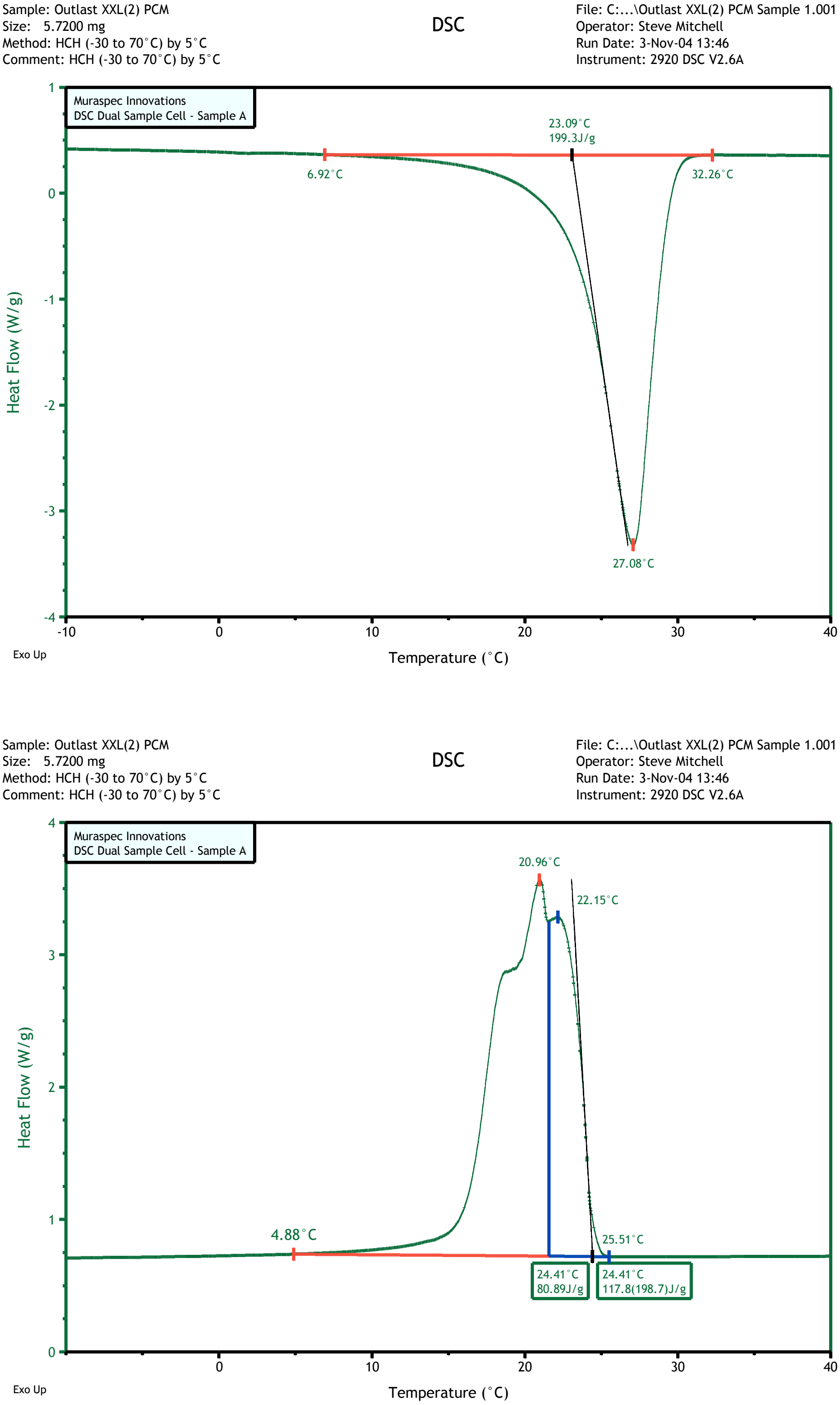


Figure 6.3 DSC results of Outlast XXL(2) Thermocules

6.3.2 Phase change wall-lining containing Outlast XXL(2)

Extensive laboratory scale formulations were undertaken to maximise the amount of Outlast XXL(2) that could be included within a plastisol formulation. The resulting formulation was coated out and a wall-lining containing 46% by weight of microencapsulated phase change materials was produced.

DSC analysis of the lab prepared phase change wall-lining was conducted and the results are shown in Figure 6.4. The phase change temperature looks to have shifted slightly to 23°C and the latent heat storage capacity is 90 J/g. As the phase transition temperature looks to have shifted from 24°C to 23°C there was concern the XXL(2) Thermocules may have been penetrated and the wax core contaminated. Thermal cycling (repeated heat then cool cycles) of the XXL(2) phase change wall-lining was undertaken to identify if there was any change in the peaks after numerous phase changes. If the wax core of the Thermocules was contaminated it is likely that each phase transition would show a different profile in the graph as the phase change material would be unable to perform in the same manner. The results, illustrated in Figure 6.5 showed that repeated heating and cooling of the phase change wall-lining did not affect the phase transition temperatures. The shape of all the peaks remained the same after 22 cycles confirming the Thermocules had not been compromised and they were robust enough not to rupture or degrade after numerous cycles.

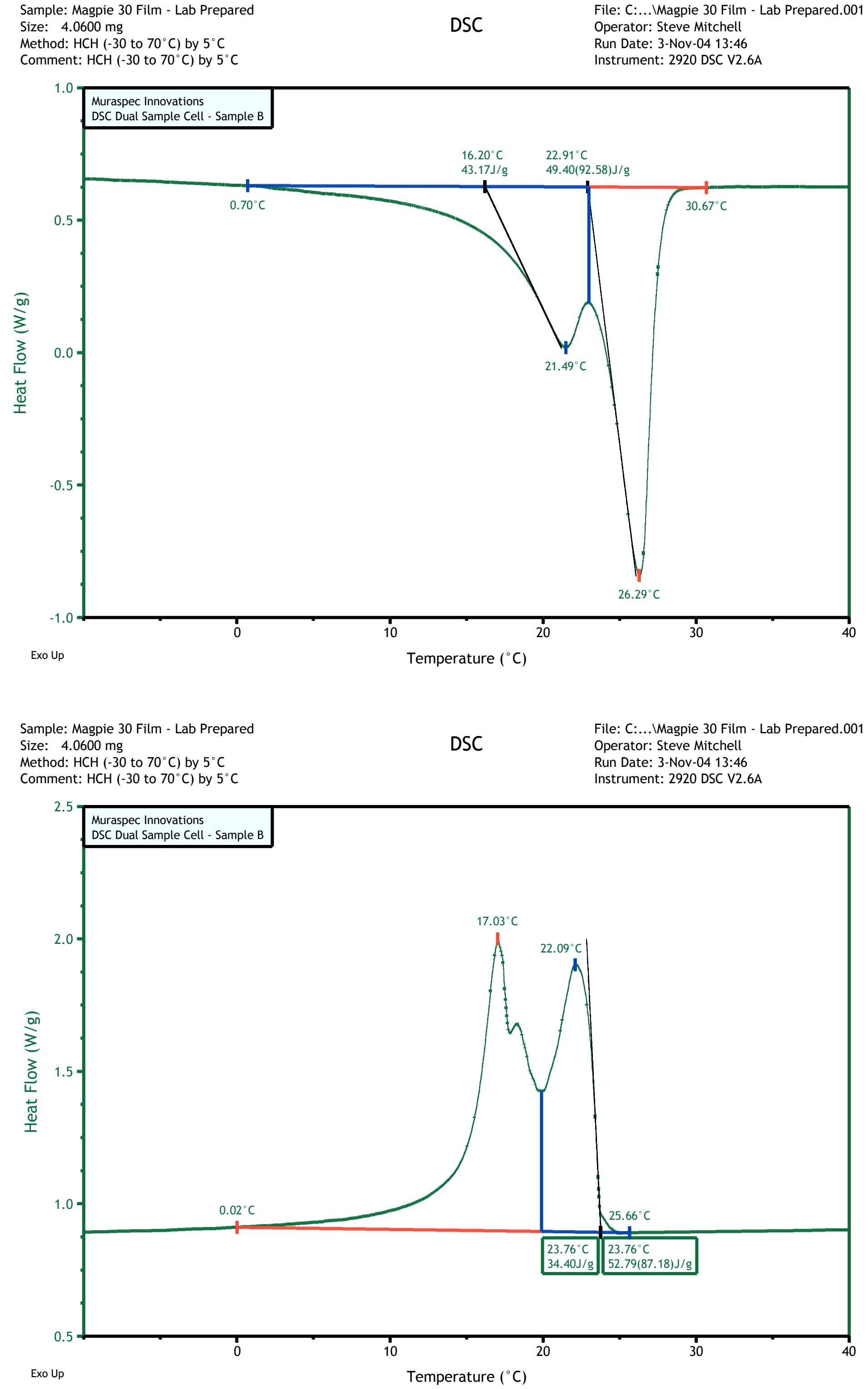


Figure 6.4 DSC results of lab prepared phase change wall-lining containing 45% Outlast XXL(2) Thermocules

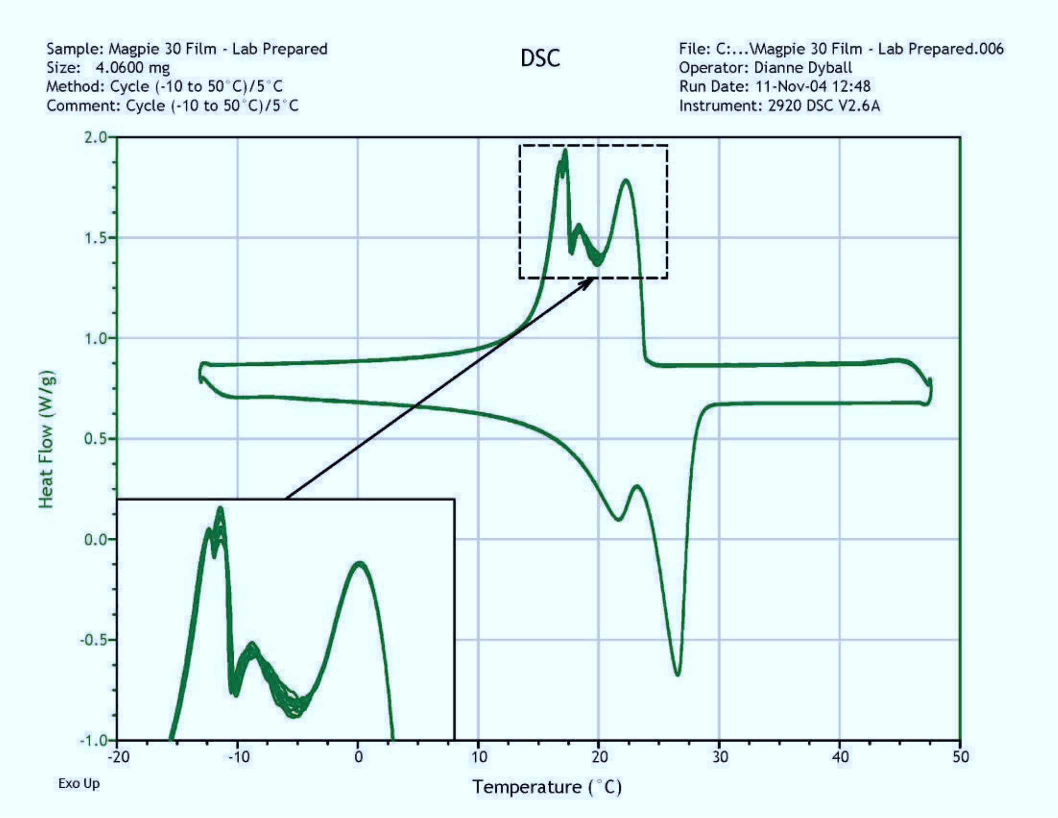


Figure 6.5 Results of thermal cycling lab prepared phase change wall-lining containing XXL(2) Thermocules

6.4 Analysis

Outlast Technologies Inc improved the formulation and manufacture of their Thermocules and provided a batch called XXL(2). The particle size analysis determined the microencapsulated PCMs to have an average particle size of 109µm.

The DSC analysis of XXL(2) showed the phase change temperature to be 23°C during heat cycle and 24°C during cool cycle. The cooling cycle of the DSC analysis, when the PCM is turning from a liquid back to a solid, showed 3 peaks in the graph. This could be due to the PCM used containing impurities or being a blend of waxes. A blend of waxes is often used as this can modify the phase change temperature or latent heat capacity without complicating the chemical processing of materials. Outlast have revealed the core material of the Thermocules is octadecane and they often use impure materials to reduce their raw materials costs. Therefore the 3 peaks exhibited during the cooling cycle will be the freeze points of the impure components of the Thermocules.

When XXL(2) was included in the optimised plastisol formulation, the phase change temperature shifted slightly to 22.91°C in heat cycle and to 23.76°C in the cool cycle and the latent heat capacity was 90 J/g. Critically, the shape of the peaks has changed raising concerns the microencapsulated PCMs had changed during the lab production of the phase change wall-lining.

Thermal cycling of the phase change wall-lining was undertaken and the results showed the thermal performance remained the same for every cycle. Therefore the phase change wall-lining formulation was successful.

6.5 Outcome

A phase change wall-lining formulation containing a high proportion of microencapsulated phase change materials, 46% by weight, has been developed with a phase change temperature of ~23°C and a latent heat capacity of 90 J/g.

The sample phase change wall-lining did not exhibit any wax residue on its surface and extensive thermal cycling demonstrated the phase change materials maintained performance. Therefore the Outlast XXL(2) Thermocules have not ruptured. This confirms the improved microencapsulation by Outlast provides shells sufficiently robust to withstand the mechanical processing of a plastisol formulation.

The next experiment is to scale up the formulation and manufacture a large quantity of phase change wall-lining that can be located on the surfaces of a room.

7 Experiment 4: Pilot Scale Manufacture of Phase Change Wall-lining

In Chapter 6, Experiment 3, improved microencapsulated phase change materials were provided by Outlast Technologies Inc, referred to as Outlast XXL(2) Thermocules. These were successfully included in a plastisol formulation and a sample phase change wall-lining was produced with a PCM content of 46% by weight, phase change temperature of 23°C and a latent heat capacity of 90 J/g.

7.1 Hypothesis

If the vinyl plastisol formulation containing microencapsulated PCMs can be up-scaled then a pilot scale production run could manufacture a large quantity of phase change wall-lining.

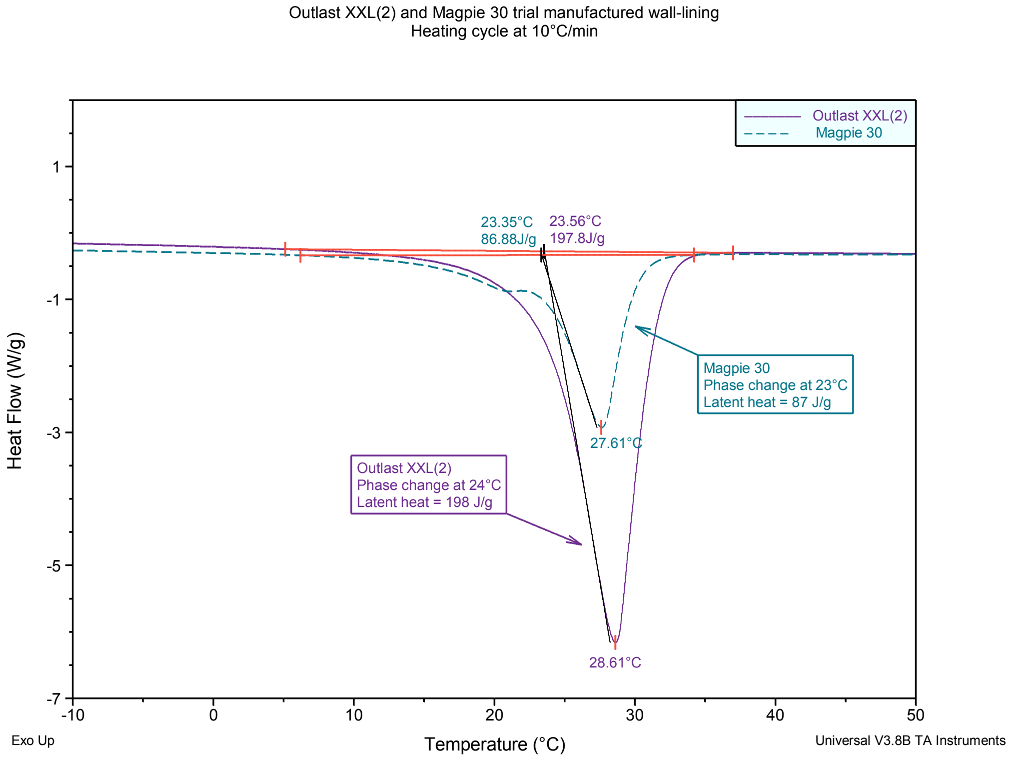
7.2 Experimental Setup

The plastisol formulation developed in Chapter 6 was scaled up and mixed in the manufacturing facilities at OMNOVA. The vinyl was manufactured at Kemmetech using the knife over roll method. Due to the limited quantity of plastisol formulation the vinyl had to be coated out in one pass. To maximise the latent heat capacity of the phase change wall-lining the plastisol was coated out as thick as possible to produce a thicker phase change wall-lining.

The produced phase change wall-lining was analysed to determine its thermal properties. Thermal analysis using differential scanning calorimetry was undertaken to determine the phase change temperature and the latent heat storage capacity. The thermal conductivity was evaluated by Gearing Scientific Ltd using a LaserComp Fox 200 thermal conductivity instrument which conforms to ISO 8301. The thermal conductivity value of a material is important as it is a measure of the rate at which heat can pass through a material.

7.3 Measurement

The pilot scale trial was successful and produced 50m of 700mm wide, 6mm thick phase change wall-lining. The wall-lining contained 45% by weight of Outlast's XXL(2) Thermocules. The thermal performance of the trial manufactured phase change wall-lining was analysed and the results are shown in Figure 7.1.



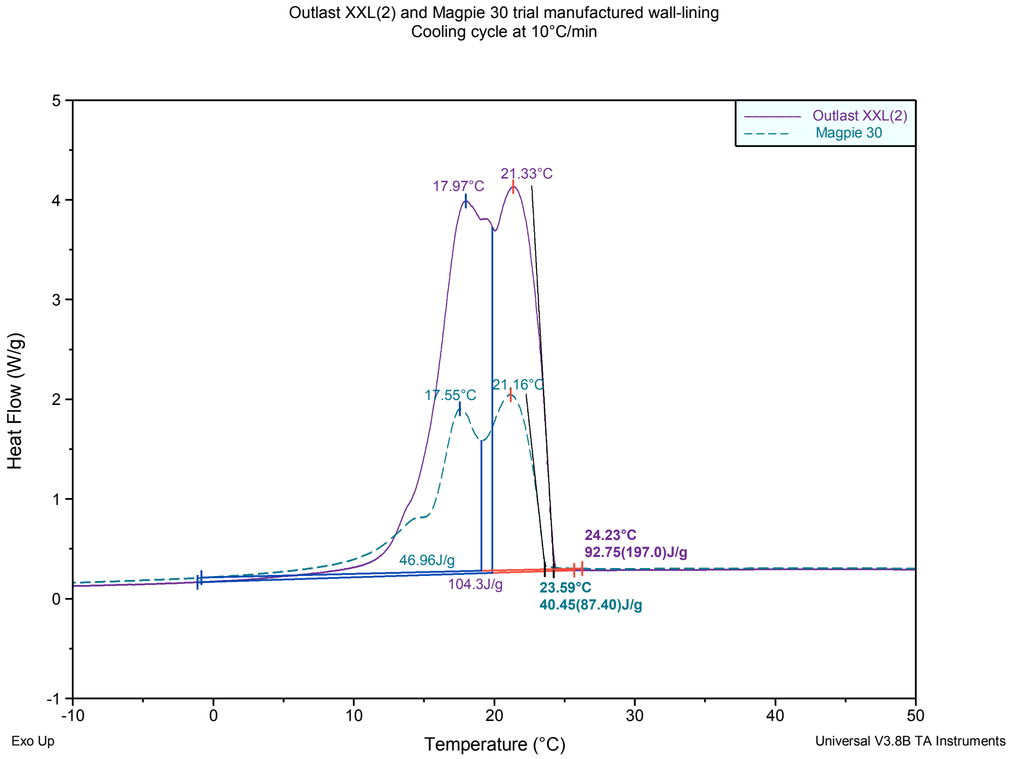


Figure 7.1 Thermal analysis results of trial manufactured phase change wall-lining

The DSC results of the manufactured phase change wall-lining, Magpie 30, show the phase transition temperature is 23°C and the latent heat storage capacity is 87 J/g. This latent heat capacity equates to 503 kJ/m^2.

The graph also includes the DSC results of the Outlast XXL(2) Thermocules used in the phase change wall-lining. This makes it easy to identify any change in the peak profiles and highlight any problems that may have occurred to the microcapsules during manufacture. From the graph in Figure 7.1 it is clear the melt point has shifted from 24°C to 23°C as happened with the lab prepared sample (Figure 6.4). As this is a consistent trait of the inclusion of XXL(2) into PVC wall-linings there is no need for concern.

The thermal conductivity value of the manufactured phase change wall-lining is 0.12 W/mK.

7.4 Analysis

The formulation for the phase change wall-lining containing Outlast XXL(2) microencapsulated phase change materials needed to be modified slightly when scaled up for the pilot scale manufacture. Mixing the larger quantity of plastisol increased the viscosity of the liquid and 1% less by weight of the XXL(2) could be included. Hence the manufactured phase change wall-lining has a latent heat capacity of 87 J/g (503 kJ/m^2) whereas the lab prepared sample in Chapter 6 was 90 J/g.

The manufactured phase change wall-lining has not fully cured in the centre. The wall-lining breaks easily when flexed and the centre has a ‘cheesy’ appearance. Due to the high cost of the raw materials, mainly the microencapsulated PCMs, there was a finite amount of plastisol for the pilot scale manufacture. Therefore there was not the opportunity to optimise the curing conditions during the production run. Despite this the thermal analysis results of the phase change wall-lining show the pilot scale production is a success.

7.5 Outcome

A pilot scale manufacturing trial produced 50m of 0.7m wide, phase change wall-lining containing 45% PCM. The 6mm phase change wall-lining has a latent heat capacity of 87 J/g (503 kJ/m^2), a phase change temperature of 23°C and a thermal conductivity of 0.12 W/mK.

8 Experiment 5 - Evaluation of Phase Change Wall-lining

In Chapter 7, Experiment 4, a pilot scale production run manufactured 50m of 0.7m wide, 6mm thick, phase change wall-lining. The phase change wall-lining has a phase change temperature of 23°C and a latent heat capacity of 87 J/g (503 kJ/m^2).

8.1 Hypothesis

If the phase change wall-lining is located on the surface of a room and exposed to different supply air temperatures and velocities then the phase change wall-lining will store and release different quantities of heat which will improve the thermal performance of the room.

8.2 Experimental Setup

The thermal performance of a building or room is the process of energy transfer between the building fabric (materials) and the surroundings. How well a building responds affects the internal conditions and energy consumption of the building. The key parameters influencing the thermal performance of the phase change wall-lining will be the air temperature and velocity. To assess the impact of these it was proposed to undertake experimental investigations using environmental test chambers subject to realistic thermal conditions.

The environmental test chambers consisted of two identical chambers with a controllable air-conditioning unit and extensive temperature monitoring equipment, all detailed in the following sections. The purpose of the experiments was to determine the amount of heat that is stored in the phase change wall-lining, how quickly it can store and release the heat and to gain an indication of the improved temperatures that can result from the use of having phase change materials on the surface of a room in a phase change wall-lining. Furthermore it was important to evaluate the effect of supply air conditions on the thermal behaviour and thermal storage capability of the phase change wall-lining.

The setup of the chambers was based upon the experimental setup of Scalat et al. (1996) who undertook full scale thermal storage tests of PCM wallboard. The basis of the setup was two thermally matched chambers, with an air-conditioning system, surface temperature sensors on the front and back of the PCM wallboard and sensors to measure the environmental temperatures.

The energy storage in the phase change wall-lining will be calculated using the temperature difference of the exhaust air from the chambers and the equation outlined in Section 2.1.1. As both chambers will be identical, with the exception of the phase change wall-lining, theoretically the resulting difference will be due to the energy stored in the phase change wall-lining. This will account for both the sensible and latent heat stored.

The velocity of the supply air will impact the air change rate and the surface heat transfer coefficient in the environmental chambers. The higher the velocity the higher the heat transfer coefficient which results in a lower surface resistance. Theoretically this will enable more heat to be stored in the phase change wall-lining. The effect of different velocities will need to be assessed to identify the impact on the amount of phase change material that can be utilised in the phase change wall-lining. To evaluate this in the chambers different air supply rates will be used for the experiments. Ideally a range of air change rates should be used, between 1-10 ach (air changes per hour). These are typical of the air exchanges within naturally ventilated buildings (lower values) and mechanically ventilated buildings (mid to higher air change rates). To control the air change rates for the experiments the air-conditioning system shall be programmed at a number of settings to provide different air change rates. These shall be calibrated using an air flow meter and fixed for the duration of the experiments.

The resulting air and comfort temperatures in the chambers will be evaluated to establish the improvement in thermal comfort that can be achieved using the phase change wall-lining.

This chapter will report on the cause and effect rather than determining the detail of how the phase change wall-lining operates.

8.2.1 Environmental Test Chambers

Two highly insulated chambers (each 13.8m^3) were constructed in an open laboratory space at the University of Brighton that has relatively stable thermal conditions, see Figure 8.1.

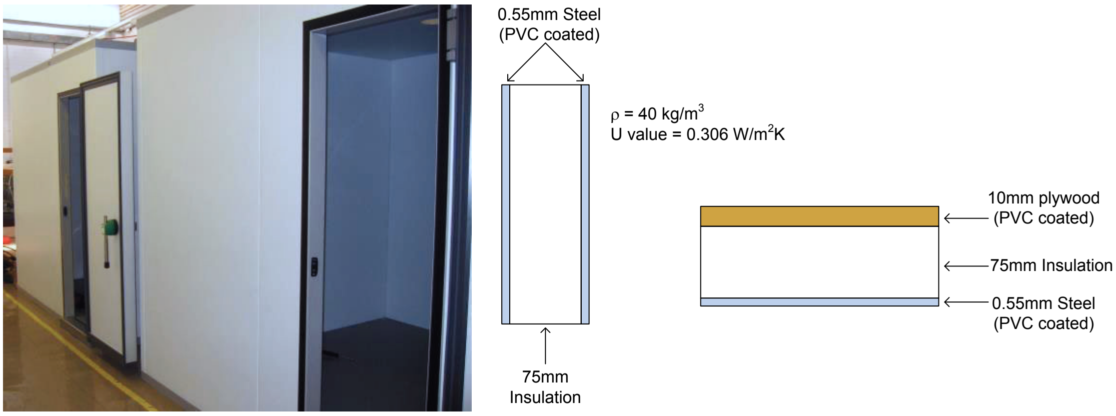


Figure 8.1 External view of environmental chambers (left) & schematic showing construction of walls, ceilings and floor (right)

Using two identical chambers provides both a Control and a Test Chamber. The Control Chamber would remain unchanged throughout the experiments and the Test Chamber would contain the phase change wall-lining. Both of the chambers were lined with timber boards to enable easy installation and removal of the phase change wall-lining in the Test Chamber.

8.2.2 Environmental Control

To enable realistic thermal conditions to be simulated in the chambers a programmable air-conditioning system was installed, Figure 8.2 and Figure 8.3.

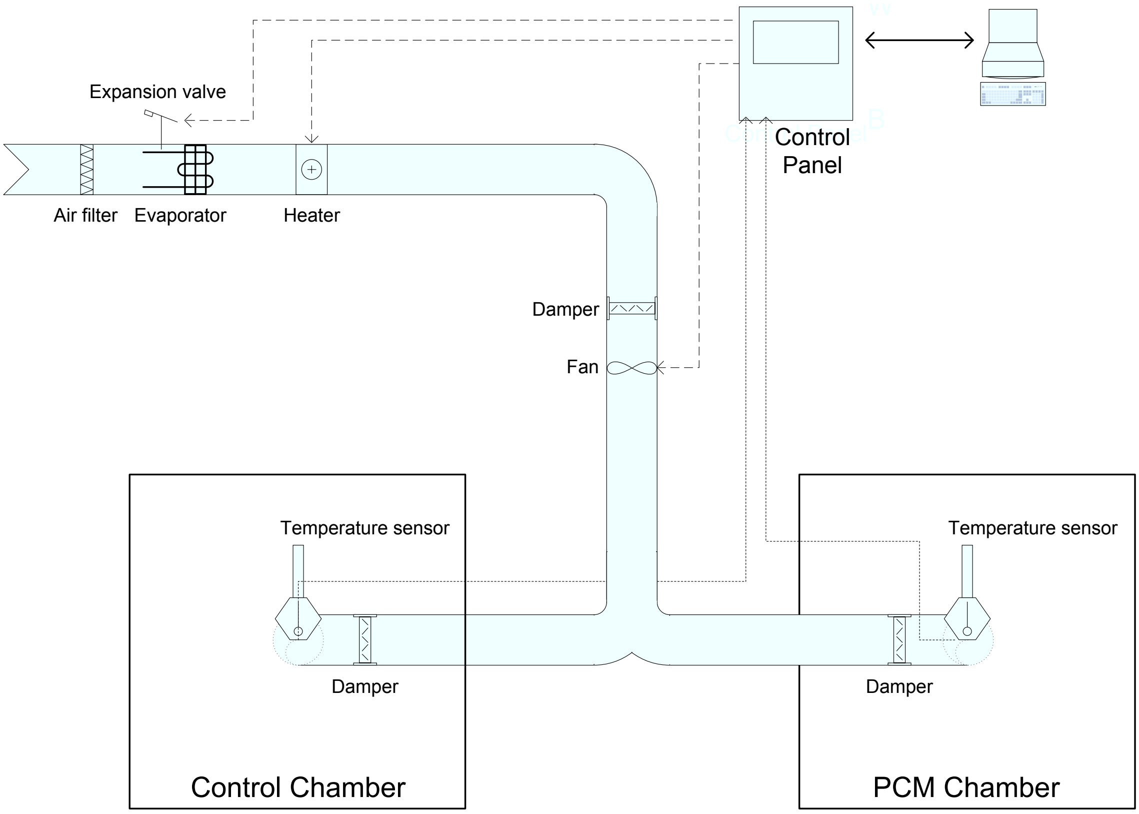


Figure 8.2 Schematic of air-conditioning system supplying environmental chambers

Figure 8.3 Photograph of air-conditioning installation to the environmental chambers

The system was designed to ensure identical thermal inputs to both chambers. The best method of achieving this was to provide one air-conditioning system and divide the air supply into both chambers. A single air supply duct is divided and equal duct lengths supply the air directly to each chamber. The air is delivered into each test chamber simultaneously via a 4-way diffuser.

The air-conditioning system contains three main components that are controllable by the operator:

1. Cooling unit – either on or off
2. Heater – 3kW proportional control
3. Fan – three phase fan with variable flow

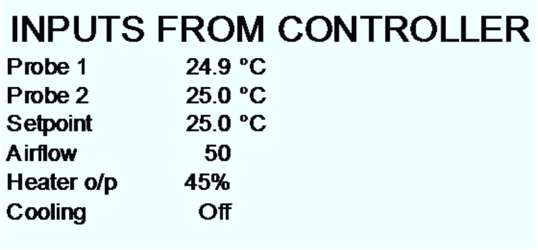
The temperature and air flow inputs are controlled by an Excel programme that operates the air-conditioning system via a programmable logic controller (PLC) in the control panel.

The supply temperature is monitored by two air temperature probes, both located in the ductwork prior to air inlet, which feeds back to the PLC and enables the program to adjust the amount of heat necessary to maintain the temperature set-point.

The air flow settings have been determined during the calibration process and are the air change rates between 1.5-10 ach are represented by values of 10-100 respectively.

Below in Figure 8.4 is an example of the input screen for the temperature and air flow set-points at half hourly intervals, and the screen providing real-time feedback of the actual temperature inputs achieved by the air-conditioning.

Time	*Temperature °C*	*Airflow Setting*
12:00 AM	15	50
12:30 AM	15	50
1:00 AM	30	50
2:00 AM	30	50
.	.	.
.	.	.
.	.	.
.	.	.
.	.	.
11:30 PM	30	50
12:00 AM	30	50



INPUTS FROM CONTROLLER

Probe 1	24.9 °C
Probe 2	25.0 °C
Setpoint	25.0 °C
Airflow	50
Heater o/p	45%
Cooling	Off

Figure 8.4 Example of Excel user interface to control air-conditioning system

8.2.3 Monitoring Equipment

To obtain the information required to evaluate the performance of the phase change wall-lining surface, air and room temperature sensors were required in the chambers. These were all connected to a data logger for data acquisition at timed intervals. The details of the monitoring equipment installed are given below and a summary given in Table 8.1.

For the heat balance of the environmental chambers, it is necessary to measure the supply air temperature, internal air temperature, exhaust air and the air temperature outside the chambers. These can be measured using air temperature sensors.

It has been proposed to use a globe sensor which averages the air and mean radiant temperature at low air velocities. The globe temperature sensor is often used as an indicator of human thermal comfort.

To calculate heat transfer through a wall it is necessary to know the temperature at each surface. This can be measured using surface temperature sensors at each layer of the wall surface. The results can then be used to evaluate how much heat has transferred through each element of the wall construction, how much heat has been stored in each material and the heat transfer rate can be calculated.

Chamber	Tile Reference	Sensor Location (see Figure 8.7)	Type of Temperature Sensor		
			Thermocouple (Surface)	Thermistor (Air)	Globe (Room)
Test	A1	front surface wall-lining	✓		
Test	A4	front surface wall-lining	✓		
Test	A7-1	front surface wall-lining	✓		
	A7-2	back surface wall-lining	✓		
	A7-3	back surface mdf tile	✓		
	A7-4	back surface lining board	✓		
	A7-5	external wall surface	✓		
Test	A14	front surface wall-lining	✓		
Test	B3	front surface wall-lining	✓		
Test	B12	front surface wall-lining	✓		
Test	B13	front surface wall-lining	✓		
Test	C7	front surface wall-lining	✓		
Test	D1	front surface lining board	✓		
Test	Pceiling	surface	✓		
Test	Pfloor	surface	✓		
Test	PAirIn	In supply ductwork		✓	
Test	PRoomAir	Centre of chamber		✓	
Test	PGlobe	Centre of chamber			✓
Test	PAirOut	Air out duct		✓	
Control	E1	front surface tile	✓		
Control	E4	front surface tile	✓		
Control	E7	front surface tile	✓		
		Back surface tile	✓		
		back surface lining board	✓		
		external wall surface	✓		
Control	E14	front surface tile	✓		
Control	F3	front surface tile	✓		
Control	F12	front surface tile	✓		
Control	F13	front surface tile	✓		
Control	G7	front surface tile	✓		
Control	H1	front surface lining board	✓		
Control	Cceiling	surface	✓		
Control	Cfloor	surface	✓		
Control	CAirIn	In ductwork		✓	
Control	CRoomAir	Centre of chamber		✓	
Control	CGlobe	Centre of chamber			✓
Control	CAirOut	Air out duct		✓	
External	ExtAir	Lab area		✓	

Table 8.1 Summary of monitoring sensors installed

Surface Temperature Sensors

A total of 35 J-type thermocouples were installed in each chamber to measure surface temperatures. They were located on the wall surfaces and between every layer of the wall at selected locations in each chamber. Thermocouples were also installed between the phase change wall-lining and the mdf backing board in addition to the timber lining and surface of the Test Chamber walls. Locating thermocouples between each layer of wall will provide the data for calculating the heat transfer rates during the experiments.

Air Temperature Sensors

Three air temperature probes were positioned to monitor the following temperatures:

Supply air – located in supply air duct
Room air – located in centre of room (see Figure 8.5)
Air out – located in extract duct

An air temperature probe was positioned in the laboratory area outside the chambers to record the external air temperature.

Room Globe Temperature

A room globe temperature sensor, Figure 8.5, comprises a thermistor within a 36mm black globe to measure the effects of radiant heat and is located in the centre of each chamber. The globe temperature sensor takes into account the air and radiant temperatures at different air velocities. The globe temperature is used as an indication of human thermal comfort, hence is often referred to as the comfort temperature (Humphreys, 1978).

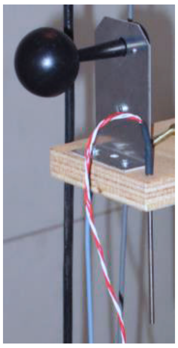


Figure 8.5 Room temperature sensor (black globe) and an air temperature probe

Data Logger

The data logger used was an Agilent Benchlink 34970A. It has three 20-channel differential voltage multiplexer cards that allow up to 60 channels of logged data. The data logger was connected to a personal computer that was used to store the data and was located in a cupboard in the laboratory area. The data logger was programmed to record data at 2 minute intervals.

Figure 8.6 The Agilent Benchlink data logger with multiplexer card (showing wiring of air temperature probes)

The air and room temperature sensors were wired directly into the data logger. The thermocouples were connected via selection boxes that were wired directly into the data logger. These selection boxes provided sockets for the thermocouples to be plugged into for recording the surface temperatures of 30 thermocouples. This enabled greater flexibility for which surface temperatures were to be recorded for the experiments as 35 were installed in the chambers but the data logger multiplexer cards only had space for 30 to be wired in.

8.2.4 Calibration and Commissioning

All the equipment has been calibrated according to manufacturer's instructions.

To ensure the environmental chambers were thermally matched they were subject to thermal cycling comprising heating at 25°C then cooling at 18°C for 6 days. If the test chambers contained the same amount of thermal mass, i.e. identical constructions, then the temperature results for both of the test chambers would be the same.

The results showed that during the cooling cycle (18°C) a temperature 'spike' would occur. To investigate the recurring temperature spike the chambers were heated at a constant 25°C for 20 hours. The temperature spike occurred again and detailed analysis of the results revealed that the AC system continually provided 30°C heating at 1:50am until 3:00am regardless of the 18°C set point that had being defined. The controls software was returned to the supplier for investigation and an error was found in the Excel program that controls the AC system. The fault in the formulae was identified, corrected and the returned program file was re-installed. The constant heating at 25°C experiment was repeated in the test chamber and the AC system functioned correctly.

In these experiments it was noticed the supply air temperature results for the Test Chamber were rather erratic. The probe operated correctly when calibrated so it was understood this was due to noise in the signal. The supply air temperature probes were initially located in the 4-way diffuser but it was decided to re-position them in the supply air duct. This would provide a better reading and enabled a more secure fixing so the noise could be removed from the signal.

As the AC system and air temperature probes were stable, the chambers were subject to heating and cooling cycles with air supply provided at 28°C and 15°C for 12 hours respectively.

The air temperature results showed the Test Chamber was heating quicker than the Control Chamber. Both chambers had closed air vents in the wall opposite the air outlet duct. Due to the side by side positioning of the chambers the air outlet for the Control Chamber was located adjacent to the closed air vent of the Test Chamber. It was suspected the faster temperature rise in the Test Chamber was due to the exhaust air from the Control Chamber entering the Test Chamber via the closed air vent. This was confirmed by switching off the AC system, sealing the air vents and air outlet ducts to prevent any ventilation, and placing a 360W radiant heater in each chamber. The chambers were heated using the radiant heaters for 7 hours and the temperatures monitored using the datalogger.

The resulting air temperature profiles for the chambers were the same. Therefore the reason the Test Chamber was heating at a faster rate was due to the Control Chamber exhaust air being forced into the Test Chamber through the closed air vent. These vents were sealed and they were heated to 28°C for 12 hours and subsequently cooled to 15°C for 12 hours with a constant air change rate of 9ach for 2 cycles. The results showed the supply air, room air and exhaust air temperatures in the Control Chamber were all within ±0.16°C of the same probes in the Test Chamber. Therefore the thermal performance of both the environmental chambers was the same.

To finalise the commissioning phase of the experimental setup, the stability test was undertaken. The AC system was set to provide a supply air temperature of 25°C during week days and 15°C at the weekends, at a constant rate of 9 air changes per hour. The aim was to ensure that all the temperature monitoring equipment was stable, maintaining performance for the duration of long experiments and did not experience any unusual spikes that may suggest a loose connection or unreliable sensor.

The stability test was run for 2½ weeks. During the first week all the air temperature probes appeared to oscillate slightly in both chambers. This settled down in the 2nd and 3rd week, therefore suggesting there may have been external influences affecting the experiment, for example building works on the floors above the laboratory area causing vibrations in the test chambers which was picked up by the monitoring equipment.

8.2.5 Installation of Phase Change Wall-lining

The manufactured phase change wall-lining weighed 5.78 kg/m^2 so for ease of installation it was mounted onto 590mm x 590mm medium density fibreboard (mdf) tiles that were securely fixed to the walls of the Test Chamber, totalling 17.5m^2 (see Figure 8.7) . This gave a total latent heat capacity of 8,803 kJ in the Test Chamber.

To maintain the same thermal capacity of the construction in both chambers, the same number of mdf boards was installed in the Control Chamber. Therefore the only difference in the two chambers was the phase change wall-lining.

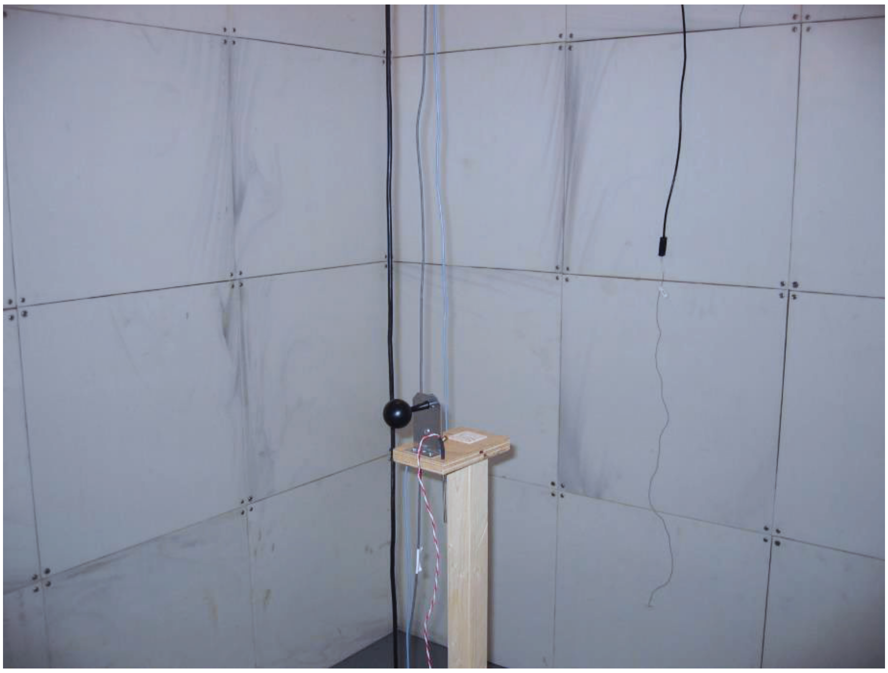


Figure 8.7 Internal view of Test Chamber containing phase change wall-lining and temperature monitoring equipment

The layout of the tiles, location of surface temperature sensors and reference numbers used in each chamber is shown in Figure 8.8 overleaf.

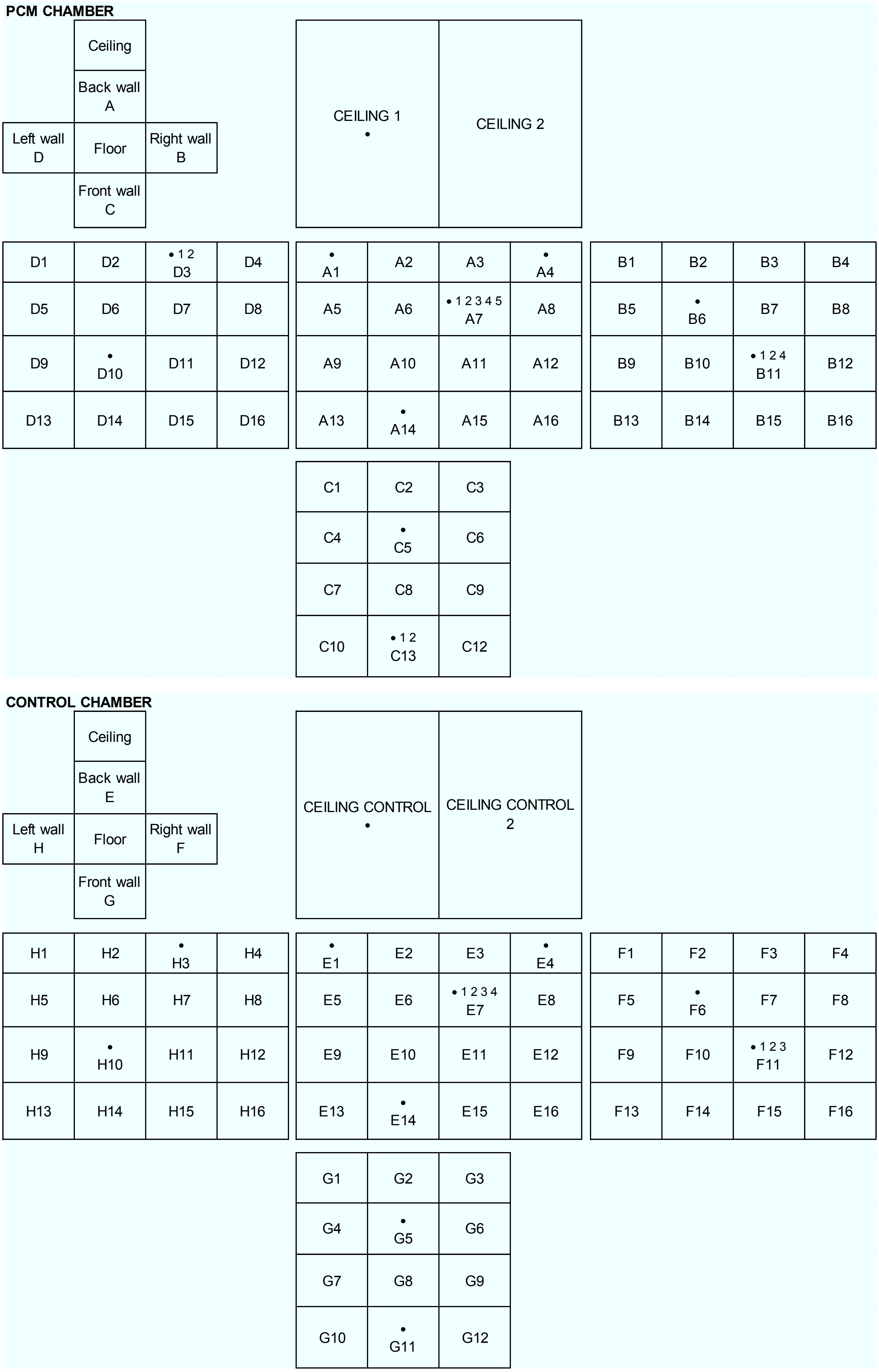


Figure 8.8 Layout of tiles, sensors and reference codes for both Chambers

8.2.6 Experimental Programme

The experimental evaluation of the phase change wall-lining is to determine if having phase change materials on the surface of a room can improve its thermal performance. Therefore the experimental programme has been developed to obtain the required data to understand the thermal behaviour of the phase change wall-lining and the resulting environmental conditions in the room.

The input variables of the experimental setup are the air supply temperature and velocity. The environmental chambers were heated and subsequently cooled to a fixed temperature. Each experiment used a different air supply rate, which remained constant throughout the duration of the experiment. The experiment continued until steady state conditions were reached.

The two set temperatures for the experiments were chosen to be 15°C and 30°C. There are two reasons for selecting this temperature range:

1. These temperatures are a few degrees outside the phase change temperature range of the wall-lining. This provides a sufficient temperature range to enable both melting and freezing phases to take place.
2. These are the boundary thermal conditions people would find acceptable in a real room environment. As the phase change wall-lining has been developed as a solution to maintaining a comfortable thermal environment, it is important realistic thermal conditions are considered in the experiments.

CIBSE provide guidance on thermal comfort and recommends that 25°C should not be exceeded for more than 5% of occupied periods and that 28°C should not be exceeded more than 1% of the occupied period (CIBSE, 2006). Therefore using an upper boundary limit of 30°C for the experiments is considered appropriate.

Pre-conditioning temperature (°C)	***Supply air temperature (°C)***	***Air change rate (ach)***
15	30	1
30	15	1
15	30	3
30	15	3
15	30	5
30	15	5
15	30	7
30	15	7
15	30	9
30	15	9
15	30	10
30	15	10

Table 8.2 Experimental programme

The different air velocities of the supply air would affect the surface heat transfer coefficient of the phase change wall-lining, consequently the potential ability to store latent heat. It was discussed in Chapter 2 that the air velocity was critical to the charge and discharge time of PCM concrete. Therefore a range of air velocities have been included in the experimental programme to understand the impact it has on the heat transfer rates and ability to store heat, using a phase change wall-lining.

This experimental programme focuses on testing the concept of having phase change materials on the surface of a room to affect the internal room air temperatures, therefore a fixed air supply temperature and velocity has been selected to test the phase change wall-lining.

Prior to each experiment the chambers were pre-conditioned for a long period of time using the starting room air temperature of the experiment (15°C or 30°C) to thermally balance the chambers. Therefore the specific heat capacity in each chamber would be identical, with the exception of the chamber containing the phase change wall-lining.

8.3 Measurement

A number of technical issues with the control of the air-conditioning system arose during the initial experimental programme. It was realised the air-conditioning system was unable to achieve the 30°C supply air temperature when the ambient air temperature in the laboratory was less than 21°C. Therefore the experimental programme had to be delayed until the spring when the laboratory was warmer. The air-conditioning system was also unable to maintain heat when the supply air was at 1 air change an hour (ach). At this lower air speed the heater would overheat and cut out. Therefore no experimental results are available for this scenario.

The limitation of not being able to undertake testing at one air change an hour is that the performance of the phase change wall-lining in the Test Chamber with minimal air movement cannot be assessed. The phase change wall-lining is being developed as a potential solution to overheating by providing thermal mass in lightweight buildings, particularly naturally ventilated buildings. These type of building would have lower air change rates, in the order to 1-2 air changes an hour, therefore understanding the phase change wall-linings ability to exchange heat within a relatively still Chamber was desired.

The experimental results selected for analysis and discussion in this section are outlined in Table 8.3. These experiments were undertaken in the months of March to May inclusive so the heating cycles have not been affected by lower ambient temperatures.

Supply air temperature (°C)	*Air change rate (ach)*
30	3
15	3
30	5
15	5
30	9
15	9

Table 8.3 Experimental results to be analysed and discussed

The experimental results have been analysed using time vs. temperature profiles over 24 and 48 hour periods to understand the effect of the phase change wall-lining on the room temperature of the Test Chamber. The quantity of heat stored and released in the phase change wall-lining has been calculated using the exhaust air temperatures and the general heat balance equation for each experiment.

The time taken to charge and discharge the heat has been determined to evaluate the effect of the different air change rates. The resulting air and room temperatures have been reviewed along with the surface temperature distribution across the walls.

These analyses will provide an understanding of how locating phase change materials on the surface of the Test Chamber improves its thermal performance.

8.3.1 Exhaust Air Temperatures

To assess if the phase change wall-lining has had any impact on the thermal conditions of the Test Chamber the exhaust air temperature results have been reviewed. Both chambers have identical supply air temperature and velocity therefore if the exhaust air temperature results are different this provides an early indication the phase change wall-lining can change the thermal performance of the Test Chamber. Furthermore this should provide an indicative analysis of the importance of the air change rate.

(a) Heating cycle

The graphical results of the exhaust air temperatures for the different air change rate experiments are shown in Figure 8.9 and it is clear the exhaust air temperature from the Test Chamber remains lower than the Control Chamber.

The 9ach results show clearly the different stages of the heat transfer process. The Control Chamber results show the initial stage when warm air begins entering the Control Chamber and the exhaust air temperature quickly ramps up to 21°C and then begins the sensible heat storage in the Control Chamber surfaces. The sensible heat storage completes at 12 hours and the exhaust air temperature remains fairly constant at 28°C for the remainder of the experiment when steady state heat transfer is underway.

Figure 8.9 shows the Test Chamber rapidly heats to 19°C and then begins a much slower rate of temperature change than the Control Chamber due to the phase change wall-lining. The temperature appears to reach steady state heat transfer at 39 hours, which is 27 hours later than the Control Chamber.

When comparing the time taken for each of the chambers to begin levelling out in temperature, Table 8.4, it is interesting to see that in the Control Chamber as the air change rate increases it reaches steady state much quicker. Whereas in the Test Chamber it takes 12 hours longer with 9ach for the exhaust air temperature to level out than with 3ach, and even then the temperatures do not appear to be at steady state as they still have a gradual increase to them when compared to the Control Chamber results.

The thermal behaviour exhibited in the Test Chamber is similar to a room with high thermal mass that slows the change in temperature, rather than maintaining a temperature set-point. A comparison of the time for the exhaust air temperatures to reach a reference temperature of 24°C in the two Chambers shows significant difference from 2, 4 and 15 hours in the Control Chamber to 4, 9 and 29 hours in the Test Chamber.

These results suggest that whilst there is a significant amount of heat going into the Chambers, the phase change wall-lining is absorbing that heat and therefore the temperature change rate and peak temperatures in the Test Chamber remain lower than in the Control Chamber.

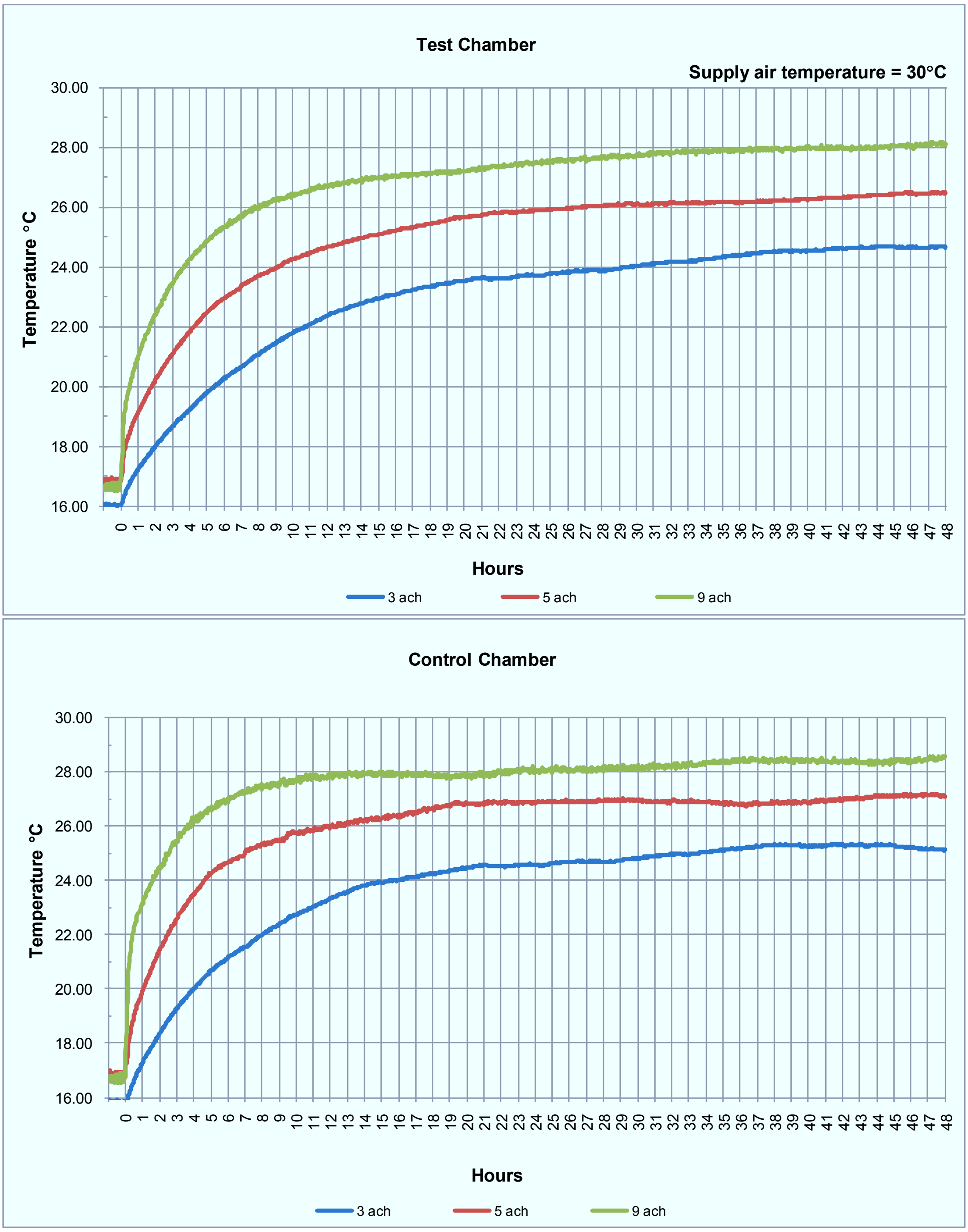


Figure 8.9 **Temperature profile of exhaust air temperature results during heat cycle**

Air Change Rate (ach)	*Control Chamber (hours)*	*Test Chamber (hours)*
3	21	27
5	20	28
9	12	39

Table 8.4 **Time taken for exhaust air temperatures to approach steady state heat transfer**

(b) Cooling cycle

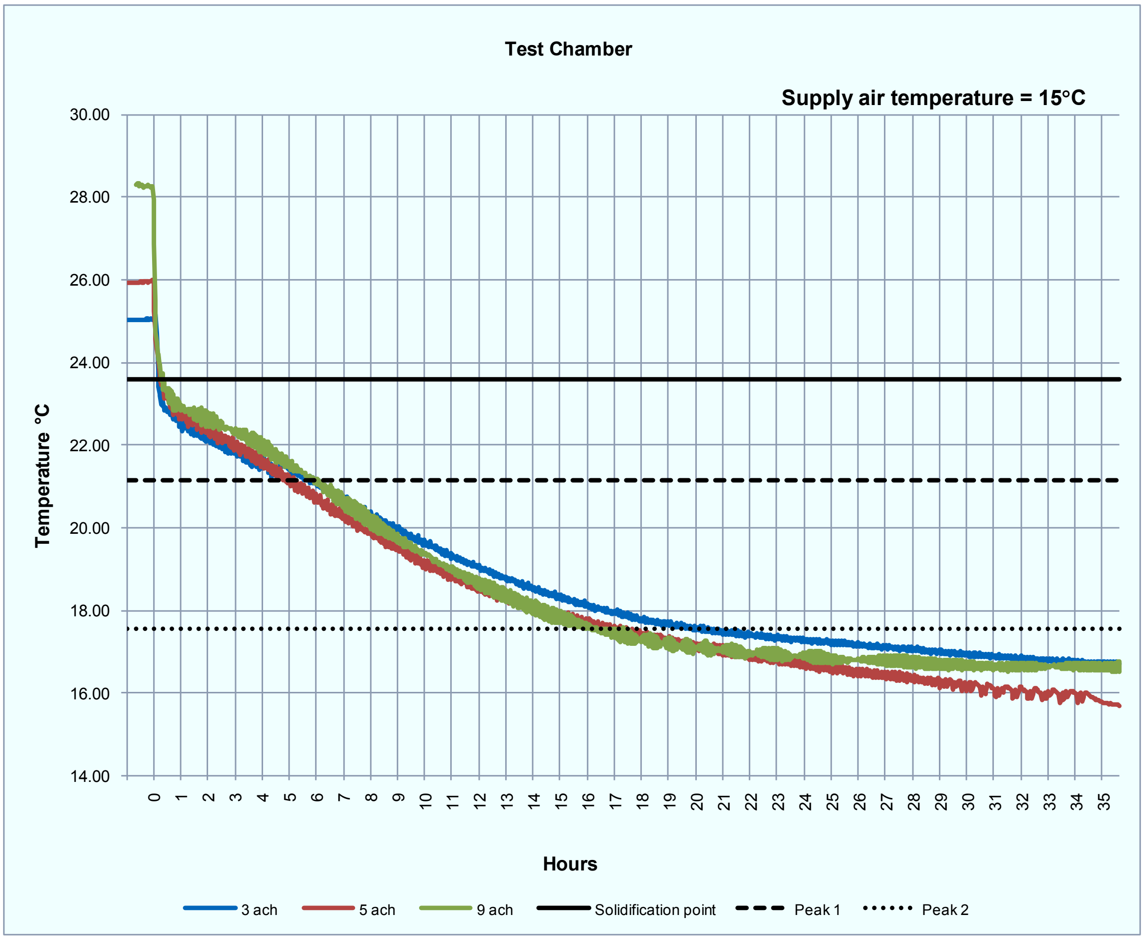
The exhaust air temperature graphs for the cooling cycle in Figure 8.10 show the temperature variations are less distinctly separated for each air change rate than those in the heating cycle. During the first hour when the warm air of the Chambers is being replaced by the 15°C supply air, the exhaust air temperature drops quickly as the thermal capacity of air is low.

A linear temperature profile is exhibited of a constant rate of change of temperature for the first 10 hours in the Test Chamber. Such characteristic is in contrast to the results for the Control Chamber where the temperature drops exhibiting a more exponential profile. This illustrates the slower rate of change of temperature in the Test Chamber is due to the stored latent heat being released from the phase change wall-lining, maintaining warmer temperatures for longer in the Test Chamber. From approximately 10 hours the rate of temperature change becomes non-linear in the Test Chamber as the sensible heat transfer becomes more dominant and the phase change wall-lining approaches the Peak 2 solidification temperature.

These results illustrate the phase change wall-linings ability to maintain a more stable thermal environment during the cooling cycle than the Control Chamber which drops in temperature at a faster rate.

From the exhaust air temperature profiles in Figure 8.10 it is not obvious if the air change rate has an impact during the cooling phase, as the resulting air temperatures for each experiment are similar.

In the following Section 8.3.2, Figure 8.12 shows the peak amount of heat discharged from the phase change wall-lining during the cooling cycle occurred at 5-6 hours for all air change rates. The impact of this is not obvious on the exhaust air temperature profile in Figure 8.10 although interestingly this is when the exhaust air is the same temperature as the Peak 1 solidification temperature and the mid-point of the linear rate of temperature change that occurs in the first 10 hours.



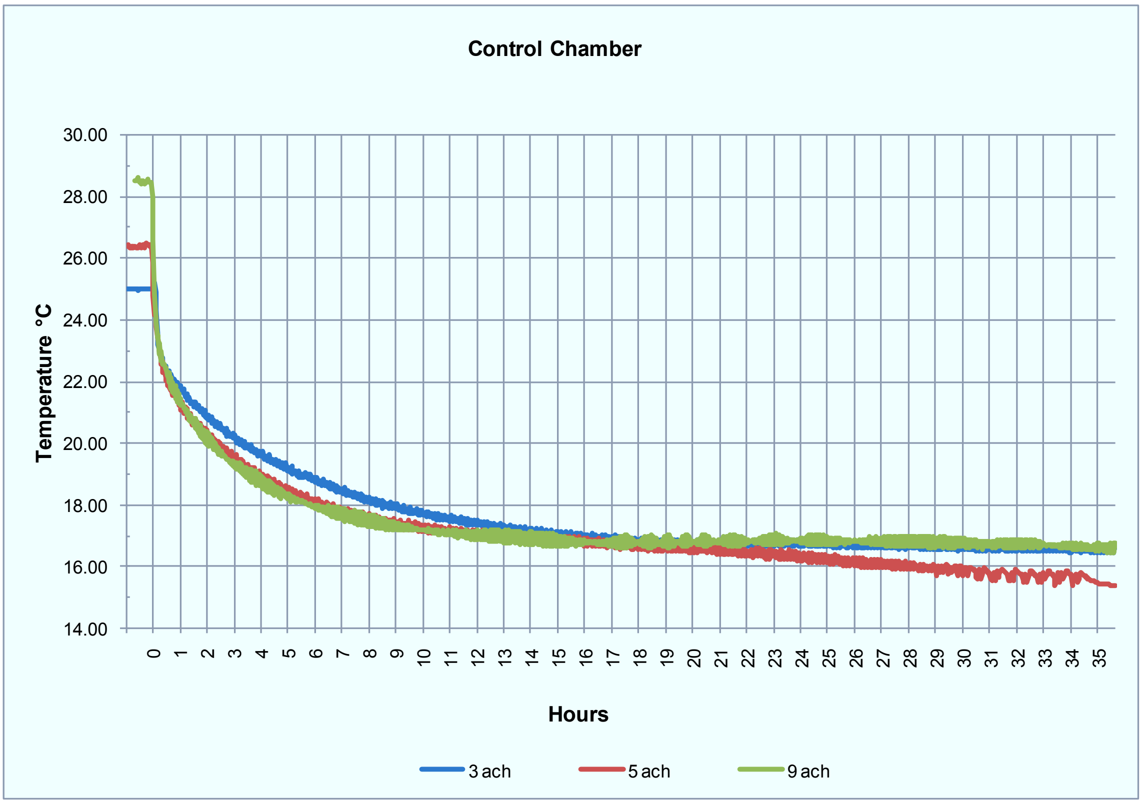


Figure 8.10 Exhaust air temperature profile of Chambers during cooling cycles

8.3.2 Energy Stored and Released in Phase Change Wall-lining

To determine the amount of heat, both sensible and latent, stored in the phase change wall-lining the thermal energy stored in the fabric of each chamber has been calculated using the exhaust air temperature results recorded every two minutes. This data has been processed using the general heat balance equation below:

$$Q = \dot{m}c_{pa}(T_{eT}-T_{eC})\Delta t$$

Where:

Q = *quantity of heat transferred to the phase change wall-lining (kJ)*

$\dot{m}$ = *mass flow rate of air (kg/s)*

c_{pa} = *specific heat capacity of air (kJ/kgK)*

T_{eT} = *exhaust air temperature from Test Chamber (°C)*

T_{eC} = *exhaust air temperature from Control Chamber (°C)*

t = *time step (seconds)*

The results from each experiment were calculated and the Control Chamber results were subtracted from the Test Chamber results. The difference will determine the amount of heat stored in the Test Chamber, discounting the sensible heat effect of all none phase change wall-lining materials. This will determine the amount of sensible and latent heat stored and released in the phase change wall-lining.

(a) Heating Cycle

The profiles for the amount of heat stored in the phase change wall-lining for each heat cycle experiment are shown in Figure 8.11.

The graphical results show for the experiment with the lowest air velocity, 3 air changes an hour, a gradual increase in the amount of heat stored for the first 5 hours. From that point forward the amount of energy stored is relatively consistent per hour. The total amount of energy stored over 48 hours using 3 air changes an hour is 1,741 kJ.

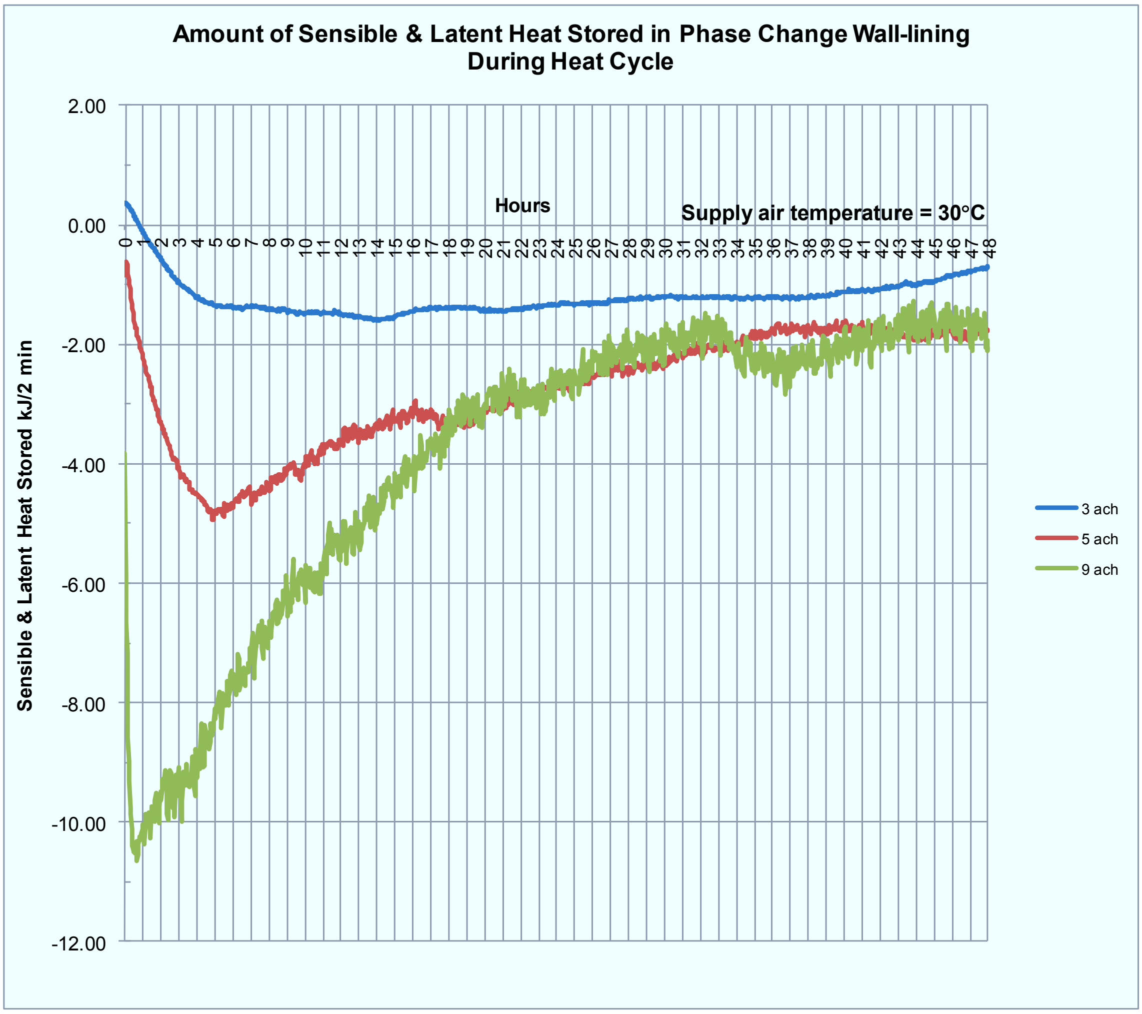


Figure 8.11 Graph showing amount of heat stored in phase change wall-lining during heat cycle

When the air exchange rate was increased to 5 air changes an hour the graph in Figure 8.11 shows a more rapid rate of heat storage took place in the first 4-5 hours. This began to slow after 5 hours and whilst heat is still being stored by the phase change wall-lining, the rate of storage is declining. A total of 4,002 kJ of energy was stored during the 48 hours of the experiment, before approaching steady state conditions.

For the highest air exchange rate, 9 air changes an hour, the amount of heat stored is greater per hour, with the overall profile showing the highest amount of heat stored in the first hour after which the amount of heat stored decreases each hour. In total, this the higher air exchange rate resulting in 5,579 kJ of total energy stored.

To determine the effectiveness of the phase change wall-lining it is important to quantify the proportions of sensible and latent heat stored. This will reveal how much of the 8,803 kJ of latent heat capacity in the phase change wall-lining was utilised in the experiments.

This has been determined by calculating the theoretical amount of sensible heat stored (Q_{SHC}) in each experiment, subtracting it from the total heat stored (Q_{total}) which will reveal the amount of latent heat stored (Q_{LHC}) during the experiment.

$$Q_{LHC} = Q_{total} - Q_{SHC}$$

The sensible heat stored was calculated using the following formula:

$$Q_{SHC} = m_{w-l}c_{pw-l}(\Delta T_s)$$

Where:

Q = *quantity of heat transferred (kJ)*

m = *mass of wall-lining (kg)*

c_{pw-l} = *Specific heat capacity of wall-lining (kJ/kgK)*

ΔT_s = *Average surface temperature of phase change wall-lining (°C)*

As the phase change wall-lining is manufactured using PVC, an approximation of the specific heat capacity of the wall-lining was taken from published figures for PVC (CIBSE, 2006).

The results of the amount of sensible heat and latent heat stored in the phase change wall-lining during each experiment are shown in Table 8.5.

Air Change Rate (ach)	***Total Heat Stored (kJ)*** Q_{total}	***Sensible Heat Stored (kJ)*** Q_{SHC}	***Latent Heat Stored (kJ)*** Q_{LHC}	***Amount of latent heat capacity of phase change wall-lining used***
3	1,741.49	945.75	795.74	9%
5	4,002.49	1,002.40	3,000.09	34%
9	5,578.87	1,137.94	4,440.93	50%

Table 8.5 Quantity of sensible and latent heat stored in the phase change wall-lining

The experiment using 3 air changes an hour shows that only 9% of the latent heat capacity of the wall-lining was utilised and the amount of sensible heat stored was greater than the latent heat stored. The higher air exchange rate (9 ach) provided the greatest amount of latent heat storage with half of the phase change materials being used.

When the surface temperature results are reviewed (see Section 8.3.4) there is a variation across the different surfaces in the Test Chamber, depending upon their location. The surface temperature distribution in both Test and Control Chambers are consistent with each other and the stratification you would expect with the higher tiles having higher surface temperatures than the tiles lower down on the walls.

For the 5 ach experiment the surface temperature sensors recorded that the surfaces of the phase change wall-lining reached the melting onset temperature of 23.39°C at different time intervals, from 2 hours to 9 hours into the experiment, although the air temperature in the Test Chamber reached this temperature after 4 hours. Only one of the phase change wall-lining tiles (D3) reached the peak melt temperature of 27.61°C at 33 hours, which confirms why all the phase change wall-lining was not utilised. If the surfaces of the phase change wall-lining do not exceed the peak melt temperature, the PCMs in the wall-lining would not be able to absorb sufficient heat to utilise all of its latent heat storage capacity.

The phase change temperature of the phase change wall-lining is 23°C. As the results in Table 8.5 show there has been latent heat stored, therefore some of the phase change materials have begun changing phase. It would be reasonable to expect the graphical profiles of the surface temperatures to exhibit a slight change in profile at the phase change temperature indicating the phase transition taking place. The surface temperature results in the Test Chamber for the three different air changes do not show this (Figure 8.14), but exhibit a slower rate of change than the surfaces in the Control Chamber.

(b) Cooling Cycle

During the cooling cycle the amount of latent heat released from the phase change wall-lining was quantified. This was determined by calculating the heat stored in both the control and phase change wall-linings and the results for the sensible heat in the control wall-lining was subtracted from the phase change wall-lining to give the latent heat stored. The results are shown in Figure 8.12 and discussed below.

An immediate observation of the results during the cooling cycle is the similarity in profile to the DSC curves for the phase change wall-lining, see Chapter 7.

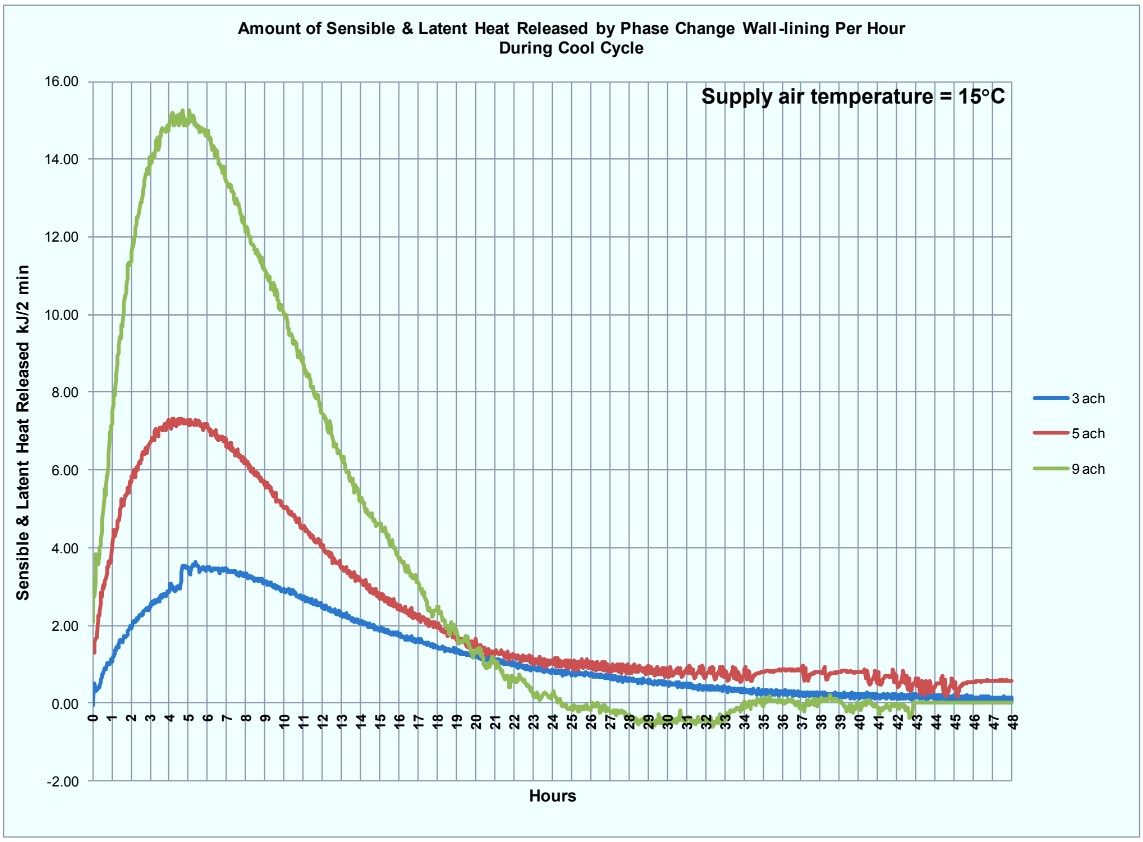


Figure 8.12 Illustration of amount of heat released by phase change wall-lining during cooling cycle

Interestingly, Figure 8.12 shows that it is over the same time period, approximately 21-22 hours that the majority of stored heat is released from the phase change wall-lining for each of the air velocities. The peak discharge occurred between 5 and 6 hours of cooling.

Figure 8.12 shows that despite the air change rates being different and the phase change wall-lining releasing different amounts of stored heat, the phase change wall-lining completes the peak discharge of heat at the same time period, between 5 and 6 hours of cooling for each experiment.

When the air temperature and exhaust air temperature graphs are reviewed at 5 hours this is the time at which the Peak 1 freeze temperature, 21.16°C, of the phase change wall-lining is reached.

Where all three lines cross in Figure 8.12 at 20 hours, this is close to the time that the air temperatures reach the phase change wall-lining's Peak 2 freeze temperature of 17.55°C.

The amount of heat released by the phase change wall-lining during each experiment is shown in Table 8.6. As with the heating cycle, it is important to determine the proportions of sensible and latent heat released from the phase change wall-lining. These have been calculated using the same formulae as previously and the results are tabled below.

Air Change Rate (ach)	***Total Heat Released (kJ)*** Q_{total}	***Sensible Heat Released (kJ)*** Q_{SHC}	***Latent Heat Released (kJ)*** Q_{LHC}	***Amount of latent heat capacity of phase change wall-lining used***
3	1,762.95	927.54	835.41	9%
5	3,363.64	1,115.68	2,247.96	26%
9	5,073.77	1,164.24	3,909.53	44%

Table 8.6 Amount of sensible and latent heat released from phase change wall-lining

These results show that using a higher air exchange rate enables a greater amount of the stored latent heat to be released from the phase change wall-lining. This is due to the increased heat transfer rate created with the higher air velocity.

This is consistent with published literature that recommends a higher air change rate is required for night-cooling a building with high thermal mass to discharge all of the stored heat. The same has been demonstrated for the phase change wall-lining.

8.3.3 Time Taken to Charge and Discharge the Wall-lining

(a) Heating Cycle

The duration of each experiment was dependent upon the time taken to reach steady state conditions. Each experiment was run and the temperature results were monitored until the air temperature stabilised in each chamber. It was then assumed that all of the heat storage capacity of the phase change wall-lining has been utilised and steady state heat transfer was in taking place. However, the results presented in Section 8.3.2 show that whilst the largest amount of heat storage took place within the first 1-5 hours and gradually diminished, the phase change wall-lining continued to store heat and only 9%, 34% and 50% of the latent heat capacity of the phase change wall-lining was utilised during the 3ach, 5ach and 9ach experiments, respectively.

The graph in Figure 8.11 showed the amount of heat being stored in the phase change wall-lining over a 48 hour period. The graph shows larger amounts of heat being stored in the initial hours and then the line plateaus showing a steady amount of heat storage per hour for the experiment which is likely to be due to the latent heat storage. The surface temperature results have been reviewed to identify the time periods where sensible and latent heat transfer would be taking place to provide a greater understanding of the heat storage profile in Figure 8.11.

Table 8.7 showed the time taken for the phase change wall-lining surface temperatures to reach the melt point of 23.35°C and peak melt temperature of 27.61°C. As the surface temperatures are higher in the upper parts of the Test Chamber, the time taken to reach the surface temperatures lower in the chamber are longer and therefore the upper and lower areas have been shown separately in the table.

The results shows that when the time taken for some of the wall-lining surfaces to reach the melt point [1] is the time at which only sensible heat transfer is taking place in the Test Chamber. Whilst all the surfaces of the phase change wall-lining are reaching the melt point, between [1] and [2] both sensible and latent heat transfer is taking place. Following the melt point, latent heat transfer is the pre-dominant, with sensible heat transfer likely to be making a small contribution. When the peak melt temperature is reached [4] all the heat transfer will be latent heat only. These heat transfer zones have been marked on the heat storage graph and are shown in Figure 8.13.

Air Change Rate (ach)	***[1] Upper walls reach melt point***	***[2] Lower walls reach melt point***	***[3] Upper wall area reaches peak melt temperature***	***[4] Lower wall area reaches peak melt temperature***
3	5 hrs	15 hrs	-	-
5	2 hrs	8 hrs	32 hrs	-
9	1 hr	5 hrs	16 hrs	41 hrs (except A14)

Table 8.7 Time taken for surface temperature of phase change wall-lining to reach melt point and peak melt temperature

Therefore in terms of the time taken for the phase change wall-lining to charge, it never fully charged in any of the experiments. However, the lower air change rate took 5 hours to begin any latent heat transfer and the predominantly latent heat transfer phase only began after 15 hours and the phase change wall-lining stored on average 1.21 kJ every two minutes.

The 5ach and 9ach experiments both began the latent heat transfer sooner, after 2 hours and 1 hour, respectively and spent the remainder of the 48 hour experiment storing mostly latent heat. For the last 12 hours of the experiment the latent heat transfer was taking place at an average of 2 kJ every two minutes.

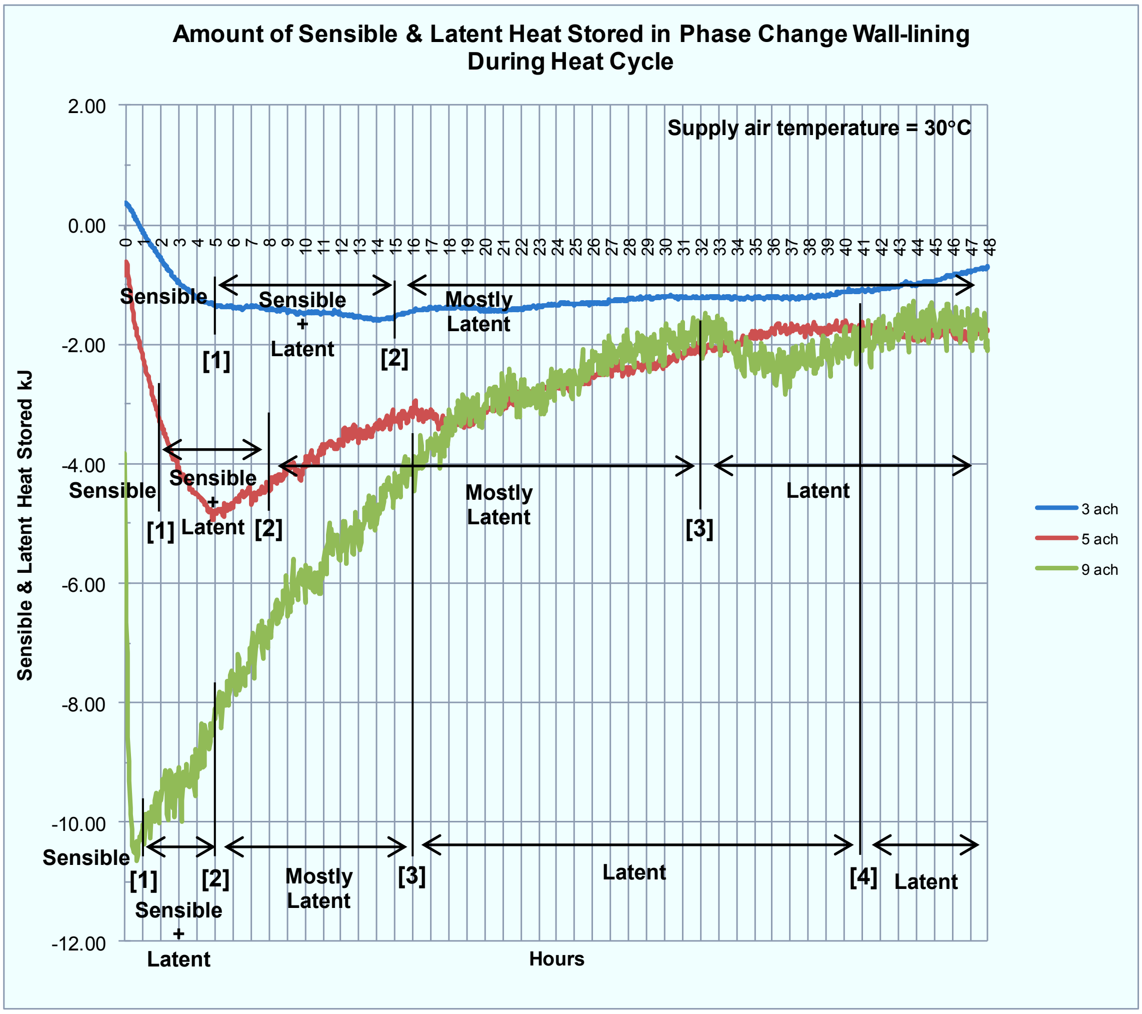


Figure 8.13 Graphical results of the heat stored in phase change wall-lining showing the intervals when different heat transfer was taking place

(b) Cooling Cycle

The results for the amount of heat released from the phase change wall-lining have been analysed on an hourly basis, as shown previously in Figure 8.12. The results show that when the air velocity was 3 air changes an hour, it took 33 hours to discharge all the stored latent heat.

Using 5 air changes an hour despite a significant amount of heat being released, 8,560 kJ over 36 hours, not all of the stored heat was released. The profile of the discharge graph suggests that all of the stored heat may be released by approximately 64 hours.

The highest air velocity, 9 air changes an hour, takes the least amount of time to fully discharge the largest quantity of stored heat, at 25 hours. This shows that to release a significant amount of stored heat quickly, a higher air exchange rate is necessary.

This is common practice for buildings using night cooling to discharge sensible heat stored in thermal mass. It is recommended 8-10 air changes an hour should be used to discharge stored sensible heat. These experimental results confirm the same is also required for a phase change wall-lining to discharge the maximum amount of stored latent heat over a time period suitable for a building application.

Figure 8.12 shows that despite the air change rates being different and the phase change wall-lining releasing different amounts of stored heat, the phase change wall-lining completed the peak discharge of heat at the same time period, 5 hours, for each experiment. This is the same time that the average surface temperatures of the phase change wall-lining reach the solidification point of 23.59°C. Therefore the largest proportion of this peak heat discharge will be the sensible heat in the phase change wall-lining.

Where all three lines cross in Figure 8.12 at 20 hours the average surface temperatures of the phase change wall-lining is the Peak 2 freeze temperature of 17.55°C, with the exception of the 3ach experiment which reaches it 5 hours later. The air temperatures in the Test Chamber are also 17.55°C. This demonstrates that the significant majority of the stored heat has been released from the phase change wall-lining. The remaining stored heat for each of the air change rates is 369 kJ for 3ach, 679 kJ for 5ach and only 81 kJ for 9ach in the 48hr experiment.

Therefore the graphical results of the cooling experiments have demonstrated it takes the same amount of time, 20 hours, for the phase change wall-lining to discharge the majority of its stored heat, regardless of the air change rate used and quantity of heat released, and that the higher the air change rate, the greater amount of heat is discharged from the wall-lining.

8.3.4 Effect of Air Change Rate on Surface Temperature Distribution

To evaluate the effect of the air velocity on the ability of the phase change wall-lining to improve the thermal conditions in the Test Chamber the exhaust air temperatures were graphed for each air change rate. This will provide an indicative analysis of the thermal performance of the phase change wall-lining.

(a) Heating cycle

In Section 8.3.2 it is identified that the higher the air change rate the greater the quantity of heat stored in the phase change wall-lining. Reviewing the surface temperature results for all of the experiments gives an insight into how the wall-lining has stored the differing amounts of heat, with the different air change rates.

The surface temperature results show a range of temperatures in accordance with the thermal stratification in the Test Chamber. Therefore the phase change wall-lining located higher on the walls (in the upper quartile of the chamber) closer to the air supply, reaches the melt point earlier than the phase change wall-lining lower down the walls. An example of this is shown in Figure 8.14 for the heat cycle at 3ach experiment.

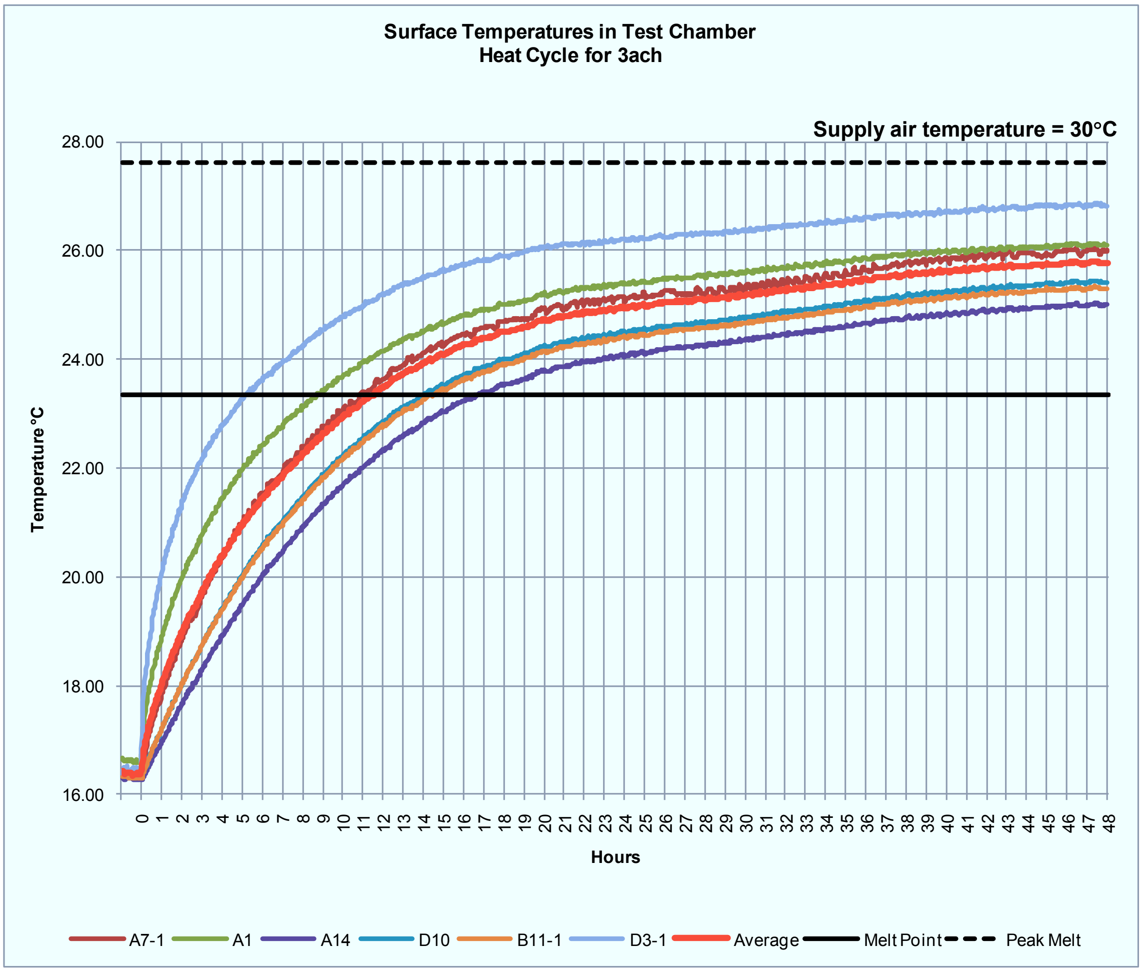


Figure 8.14 **Surface temperature distribution across the phase change wall-lining locations in the Test Chamber during the heat cycle with 3ach**

The time taken for the phase change wall-lining surfaces to reach the melt point of 23°C and peak melt of 27.61°C for each of the experiments is shown in Table 8.8.

Set-point	***3ach***		***5ach***		***9ach***	
	Control	***Test***	***Control***	***Test***	***Control***	***Test***
23.35°C	4 - 12 hrs	5 - 17 hrs	2 - 5 hrs	2 - 9 hrs	2 - 3 hrs	1.5 - 5 hrs
27.61°C	-	-	-	33 hrs (only D3-1)	23 - 36 hrs	16 - 41 hrs (except A14)

Table 8.8 **The time intervals at which the surface temperatures of the phase change wall-lining reached phase transition temperatures during heat cycle**

Using the lower air change rate slows the temperature rise throughout the Test Chamber. The phase change wall-lining in the upper part of the chamber reaches the phase transition temperature after 5 hours whereas the lowest surface temperature sensor, A14, takes a further 12 hours to reach the melt point. When this is compared against the surface temperature results for the Control Chamber, the higher surfaces reach 23.35°C an hour earlier than in the Test Chamber, yet the lowest sensor reaches the same temperature set-point 5 hours earlier than the corresponding sensor in the Test Chamber.

Conversely, in the Test Chamber using 9 air changes an hour, the surface temperature at the top of the Chamber, location D3-1, reached the melt point half an hour quicker than the Control Chamber. The time delay from the upper quartile of the Test Chamber to the lower quartile surface temperatures reaching the melt point was 3.5 hours whereas all the surfaces in the Control Chamber reached 23.35°C within 1 hour.

These results indicate the warm supply air entering at ceiling levels is being absorbed by the phase change wall-lining in the upper parts of the Test Chamber enabling the lower sections to remain cooler for longer.

The surface temperatures in the upper three quartiles of the Test Chamber reached the peak melt temperature of 27.61°C between 16 and 41 hours. This suggests the phase change wall-lining in those parts of the Test Chamber have absorbed at least 50% of the total latent heat storage capacity of the wall-lining, as this is half the area under the curve in the DSC graph, see Figure 7.1. This is consistent with the calculations for the amount of heat stored in the phase change wall-lining, discussed in Section 8.3.2 and shown in Table 8.5. From reviewing the DSC curve in Figure 7.1 it looks as though the surface temperature of the phase change wall-lining would need to reach 34°C to absorb 100% of the latent heat capacity.

For the 3ach experiments, none of the surface temperatures reached the peak melt temperature and only reached 25-26°C. When this temperature range is assessed against the DSC results for the wall-lining in Figure 7.1, you would expect that only a relatively smaller proportion of the latent heat capacity has been utilised, less than a quarter perhaps. The results in Table 8.5, Section

8.3.2, show that only 9% of the latent heat capacity was utilised and a greater amount of sensible heat was stored in the phase change wall-lining than latent heat.

As the phase change wall-lining in the Test Chamber reaches the peak melt temperature of 27.61°C in half the time of the Control Chamber, this suggests that the PCMs in the wall-lining are drawing in a lot of the heat in the upper quartile of the Chamber. During phase transition the PCMs would maintain their temperature whilst continuing to absorb greater amounts of heat, whereas the PVC matrix of the wall-lining continues to increase in surface temperature as the heat is pulled through it by the PCMs, due to the specific heat capacity of the PVC.

This theory is supported in the 9ach experiment by the fact that the lowest surface temperature sensor in the Test Chamber, A14, does not reach the peak melt temperature during the 48 hour experiment whereas the corresponding sensor in the Control Chamber reaches 27.61°C at 36 hours.

To illustrate the thermal stratification in the Chambers during the experiments the surface temperature distribution across the phase change wall-lining tiles after 10 hours of experiment is shown in Figure 8.15.

During the heat cycle it was expected that the faster air change rate would provide evenly mixed air due to the air velocity and the surface temperatures would be uniform throughout the chambers. However the results presented have demonstrated that the higher air change rate is transferring the heat into the phase change wall-lining at a faster rate in the upper part of the Test Chamber. Therefore the supply air is cooler when it reaches lower surfaces in the Test Chamber.

As the heat is being supplied from the ceiling it suggests the phase change wall-lining will be more effective the closer it is located to the heat source.

Figure 8.15 Surface temperature distribution in Environmental Chambers after 10 hours

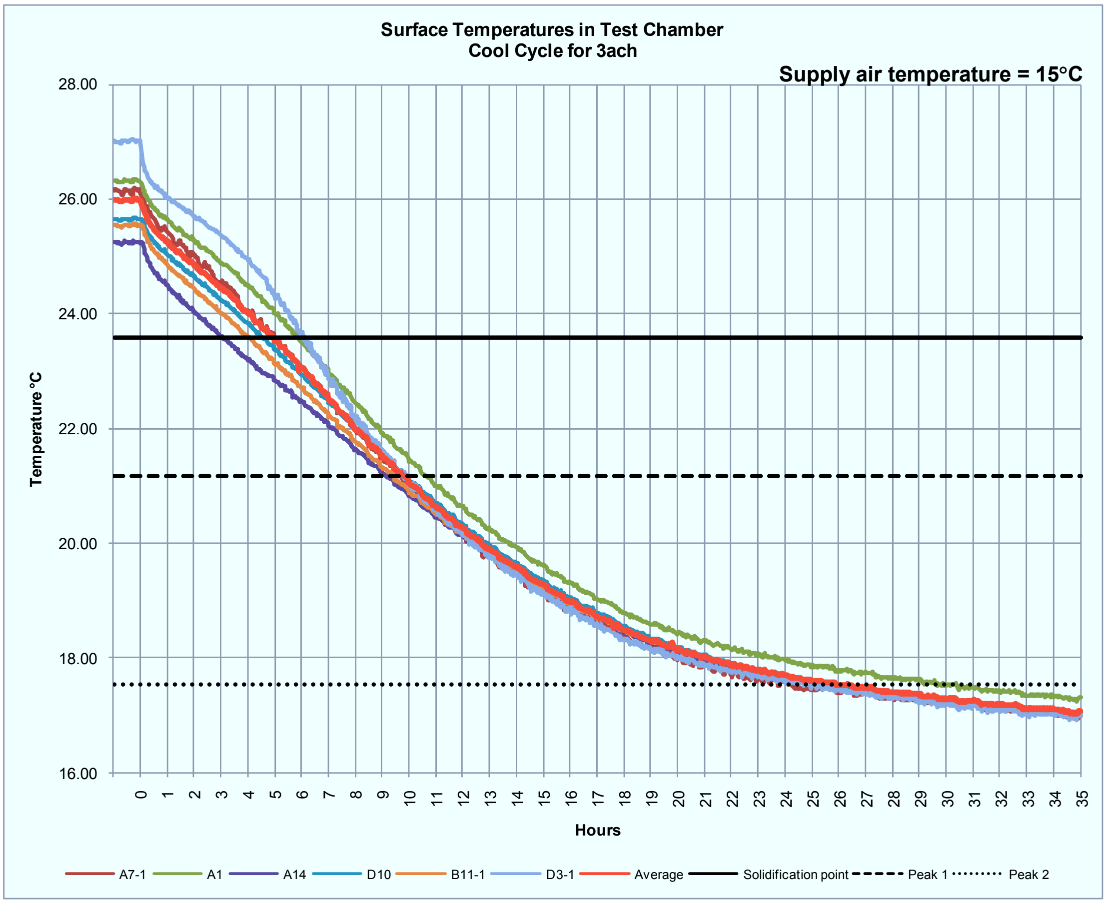
(b) Cooling cycle

Reviewing the surface temperature profiles of the Test Chamber during the cooling cycle for all of the air changes shows a more pronounced profile that correlates with the solidification temperatures and again suggests thermal stratification throughout the Test Chamber because each phase change wall-lining tile meets the temperature set-points at different times. The surface temperature profiles for the 3ach and 5ach results are shown in Figure 8.16.

The time taken for the phase change wall-lining surfaces in the Test Chamber to reach the solidification point of 23.59°C, Peak 1 solidification of 21.16°C and Peak 2 solidification point of 17.55°C are shown in Table 8.9 below. These results show that although the air change rate does not seem to make a significant difference in the time taken to reach the temperature set-points in each Chamber, the Test Chamber does take considerably longer than the Control Chamber to cool down, again confirming the phase change wall-linings ability to maintain a more stable thermal environment.

Set-point	***3ach***		***5ach***		***9ach***	
	Control	***Test***	***Control***	***Test***	***Control***	***Test***
23.59°C	1 - 2 hrs	3 - 6 hrs	½ - 1 hr	4 - 6 hrs	1 - 1 ½ hrs	2 - 7 hrs
21.16°C	3 - 5 hrs	9 - 11 hrs	2 - 3 hrs	7 - 10 hrs	2 - 3 hrs	6 - 10 hrs
17.55°C	14 - 16 hrs	23 - 30 hrs	10 - 14 hrs	18 - 22 hrs	10 - 14 hrs	16 - 21 hrs

Table 8.9 The time intervals at which the surface temperatures of the phase change wall-lining reached phase transition temperatures during cool cycle



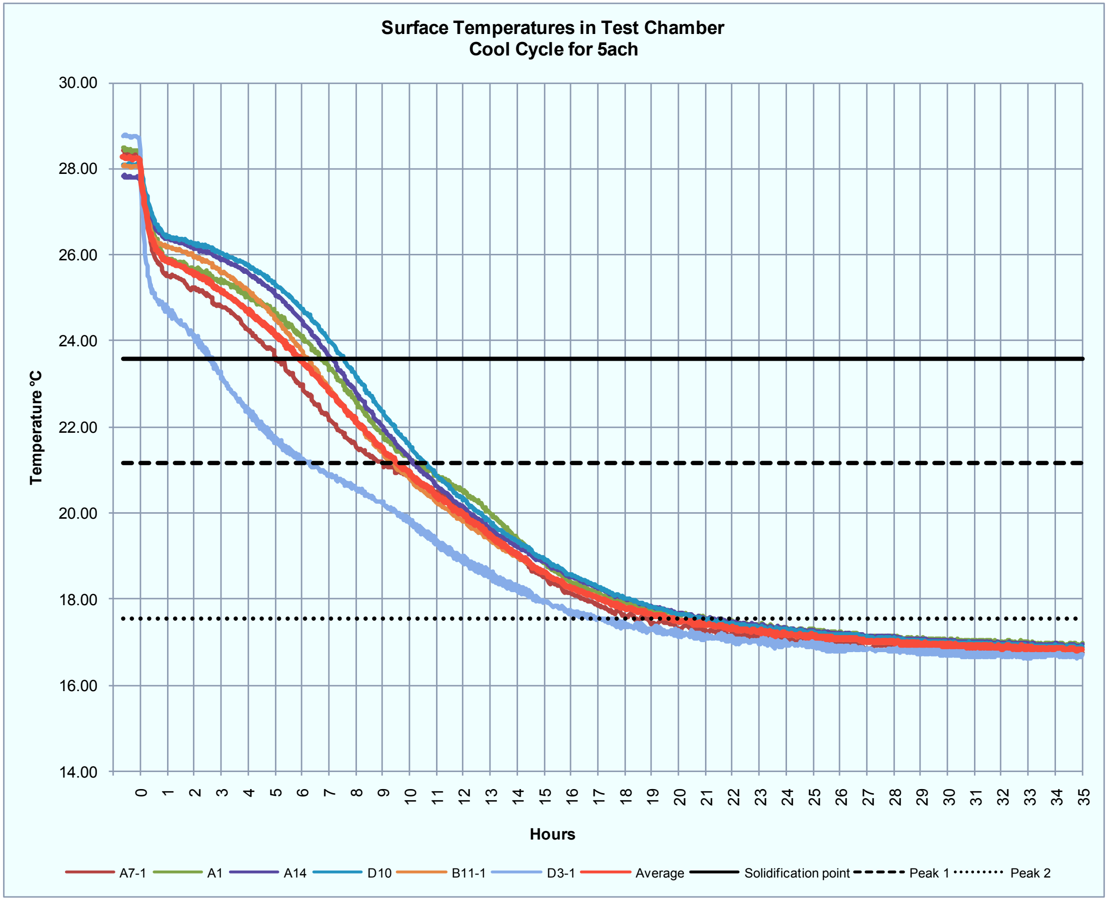


Figure 8.16 Surface Temperature profiles in Test Chamber during cooling cycle

8.3.5 Chamber Temperatures and Thermal Comfort

To evaluate the impact the latent heat storage ability of the phase change wall-lining has on the thermal conditions in the Test Chamber, the air and globe temperature measurements have been analysed and are discussed below.

(a) Heating Cycle

The air temperature results that were measured at the centre of each environmental chamber are shown in Figure 8.17. It is immediately clear that for each of the experiments, the air temperature in the Test Chamber rises at a much slower rate and the peak temperatures are lower than in the Control Chamber.

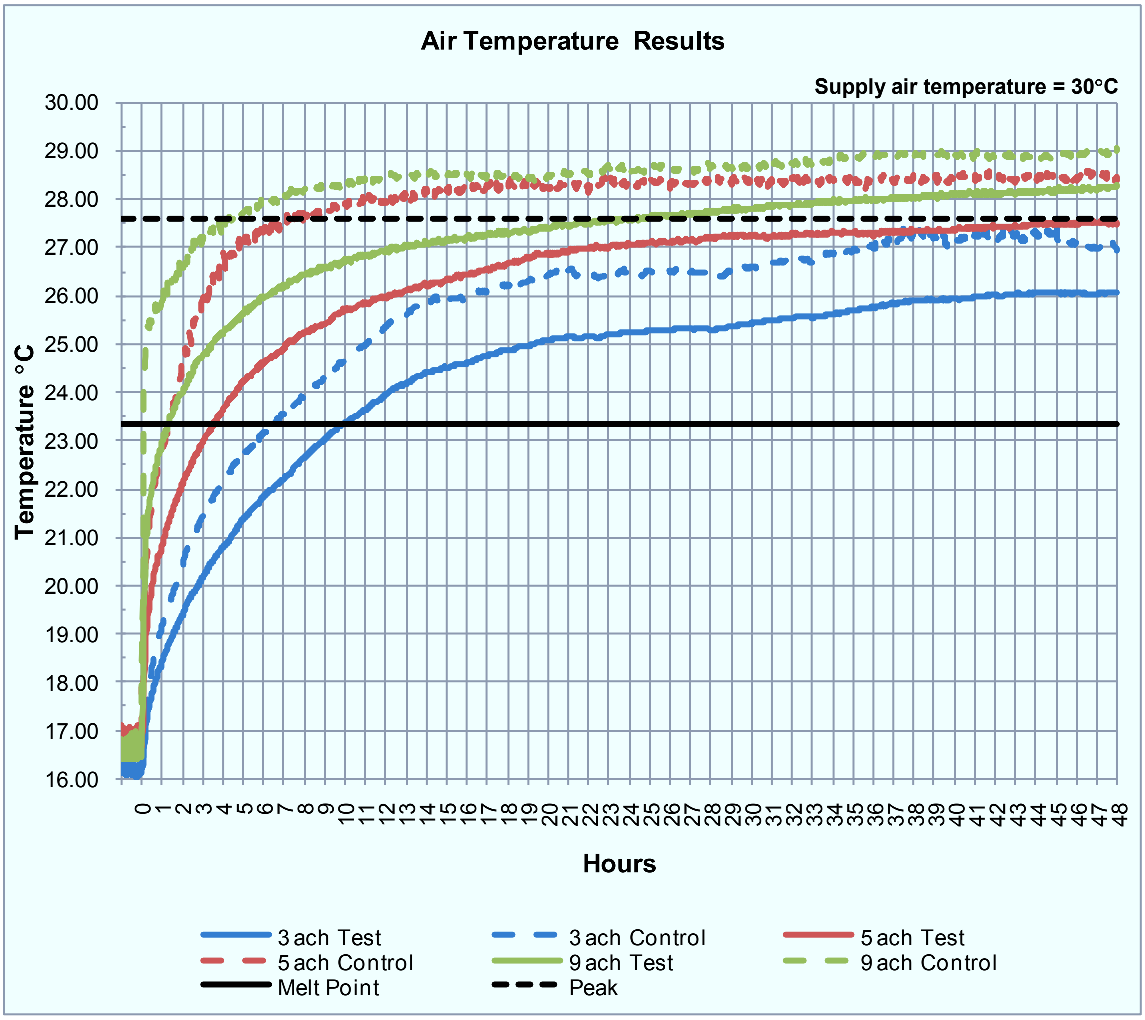


Figure 8.17 Air temperature results in the Chambers during the heat cycle

Reviewing Figure 8.17 the 9ach profiles shows that when the chambers are provided with 30°C supply air, the air temperature in the Control Chamber immediately rises to 25°C, at which point the sensible heat capacity of the Control Chamber begins to slow the temperature rise. However, the air temperature in the Test Chamber, when also provided with the 30°C supply air, ramps to 21°C and then the temperature increase slows. It takes the Test Chamber 4 hours to reach 25°C.

For each experiment the fastest temperature change rate occurs in the first hour. This is due to the initial heat up of the air in the test chambers. The input air is 30°C and mixes with the 16°C air in the chambers resulting in a rapid 'warm up' period for the first hour in the environmental chambers. Although the fastest temperature change rates occurred in the first hour the Test Chamber always maintained a slower rate of change than the Control Chamber.

The air temperature profiles do not exhibit obvious changes to indicate when the phase transition of the phase change wall-lining takes place. The melt point and peak melt temperature of the phase change wall-lining is shown on the results in Figure 8.17 but no changes or shifts of the air temperature profiles occur at those set-points. Each experiment lasted for over 48 hours during which time the chambers never reached the same peak temperature.

Despite there being no obvious change in the profiles the phase change wall-lining maintains a lower air temperature for a longer period of time in the Test Chamber than the Control Chamber.

Table 8.10 summarises the time taken for both Chambers to reach critical air temperature set-points. These set-points are based on the phase change wall-lining onset melt temperature, peak temperature for heat absorption and a mid-point of 25°C. The table clearly shows how successful the phase change wall-lining is at delaying the time taken to reach the air temperature set-points and its ability to maintain a cooler environment for longer. The lower air change rates prolongs the time taken to reach each set-point.

Set-point	***3ach***		***5ach***		***9ach***	
	Control	***Test***	***Control***	***Test***	***Control***	***Test***
23.35°C	6 hrs	10 hrs	1 hr	4 hrs	(5 mins)	1 hr
25.00°C	11 hrs	19 hrs	2hrs	7 hrs	(10 mins)	4 hrs
27.61°C			7 hrs	53 hrs	5 hrs	25 hrs
28.00°C			11 hrs		6 hrs	34 hrs

Table 8.10 Number of hours taken to reach key air temperatures in the Chambers

A visual assessment of the graphical air temperature results shows that generally the peak temperature reduction achieved by the phase change wall-lining is approximately 1.25-1.5°C for each experiment. However a more detailed analysis of the results reveals that much greater temperature differences are achieved during the experiments, see Table 8.11. The most significant temperature difference is with the higher air change rate of 9ach. In the first hour the air temperature in the Test Chamber is 4.57°C lower than the Control Chamber. After 4 hours with 5ach the air temperature remained over 3°C and 1.5°C lower with 3ach in the Test Chamber.

Air Change Rate (ach)	***Peak Air Temperature Difference***	***Time Occurred***
3	1.53°C	During 15th hr
5	3.23°C	During 5th hr
9	4.57°C	During 1st hr

Table 8.11 The peak air temperature difference achieved between the environmental chambers as a result of the phase change wall-lining

These results are compared with the room globe temperature results that were recorded during the experiments using the black globe sensor. These indicate the effect of the phase change wall-lining on the thermal comfort conditions of the chambers.

The globe temperature results, shown in Figure 8.18, show that the phase change wall-lining slows the rate of temperature change in the Test Chamber and the globe temperatures always remains lower in the Test Chamber than the Control Chamber.

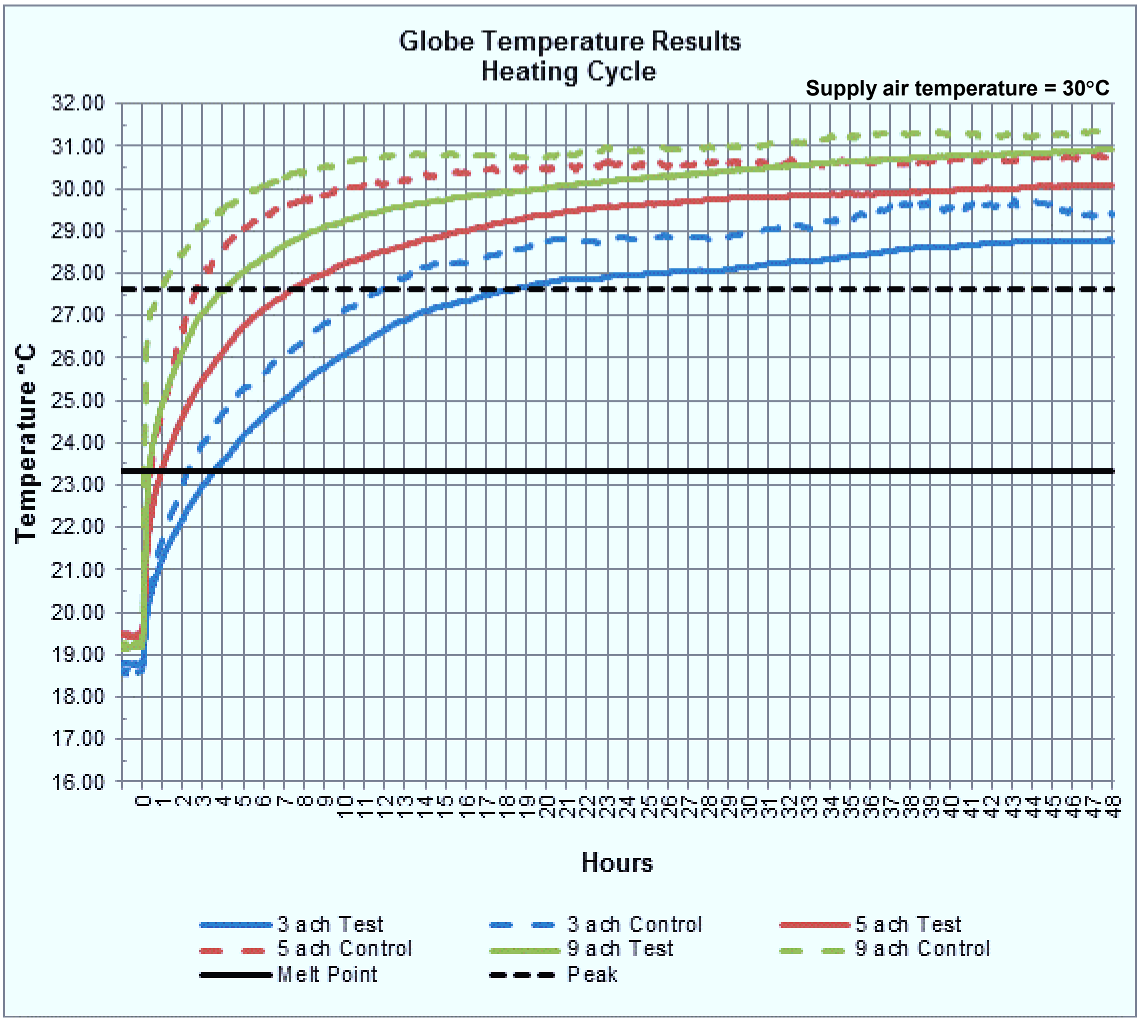


Figure 8.18 Globe temperature results in the Chambers during the heat cycle

The critical temperatures for thermal comfort in offices, as described in Section 8.2.6, are:

- 23°C: comfort temperature is 22-24°C
- 25°C: should not be exceeded for more than 5% occupied period
- 28°C: should not be exceeded for more than 1% occupied period

Table 8.12 presents the improved thermal comfort conditions experienced in the Test Chamber, as the peak globe temperature difference is over 2°C in the 5ach experiment. The phase change wall-lining delays the time taken to reach the key thermal comfort conditions.

Air Change Rate (ach)	***Peak Globe Temperature Difference***	***Average Globe Temperature Difference in first 10 hours***	***Time Delay for Test Chamber to reach 25°C***	***Time Delay for Test Chamber to reach 28°C***
3	1.13°C	0.97°C	2.5 hrs	11 hrs
5	2.41°C	2.03°C	1 hr	6 hrs
9	1.91°C	1.85°C	1 hr	3 hrs

Table 8.12 The peak globe temperature reduction and time delay in the Test Chamber

(b) Cooling Cycle

During the cooling cycle the profile of the graph changes during the first hour when compared with the Control Chamber, see Figure 8.19. The air temperature at that point in the Test Chamber is 23.62°C, close to the phase change wall-linings phase transition point of 23.59°C. Unlike the heating cycle which did not exhibit the phase change period, the graphical results of the air temperature profile at the centre of the Test Chamber during the cooling cycle clearly indicates the time at which the heat began to be released from the phase change wall-lining.

The rate of temperature change for the cooling results shows the Test Chamber cools at a slower rate than the Control Chamber for the first 5 hours for the 3ach and 5 ach experiments, and 6 hours for the 9ach experiment. These time intervals were when the peak amount of heat was discharged from the phase change wall-lining, the majority of which was sensible heat, as illustrated and discussed in Section 8.3.2.

After these time intervals the Test Chamber cools at a faster rate than the Control Chamber and slows for the duration of the experiment.

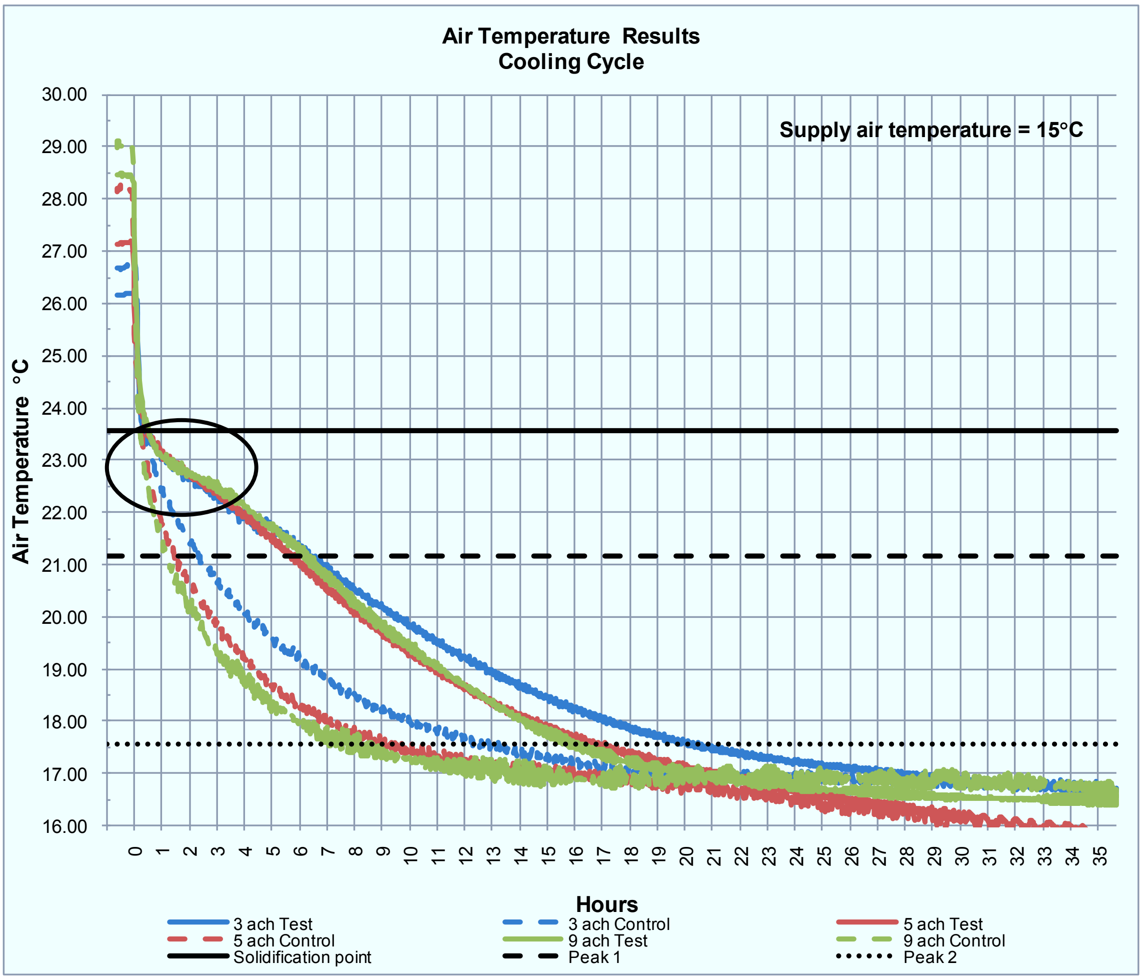


Figure 8.19 Air temperature results of Chambers during cooling cycle

Despite the higher quantity of released heat, for the 9ach air change rate, the temperatures in the Test Chamber are very similar to those with the lower air change rates (see Figure 8.19). This is due to the higher air velocity removing the warm air from the Test Chamber quickly.

8.4 Analysis

Environmental chambers were set-up containing extensive monitoring equipment to measure the key thermal performance indicators for the phase change wall-lining.

The results obtained from the testing programme have shown that during the heating cycle the phase change wall-lining delays the rate of a temperature change, reduces the peak temperature and provides a more stable air temperature in the Test Chamber. The phase change wall-lining acts in a similar way to materials that have high thermal mass that slow the temperature rise in a room.

When considering the application for a phase change wall-lining in non-domestic buildings it is useful to analyse the peak temperature reduction for a typical working day. The peak air and globe temperature reductions for each air change rate after 10 hours, Table 8.13 shows the phase change wall-lining is able to reduce the air temperature by over 2°C and the globe temperature by up to 1.75°C.

Air Change Rate (ach)	***Peak Air Temperature Reduction***	***Peak Globe Temperature Reduction***
3	1.31°C	1.05°C
5	2.15°C	1.75°C
9	1.57°C	1.36°C

Table 8.13 The peak air and globe temperature reduction in Test Chamber after 10 hours

Care needs to be taken when reporting, or reading in published literature, the peak temperature reduction. For this experiment the air temperatures showed that when the maximum air temperature was reached in the Control Chamber, the Test Chamber was approximately 1.25°C-1.5°C lower for each air change rate. When considering the temperature reduction after 10 hours the phase change wall-lining reduced the air temperature in the Test Chamber up to 2.15°C, depending on the air change rate. When assessing the maximum air temperature difference between the environmental chambers, this ranged from 1.53°C to 4.57°C and occurred at significantly different times, depending upon the air change rate. Each of these instances could be reported as ‘peak temperature reduction’ but would not be representative of the phase change wall-linings overall performance.

The peak globe temperature reduction achieved by the phase change wall-lining in the Test Chamber was 2.41°C whereas the globe temperature reduction after

10 hours was not quite as high as the air temperature difference, at a maximum of 1.75°C with 5ach.

Interestingly the globe temperature results, shown in Figure 8.18, are higher than the air temperature results by approximately 2.5°C throughout the testing. The globe temperature takes account of radiant temperature and air velocity as well as air temperature. These results demonstrate it is important to consider all these parameters when evaluating the improvement in thermal comfort of the phase change wall-lining as occupants often feel warmer than the air temperature would suggest.

The experiments showed that during the cooling cycle when the stored heat was being discharged from the phase change wall-lining the different supply air rates results in the same air temperature in the Test Chamber. This air temperature remained higher than the air temperature in the Control Chamber due to the released heat from the phase change wall-lining.

The peak amount of heat stored and released between 5 and 6 hours, which was predominantly the sensible heat of the phase change wall-lining. After this the phase change wall-lining continued to store or release the latent heat. It takes the same amount of time to fully discharge the phase change wall-lining regardless of the air change rate.

The results the higher the air change rate, the greater quantity of latent heat stored and released however only 9%, 34% and 50% of the latent heat capacity of the phase change wall-lining was utilised during the 3ach, 5ach and 9ach experiments.

The Outlast XXL(2) PCM selected for the phase change wall-lining has a relatively broad peak during the melt phase with an onset melt point of 23.35°C, peak melt of 27.61°C and completes the phase transition at 34°C. However the peak for the solidification phase is much broader with the onset point 23.59°C, double minima peaks of 21.18°C and 17.55°C with completion at 15°C.

Therefore to utilise all of the latent heat capacity of the phase change wall-lining the surface temperature of the wall-lining would need to exceed 30°C and 15°C during the heating and cooling cycles. This would only be possible with air temperatures beyond these set-points.

The experiments used supply air temperatures of 30°C and 15°C for the heating and cooling cycles, respectively. During the heating cycle the surface temperatures reached between 26°C and 28°C for each of the air change rates. With the 9ach heat cycle the phase change wall-lining stored only 50% of the latent heat capacity which is understood when comparing the surface temperature results of the phase change wall-lining against the DSC curve. As the surfaces did not reach the maximum 30°C they were not able to complete the phase transition and utilise all of the latent heat storage capacity of the phase change wall-lining.

A further study was undertaken heating the chambers to 40°C at 5 air changes an hour. The surface temperature results for this experiment, shown in Figure 8.20, clearly show a change in the profile around 28°C. This is when the peak melt of the phase change wall-lining takes place. The results also show that many of the surfaces exceeded the temperature at which the phase change wall-lining would complete the phase transition, 34°C. Theoretically a greater proportion of the latent heat storage capacity of the phase change wall-lining should have been utilised than when the experiment was undertaken with a supply air temperature of 40°C.

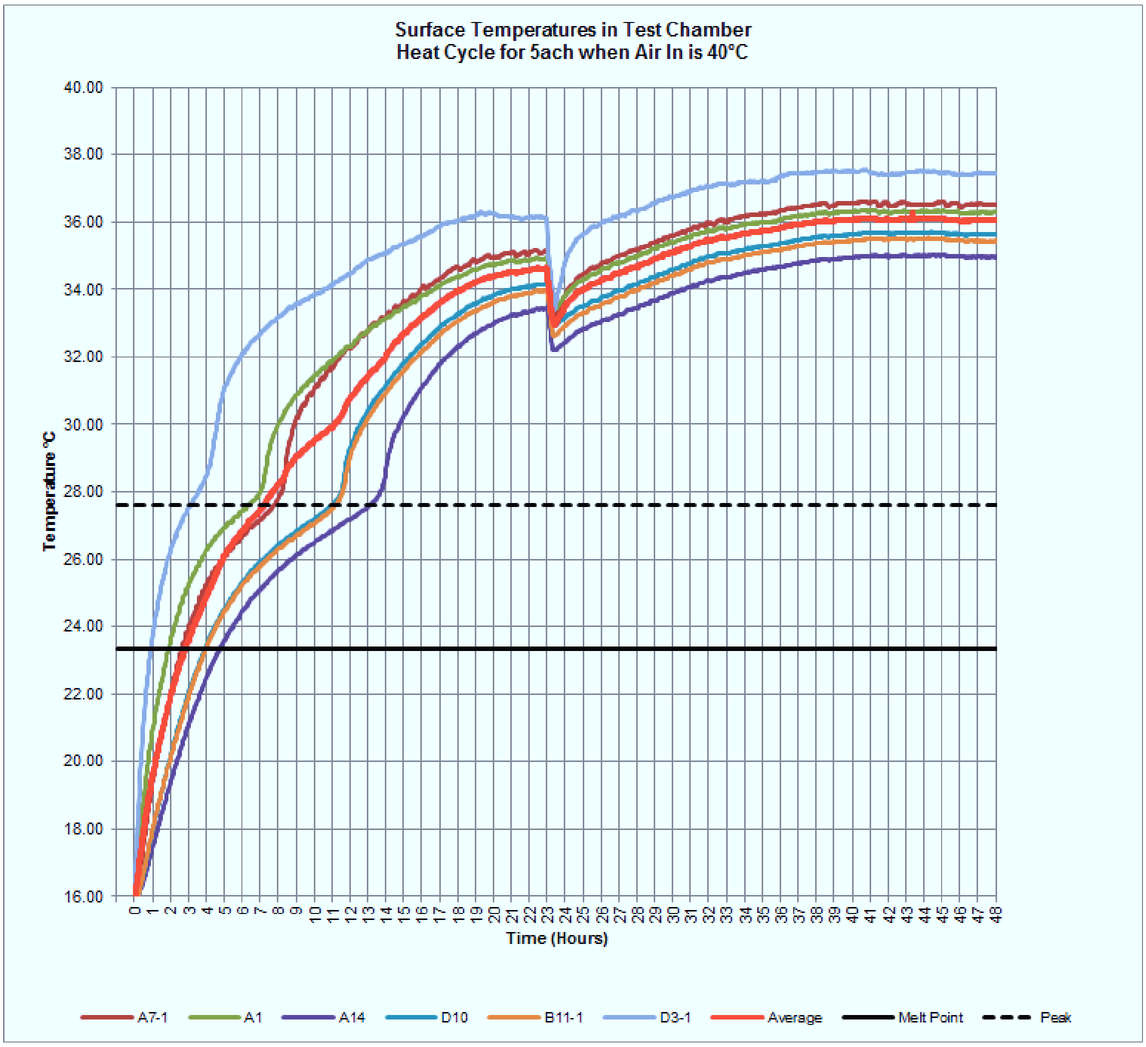


Figure 8.20 **Surface temperature results of phase change wall-lining when supply air temperature is 40°C**

Please note, during the experiment at 23 hours the supply air temperature set-point changed to 15°C for half an hour. This is why the surface temperature profile drops at 23 hours. The results have been analysed up to this point.

The amount of sensible heat and latent heat stored in the phase change wall-lining when heated to 40°C has been calculated and is shown in Table 8.14.

Air Change Rate (ach)	***Total Heat Stored (kJ)*** Q_{total}	***Sensible Heat Stored (kJ)*** Q_{SHC}	***Latent Heat Stored (kJ)*** Q_{LHC}	***Amount of latent heat capacity of phase change wall-lining used***
5	4,374.72	1,901.10	2,473.62	28%

Table 8.14 Quantity of sensible and latent heat stored in the phase change wall-lining when supply air temperature was 40°C

The period of analysis is less at 23 hours rather than 48 hours for the 30°C experiment, however the graphical results in Figure 8.21 shows there is minimal heat stored after 23 hours. Therefore it can be deduced that although the 40°C supply air temperature goes significantly beyond the phase transition completion temperature of 34°C a similar amount of latent heat is stored as when the chamber was heated to 30°C and utilised 34% of the latent heat capacity. There may be a maximum depth to which the heat transfer occurs with the phase change wall-lining for the air change rate used.

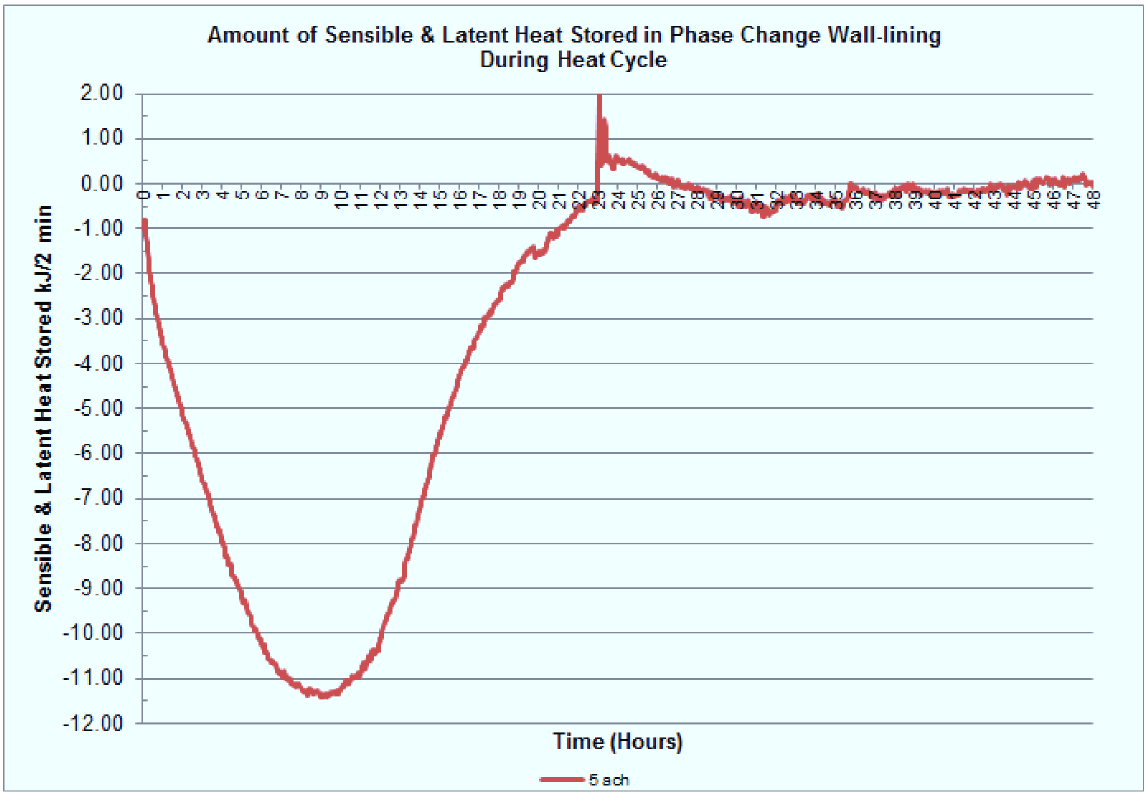


Figure 8.21 Graph showing amount of heat stored in phase change wall-lining when supply air temperature is 40°C

Furthermore the surface temperature results showed the areas of phase change wall-lining closer to the heat source store greater quantities of heat than those located further away from the heat source. Therefore both the location and thickness of the phase change wall-lining may be important when evaluating the quantity of its latent heat capacity that can be utilised.

8.5 Outcome

The phase change wall-lining successfully slows the temperature rise of the Test Chamber and reduces the peak temperature by over 2°C. It was identified that the phrase 'peak temperature reduction' should be clearly defined when reported in literature as a number of variables with very different results could be reported using this terminology which would be misleading.

During a heat cycle the air change rate affects both the rate of air temperature change in the Test Chamber and the quantity of heat stored in the phase change wall-lining, with higher air change rates storing more heat. The latent heat storage capacity utilised in these experiments was 9%, 34% and 50% for the 3ach, 5ach and 9ach experiments, respectively. The air change rate affects the quantity of heat that can be discharged from the phase change wall-lining yet the time taken to discharge the stored heat is always the same regardless of the air change rate. When the stored heat is being discharged the resulting air temperature profile in the Test Chamber is the same despite the air change rate.

It was initially thought that not all the latent heat capacity of the phase change wall-lining was being used due to the supply air temperature not being high enough for the phase transition to be completed. However further testing established similar quantities of latent heat was stored when the supply air temperature was 40°C. The air change rate used will provide different air velocities across the surface of the phase change wall-lining which will affect the surface heat transfer coefficient and therefore the amount of heat transferred into the phase change wall-lining. There may be a limit to the quantity of latent heat that can be utilised in the phase change wall-lining, potentially due to the thickness of the phase change wall-lining and the depth of heat transfer.

This experiment has demonstrated that locating phase change materials within a vinyl wall-lining on the surface of a Test Chamber can improve the thermal performance of the room as the storing and releasing of latent heat minimises the peak air and globe temperatures and slows down the rate of temperature change.

9 Findings and Conclusions

9.1 Review of Research

The design of buildings has developed in the UK to provide highly insulated buildings that utilise energy consuming technology control the internal conditions. A trend in the construction industry is to move towards lightweight construction to reduce cost and enable shorter construction time, which in turn saves costs. Lightweight buildings lack the ability to exchange heat with the internal environment and as a consequence they rapidly heat up and cool down resulting in poor thermal comfort conditions. Mechanical cooling is often retro-fitted resulting in additional energy being required to control peak temperatures.

A solution to reduce overheating in lightweight buildings is to incorporate phase change materials into the building fabric. Phase change materials (PCMs) are materials that absorb and release latent heat during phase transition. PCMs have a high latent heat capacity which could be used in buildings to significantly increase the thermal mass due to this ability to store greater amounts of heat than conventional building materials. For example calcium chloride hexahydrate is an inorganic phase change material that can store almost two hundred times more heat during phase transition than concrete.

All previous research that included phase change materials in buildings, focused on incorporation of them into building materials that would be located within the structure of a building. This research identified that if the phase change materials (PCMs) could be located on the surface of a room they would have direct exposure to heat exchange with a room to facilitate storage of excess internal heat gains, similar to the function of thermal mass in heavyweight buildings. The resulting research question was *Is it possible to locate phase change materials on the surfaces of a room and can they effectively improve the thermal performance of a room?*

The research questions was addressed in two parts. Firstly *is it possible to locate phase change materials on the surface of a room?* and secondly *can they effectively improve the thermal performance of a room?*

To address the research question a series of experiments were undertaken using the classic scientific method, with each experiment following on from the last and each contributing to addressing the original research question. The experiments are described in the following sections.

9.1.1 Experiment 1

As vinyl wallcoverings are a commonly used decorative wall finish different types of phase change materials were incorporated into existing vinyl formulations in Experiment 1. These included bulk organic and inorganic phase change materials, microencapsulated phase change materials and PCMs absorbed within a matrix. All were able to be included in a plastisol formulation which was coated out and cured to form sample wall-linings but none could be included in a calendaring formulation as the PCMs lubricated the rollers preventing any friction building up to form the compound.

The plastisol formulation route demonstrated that it was viable to locate phase change materials on the surface of a room by including them within a PVC wall-lining. The thermal analysis data showed that similar latent heat capacities were achieved using PCMs ‘absorbed within a matrix’ and ‘microencapsulated’ PCMs. However greater loadings of the matrix PCMs were required and the phase change wall-lining samples were brittle and the matrix PCMs would fall out as there was insufficient PVC in the formulation. Using the matrix PCMs would require the PCM loading to be reduced during formulation development which would decrease the latent heat capacity of the phase change wall-lining. Therefore microencapsulated PCMs, which have a higher latent heat capacity than the matrix PCMs, are the best route to maximise the latent heat capacity in the phase change wall-lining.

This successful experimental outcome was included in a patent (PCT) application which was granted in 2003.

9.1.2 Experiment 2

Following the determination in Experiment 1 that using microencapsulated phase change materials was the best form of PCM for maximising the latent heat storage capacity of the phase change wall-lining Experiment 2 set out to identify if using large microencapsulated PCMs would result in a phase change wall-lining with high latent heat storage capacity. The particle size and thermal analysis ascertained that the large XXL Thermocules from Outlast Technologies Inc had a high latent heat capacity and a greater quantity could be included in the plastisol formulation than the smaller microencapsulated PCMs. The resulting phase change wall-lining sample had a higher PCM content and a higher latent heat capacity.

The Outlast XXL microencapsulated phase change materials showed evidence that the shells had ruptured as wax appeared on the surface of the wall-lining samples. Further work was required by Outlast to improve the formulation of the microcapsules.

An anomaly between the published and measured phase change temperatures of the commercially available PCMs was identified during this experiment. It was found when reviewing the thermal analysis results that the published phase change temperature was in fact the peak melt temperature. This would mean the phase change temperature would be different for the heating and cooling cycles.

This was important to identify as the phase change temperature is a critical consideration for a PCM product and its application. It was decided in this research to use the onset temperature as the phase change temperature as this is when the PCM begins to change phase and is similar for both the heating and cooling cycles.

9.1.3 Experiment 3

Microencapsulated PCMs were developed by Outlast Technologies Inc for this research. They trial manufactured larger particle sizes and improved their microencapsulation formulation and method of manufacture to produce shells that could withstand the mechanical processing of the plastisol formulation route to minimise risk of shells fracturing and the PCMs escaping. These were evaluated in Experiment 3 and a plastisol formulation optimised. When the XXL(2) Thermocules were included in the lab sample phase change wall-lining the thermal analysis results showed the phase change temperature had shifted 1°C lower and the shape of the peaks had changed. Thermal cycling was completed using differential scanning calorimetry which showed the PCMs repeatedly performed in the same manner, therefore the formulation was a success.

9.1.4 Experiment 4

The plastisol formulation containing the Outlast XXL(2) Thermocules was scaled up in Experiment 4 and a successful pilot scale manufacturing produced 50m of phase change wall-lining. The phase change wall-lining contained 45% by weight of microencapsulated PCMs resulting in a latent heat storage capacity of 87 J/g and phase change temperature of 23°C.

The successful manufacture of the phase change wall-lining was a critical element of the research as it addresses the first half of the research question. The inclusion of phase change materials in a vinyl wall-lining demonstrates it is possible to locate phase change materials on the surface of a room. This concludes the first part of the research question.

9.1.5 Experiment 5

To address the second part of the research the phase change wall-lining was tested using environmental chambers in Experiment 5. There has been limited testing of PCM products in rooms with realistic boundary conditions that are acceptable in a building. In this experiment two identical chambers were set up, a Control Chamber and a Test Chamber, with a controllable air-conditioning unit and extensive temperature monitoring equipment. The phase change wall-lining was affixed to the surface of the Test Chamber walls. The air supply temperatures and velocities were set using ranges that are applicable in a building.

The measurements demonstrated the phase change wall-lining successfully slowed the increase in temperature and reduced the peak temperatures in the Test Chamber by over 2°C. The phase change wall-lining delayed the time taken to reach acceptable comfort temperatures, depending upon the air change rate used. The lower the air change rate, the longer the time delay. For instance, the time taken to reach 25°C was 19 hours for the 3ach experiment and 4 hours for the 9ach experiment.

During the cooling cycle the phase change wall-lining maintained higher air temperatures for longer in the Test Chamber. This was due to the sensible and latent heat being released from the phase change wall-lining. After 5 hours the air temperature in the Test Chamber was 3°C higher and 2°C higher after 10 hours.

The phase change wall-lining has demonstrated it can minimise air, globe and surface peak temperature fluctuations in a room which improves thermal comfort. Thermal comfort is affected by the thermal performance of the fabric of a building. Therefore the improved thermal comfort demonstrates thermal performance of a room is improved with the phase change wall-lining.

9.2 Key Findings

When developing the phase change wall-lining using large 40-120μm microencapsulated phase change materials enabled a greater PCM content by weight, and resulted in a higher latent heat capacity for the phase change wall-lining to be achieved, compared with using the smaller 5μm microencapsulated PCMs.

When tested in environmental chambers the phase change wall-lining successfully reduced peak air and globe temperatures by over 2°C and delayed key temperature set-points being reached by up to 19 hours, depending on the supply air conditions. These improved thermal comfort conditions are due to the phase change wall-lining exchanging heat with the room. Therefore it has been successfully demonstrated that locating phase change materials on the surface of a room, within a vinyl wallcovering does improve the thermal performance of a room.

Consideration of the temperatures at which phase transition completes has not previously been addressed as all previous research has focussed on the melt point of a PCM product rather than the temperature range over which the whole phase change occurs. A discrepancy between the different interpretations of the phase change temperature was identified in this research. The phase change temperature is a term some suppliers and researchers use which is actually the peak melt or freeze temperature. Others use the onset temperature, the temperature at which the phase change begins, as the phase change temperature. This is important when determining the boundary conditions for a phase change wall-lining to ensure it can operate within realistic thermal conditions for a room or building and all of the thermal energy storage capacity can be utilised.

During Experiment 5 not all of the available latent heat storage capacity of the phase change wall-lining was utilised. When the supply air temperature was significantly higher than when the phase change materials in the wall-lining should complete their phase change transition only half of the latent heat capacity was used. It is possible there is a limit to the depth to which the heat can transfer into the phase change wall-lining within the temperature limits and air change rates used. The thermal conductivity of the phase change wall-lining is 0.12 W/mK which is low. Increasing this would improve the heat transfer and enable more heat to be stored in the phase change wall-lining. This could be achieved by selecting an alternative wall-lining matrix to PVC, as PVC has insulating properties, or by including additives such as graphite to improve the thermal conductivity.

The surface temperature results from the environmental chambers has shown that the air distribution pattern in a room is important. The air distribution affects the air temperature and the surface heat transfer coefficient. The results have shown the phase change wall-lining tiles closer to the heat source, the supply air diffuser, had a higher surface temperature therefore is likely to have stored more heat than the areas of phase change wall-lining lower down the walls. Therefore establishing the air velocity and temperature distributions on wall surfaces is vital in determining where to place the phase change wall-lining for best thermal performance in a room.

9.3 Technical Issues

9.3.1 Technical Challenges of Manufacturing a Phase Change Wall-lining

This research was undertaken in collaboration with OMNOVA Wallcoverings (UK) Ltd, a company that manufactures PVC wallcoverings. The development of the phase change wall-lining began with incorporating a range of PCMs into a conventional PVC wall-lining product using either the plastisol or calendaring manufacturing process.

The plastisol formulation was the successful method of achieving a phase change wall-lining and using microencapsulated phase change materials achieved the highest possible latent heat capacity. The chalk filler in the formulation was replaced with the PCMs and maximised to achieve the highest possible loading. Due to the number of components required to produce a PVC wall-lining and the resulting viscosity there was a limitation to the amount of microencapsulated phase change materials that can be integrated. A range of formulations and mix procedures were undertaken using different PCMs to achieve the highest loading possible resulting in the highest thermal storage capacity possible for the phase change wall-lining.

During the lab scale developments it was found that the PCMs had compatibility issues with a number of plasticisers. After a number of days of being produced the phase change wall-lining sample was found to have a greasy coating on the surface. It was concluded this was plasticiser that had migrated from the phase change wall-lining out onto the surface. Experiments immersing the microencapsulated PCMs in different vials of plasticisers determined which were compatible for use in a plastisol formulation.

The plastisol formulation when coated out often had a bubbly surface. This was due to the air pockets in the formulation and therefore the plastisol mix needed to be vacuumed prior to being coated out and cured to produce the wall-lining. This was less difficult for a lab scale sample but was an onerous and time consuming task for the pilot scale trial manufacture. This issue would need to be overcome during the mix process to eliminate the requirement for the vacuum process in large scale manufacture.

Once the highest loading of phase change materials had been achieved in the PVC plastisol formulation, the thickness of the wall-lining was increased to maximise the thermal energy storage capacity available. This also has limitations due to the capabilities of the lab scale and large scale manufacturing process. In the lab it was possible to achieve a 6mm coating but the factory coating equipment at OMNOVA was only capable of achieving a 4mm thick coating. To produce the prototype wall-lining an alternative manufacturer was sourced that had coating machines that could produce coatings up to 6mm thick in one pass.

9.3.2 Performance of PCMs Post-production

Laboratory developed microencapsulated wax phase change materials were supplied by Outlast Technologies Inc. When these Outlast microencapsulated PCMs were included in lab scale developments they exhibited slightly changed characteristics following the manufacture of the phase change wall-lining. The phase change materials prior to inclusion in the PVC exhibited two peaks which suggest the core PCM was potentially a blend of two different types of paraffin. Post-production the phase transition temperatures for the phase change wall-lining samples had shifted by almost 1°C and the peaks had become broader from the original PCM prior to inclusion in the PVC formulation. Despite this the DSC analysis results of the phase change walling showed that after a number of thermal cycles the phase transition temperatures and latent heat capacity remained consistent in the phase change wall-lining.

Following the experimental programme the chambers remained in-situ with the air-conditioning switched off. After a number of months when the Test Chamber was opened the wall-lining had changed in appearance. Crystals had formed on the surface of the phase change wall-lining. The same appearance was exhibited during the laboratory experiments when bulk paraffin wax was included in a wall-lining, as described in Chapter 4.3.5. The Outlast capsule shells must have ruptured either as a result of extensive thermal cycling or as a result of chemical degradation of the shells allowing the wax phase change material to leak from the microencapsulated shells and leach out of the phase change wall-lining.

Further work is required by Outlast Technologies Inc to provide microencapsulated phase change materials that are compatible with the required components in a vinyl formulation. The microencapsulated PCMs need to be able to function for as long as the life expectancy of the phase change wall-lining which would need to be established.

9.3.3 Weight of Phase Change Wall-lining

The manufactured phase change wall-lining weighs 5.78kg/m^2 which is considerably greater than a standard wallcovering product. A typical wallcovering is affixed to walls in large sheets using an adhesive. Due to the weight of the phase change wall-lining it was glued to smaller mdf boards which were screwed onto the walls of the Test Chamber. This reduced the risk of the phase change wall-lining becoming detached during the experimental programme and eliminated the need to investigate different adhesives.

The phase change wall-lining is similar to a building material rather than a decorative finishing material. The method of installation requires further investigation to determine an appropriate solution. Potential solutions include a type of framing system or laminating the wall-lining to solid panels or plasterboard prior to installation.

9.3.4 Fire Risk

Organic PCMs are a paraffin wax and therefore highly flammable. To introduce additional fire retarders into the phase change wall-lining formulation the PCM content is likely to be reduced, consequently resulting in a lower thermal storage capacity. One solution could be to develop a fire resistant coating for the phase change wall-lining to delay the onset of fire and reduce the spread of flame. Care would need to be taken with this approach to ensure the heat exchange between the phase change wall-lining and the environment can still take place. The use of a coating has the risk of insulating the phase change wall-lining and reducing the heat transfer to and from the wall-lining by acting as a barrier on the exposed face of the phase change wall-lining.

An alternative solution is to include fire retardant additives to the plastisol formulation, although this is likely to impact on the quantity of microencapsulated phase change materials that can be included. Expandable graphite is a potential solution that would improve the fire resistant properties and also the thermal conductivity of the phase change wall-lining.

9.4 Implications of the Research

This research identified that if phase change materials could be located on the surface of a room, directly exposed to internal heat gains, the thermal performance of that room could be improved.

A phase change wall-lining has been successfully developed by incorporating microencapsulated phase change materials into a vinyl wallcovering. The importance of the microencapsulation of the phase change materials has been demonstrated. The size and strength of the particles have been crucial in this research to achieve the phase change wall-lining. The large particle sizes contain more paraffin wax phase change material and therefore have a high latent heat capacity. In addition a greater quantity were able to be included in the vinyl formulation. This enabled the phase change wall-lining to have a greater heat storage capacity than when smaller microencapsulated phase change materials were used. Conversely this provides the opportunity to minimise the quantity of phase change wall-lining that may be required in a room to meet the cooling requirement. If the optimum amount of heat storage capacity required in a room is determined, using large microencapsulated phase change materials with high latent heat capacity could reduce either the thickness or area of phase change wall-lining required.

The mechanical strength and chemical resistance of the shells of the microencapsulated phase change materials is crucial to achieving a phase change wall-lining. The shells of the particles need to be compatible with components of a plastisol formulation and be able to withstand the mechanical processing of both the manufacturing process and the thermal cycling when installed in a room.

The Outlast XXL(2) Thermocules used in the research were formulated and manufactured by Outlast Technologies Inc to improve the mechanical strength of the shell which successfully remained intact for the manufacture of the phase change wall-lining and the test experiment in the environmental chambers. However, a number of months after Experiment 5 was concluded, wax began to form on the surface of the phase change wall-lining. Therefore the shells of some of the microencapsulated phase change materials must have ruptured. This could be due to the extensive thermal cycling or as a result of chemical degradation. During thermal cycling the shells would need to expand and contract due to the paraffin wax changing phases from solid to liquid to solid. The flexural strength of the shells may need improving to withstand thermal cycling for the life expectancy of a phase change wall-lining. There may be long term compatibility issues with the plasticisers and the microencapsulated phase change materials. Further work is required to improve the microencapsulation of the phase change materials for use in a phase change wall-lining.

The testing of the phase change wall-lining demonstrated it can successfully minimise peak temperature fluctuations, providing a more stable internal environment which improves thermal comfort conditions. Therefore the thermal performance of the room is improved by the phase change wall-lining.

The thickness of the phase change wall-lining for the purpose of this research was manufactured as thick as possible to maximise the heat storage capacity. However the testing in the environmental chambers showed only half of the latent heat capacity of the phase change wall-lining was utilised. The test results also showed the location of the phase change wall-lining in a room is important. The ability for the phase change wall-lining to exchange heat with the room is affected by the air temperature and the surface heat transfer coefficient. Therefore the air distribution in the room and the air temperature and velocity on the wall surface needs to be considered to identify the best location and optimum thickness for the phase change wall-lining.

This research shows there needs to be a step-change in the way buildings are designed. The internal conditions of a room need to be factored in when considering the location for and quantity of a phase change wall-lining. The thermal interactive phase change wall-lining needs to be considered as an active system in the way a conventional cooling system would be, rather than a conventional building material. This will maximise the improvement in the thermal performance of a room or building and the resulting thermal comfort conditions that can be achieved.

The ability for the phase change wall-lining to delay the time taken to reach extreme temperatures provides an energy saving opportunity in buildings with air-conditioning. The phase change wall-lining can shift peak temperatures beyond the occupied period or could shorten the time that mechanical cooling is required and reduce the cooling load. This would reduce energy costs and CO_2 emissions from a building.

The phase change wall-lining provides a viable solution for addressing overheating in existing lightweight buildings. Rather than using mechanical cooling, the phase change wall-lining can be affixed to the surfaces of rooms to improve the thermal performance of the building fabric. This is an energy saving alternative to mechanical cooling in existing buildings. Furthermore, for new buildings the phase change wall-lining provides thermal mass without the weight of a heavyweight construction.

9.5 Conclusion

Locating phase change materials on the surface of a room, in the form of a wall-lining, has demonstrated the potential for improving the thermal performance of a room through experimental studies.

9.6 Future Research

The potential for using a phase change wall-lining on the surface of a room to improve the thermal performance of the room has been demonstrated. To continue to move this research forward requires further research to enable the potential of the phase change wall-lining to be realised.

9.6.1 Microencapsulation of Phase Change Materials

It was established in this research that using microencapsulated phase change materials was the best method of maximising the latent heat storage capacity of the phase change wall-lining. The XXL(2) Thermocules produced by Outlast Technologies Inc need further formulation development to improve the shells of the microcapsules. The shells need either the mechanical properties improving, for example the flexural strength to enable the shells to withstand extensive thermal cycling, or the chemical resistance to prevent the shells breaking down over time.

All of the microencapsulated phase change materials evaluated in this research contained organic paraffin wax. Currently there are no commercially available microencapsulated inorganic phase change materials. Inorganic phase change materials have a higher latent heat capacity and do not have the fire risks of the organic paraffin wax. Inorganic PCMs contain water molecules in the chemical compound and the number of molecules must remain unchanged for the phase change material to be able to undertake repeated thermal cycles. During the microencapsulation manufacturing process it is difficult to maintain the moisture content of the inorganic phase change material and the capsule shell. As yet no manufacturer has managed to overcome this issue. If microencapsulated inorganic phase change materials were available a phase change wall-lining with greater latent heat capacity could be achieved.

9.6.2 Thickness of Phase Change Wall-lining

Future work to investigate the phase change wall-lining thickness would be important to identify if there is an optimum depth to which the heat transfer can penetrate. Findings of previous research into PCM wallboard by Chen et al (2005) found that if the thickness of phase change wallboard is doubled, then the heat transfer quantities through the PCM will be halved. Furthermore, research by DuPont (Virgone, 2010) concluded that the 5mm thickness of their Energain panel provided 75% of the performance of doubling the thickness to 10mm. Increasing the thickness from 10mm to 20mm gave no improvement in performance.

9.6.3 Thermal Energy Storage Capacity of Phase Change Wall-lining

Further work is required to determine if it is possible to utilise all of the latent heat capacity. The temperature range that the phase change materials would need to operate must be considered during selection. To utilise all of the latent heat capacity the onset melt temperature, peak temperature and completion temperature of the phase transition needs to be compared against the likely operational temperatures in a building. The smaller the temperature range, the narrower the peaks on the DSC graph and conversely the larger the temperature range the broader the peaks.

9.6.4 Design Criteria

It has been established that the air velocity and temperature distributions across the wall surfaces is vital in predicting the performance of the phase change wall-lining. Further work to determine the optimum air velocity and surface heat transfer coefficients is important to continue to move this research forward.

9.6.5 Large Scale Test Installation

The dynamic thermal performance of a phase change wall-lining in a real room needs to be evaluated. The phase change wall-lining should be fitted in a number of real rooms of a lightweight building to ascertain the thermal performance during a spring through to autumn period. This will provide crucial performance data on how effective the phase change wall-lining is at improving thermal performance and the resulting thermal comfort conditions.

9.6.6 Thermal Model

Performance criteria obtained through further test studies and a large scale test installation should be used to develop a thermal model. It is important to thermally simulate the impact the phase change wall-lining could have in a room or building using computer software. This would enable designers and engineers to evaluate the thermal performance of their building with the phase change wall-lining fitted. This will led to greater confidence in specifying a phase change wall-lining and greater commercial success.

References

ABHAT, A. 1983. Low temperature latent heat thermal energy storage: Heat storage materials. *Solar Energy,* 30**,** 313-332.

AHMAD, M., BONTEMPS, A., SALLEE, H. & QUENARD, D. 2006a. Experimental investigation and computer simulation of thermal behaviour of wallboards containing a phase change material. *Energy and Buildings,* 38**,** 357-366.

AHMAD, M., BONTEMPS, A., SALLEE, H. & QUENARD, D. 2006b. Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material. *Energy and Buildings,* 38**,** 673-681.

ATHIENITIS, A. K., LIU, C., HAWES, D., BANU, D. & FELDMAN, D. 1997. Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. *Building and Environment,* 32**,** 405.

BARNARD, N. Thermal mass and night ventilation "utilising hidden" thermal mass. *In:* EGOLF, P. W. & SARI, O., eds. Phase Change Material & Slurry Scientific Conference & Business Forum, 23-26 April 2003 Yverdon-les-Bains, Switzerland. 71-77.

BASF. 27th July 2004. *RE: Storing Latent Heat with Phase-Change Materials – An alternative to insulation or an enhancement?* Type to OMNOVA.

BENTZ, D. P. & TURPIN, R. 2007. Potential applications of phase change materials in concrete technology. *Cement and Concrete Composites,* 29**,** 527-532.

BRAHAM, D., BARNARD, N. & JAUNZENS, D. 2001. Thermal Mass in Office Buildings - Design Criteria. *Digest 454 Part 2.* Watford: BRE.

BRIGHTON, U. O. 2014. *Knowledge Transfer Partnerships at University of Brighton* [Online]. Available: http://www.brighton.ac.uk/ccp/ktp/ 2014].

CABEZA, L. F., CASTELLON, C., NOGUES, M., MEDRANO, M., LEPPERS, R. & ZUBILLAGA, O. 2006. Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings,* In Press, Corrected Proof.

CABEZA, L. F., CASTELLON, C., NOGUES, M., MEDRANO, M., LEPPERS, R. & ZUBILLAGA, O. 2007. Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings,* 39**,** 113-119.

CABEZA, L. F. & IBAÑEZ, M. 2004. An approach to the simulation of PCMs in building applications using TRNSYS. *International TRNSYS Users' Day.* Barcelona.

CABEZA, L. F., SOLÉ, C., NOGUÉS, M., MEDRANO, M. & CASTELLÓN, C. 2005. The MOPCON Project. *IEA, ECES IA Annex 17 7th Workshop.* Kizkalesi, Turkey.

CARBONARI, A., DE GRASSI, M., DI PERNA, C. & PRINCIPI, P. 2006. Numerical and experimental analyses of PCM containing sandwich panels for prefabricated walls. *Energy and Buildings,* 38**,** 472-483.

CHANDRA, S., KUMAR, R., KAUSHIK, S. & KAUL, S. 1985. Thermal performance of a non-air-conditioned building with PCCM thermal storage wall. *Energy Conversion and Management,* 25**,** 15-20.

CHEN, X., GUOHUI, F., GUANGYU, C. & HU, Y. Optimization of Performance of Phase Change Thermal Storage Wallboards. The 2005 World Sustainable Building Conference, 27-29 September 2005 2005 Tokyo, Japan. 1123-1126.

CHI, O., LAI, C.-M., HSIAO, C.-C. & HO, C. J. Preliminary Investigations on the Enhancement of Rooftop Thermal-Insulation Capability of Hollow Bricks with PCM Incorporated. The 2005 World Sustainable Building Conference, 27-29 September 2005 2005 Tokyo, Japan. 230-233.

CIBSE 1999. *Guide A: Environmental Design,* London, The Yale Press Ltd.

CIBSE 2005. *KS 3: Sustainable Low Energy Cooling: An Overview*, CIBSE Publicaitons.

CIBSE 2006. *Guide A: Environmental Design,* London, Chartered Institute of Buildings Services Engineers.

CLIMATOR 2006. Pouches.

COLLIER, R. K. & GRIMMER, D. P. The Experimental Evaluation of Phase Change Material Building Walls Using Small Passive Test Boxes. *In:* RICHARDS, D., MILLER, H. & RIORDAN, M., eds. Proceedings of the 3rd National Passove Solar Conference, 1979 San Jose, California. 547-552.

COSTA, M., BUDDHI, D. & OLIVA, A. 1998. Numerical simulation of a latent heat thermal energy storage system with enhanced heat conduction. *Energy Conversion and Management,* 39**,** 319-330.

DARKWA, J. & ZHOU, T. 2011. Enhanced laminated composite phase change material for energy storage. *Energy Conversion and Management,* 52**,** 810-815.

DARKWA, K. 2000. Mathematical Evaluation of Phase Change Wall Systems: for Reducing Energy Consumption in Buildings and CO_2 Emissions in the United Kingdom. *Architectural Science Review,* 43**,** 221-228.

DARKWA, K. & KIM, J. S. 2004. Heat transfer in neuron composite laminated phase-change drywall. *Proceedings of the I MECH E Part A: Journal of Power and Energy,* 218**,** 83-88.

DARKWA, K. & KIM, J. S. 2005a. Dynamics of energy storage in phase change drywall systems. *International Journal of Energy Research,* 29**,** 335-343.

DARKWA, K. & KIM, J. S. 2005b. Thermal analysis of composite phase change drywall systems. *Journal of Solar Energy Engineering,* 127**,** 352-356.

DARKWA, K. & O'CALLAGHAN, P. W. 2006. Simulation of phase change drywalls in a passive solar building. *Applied Thermal Engineering,* 26**,** 853-858.

DAVID, D., KUZNIK, F. & ROUX, J.-J. 2011. Numerical study of the influence of the convective heat transfer on the dynamical behaviour of a phase change material wall. *Applied Thermal Engineering,* 31**,** 3117-3124.

DINCER, I. 2002. General Introductory Aspects for Thermal Engineering. *In:* DINCER, I. & ROSEN, M. A. (eds.) *Thermal Energy Storage - Systems and Applications.* Chichester, England: John Wiley & Sons.

DINCER, I. & ROSEN, M. A. 2002. *Thermal Energy Storage Systems and Applications,* Chichester, John Wiley & Sons.

DUPONT 2007. A New Approach to Adding 'Thermal Mass' to Buildings. *Modern Building Services.*

DUPONT 2011. DuPont Energain - Product Datasheet. DuPont de Nemours (Luxembourg) S.à r.l.

DYBALL, D., IP, K., MILLER, A. & CORNER, T. 2005. Development of Phase Change Wall-linings to Enhance Thermal Storage of Buildings. *The World Sustainable Buildings Conference (SB05).* Tokyo, Japan.

EPS 2001. Phase Change Materials & Eutectic Solutions Special Applications.

FABERMAUNSELL 2003. CoolDeck.

FAROUK, B. & GÜÇERI, S. Temperature Regulation of Residential Air Spaces Using PCM Thermal Wall Panels. Solar Energy and Conservation Workshop, December 1978 Elmsford, New York. Pergamon Press, 367-392.

FELDMAN, D., BANU, D., HAWES, D. & GHANBARI, E. 1991. Obtaining an energy storing building material by direct incorporation of an organic phase change material in gypsum wallboard. *Solar Energy Materials,* 22**,** 231-242.

FEUSTAL, H. E. 1995. Simplified Numerical Description of Latent Storage Characteristics for Phase Change Wallboard. Berkeley, CA: Lawrence Berkeley National Laboratory.

FISCH, M. N. & KÜHL, L. 2006. Use of Microencapsulated Phase Change Materials in Office Blocks. BASF.

FRAISSE, G., JOHANNES, K., TRILLAT-BERDAL, V. & ACHARD, G. 2006. The use of a heavy internal wall with a ventilated air gap to store solar energy and improve summer comfort in timber frame houses. *Energy and Buildings,* 38**,** 293-302.

GEORGE, K. & SHEPARD, M. 1993. *Phase Change Wallboard For Peak Demand Reduction* [Online]. E Source.

GHIABAKLOU, Z. 2003. Thermal comfort prediction for a new passive cooling system. *Building and Environment,* 38**,** 883.

HALAWA, E., BRUNO, F. & SAMAN, W. 2005. Numerical analysis of a PCM thermal storage system with varying wall temperature. *Energy Conversion and Management,* 46**,** 2592-2604.

HALFORD, C. K. & BOEHM, R. F. 2007. Modeling of phase change material peak load shifting. *Energy and Buildings,* 39**,** 298-305.

HASNAIN, S. M. 1998. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management,* 39**,** 1127-1138.

HAWLADER, M. N. A., UDDIN, M. S. & KHIN, M. M. 2003. Microencapsulated PCM thermal-energy storage system. *Applied Energy,* 74**,** 195-202.

HE, B., MARTIN, V. & SETTERWALL, F. 2004. High-capacity cool thermal energy storage for peak shaving. *IEA, ECES IA Annex 17 6th Workshop.* Arvika, Sweden.

HED, G. 2005. *Service Life Estimations in the Design of a PCM Based Night Cooling System.* PhD Doctoral, University of Gävle.

HEIM, D. & CLARKE, J. A. Numerical Modelling and Thermal Simulation of Phase Change Materials with ESP-r. Eighth International IBPSA Conference, 11-14 August 2003 2003 Eindhoven, Netherlands. 459-466.

HEIM, D. & CLARKE, J. A. 2004. Numerical modelling and thermal simulation of PCM-gypsum composites with ESP-r. *Energy and Buildings,* 36**,** 795-805.

HONG, H., KIM, S. K. & KIM, Y.-S. 2004. Accuracy improvement of T-history method for measuring heat of fusion of various materials. *International Journal of Refrigeration,* 27**,** 360-366.

HUMPHREYS, M. A. 1978. The Optimum Diameter for a Globe Thermometer For Use Indoors. Watford, UK: Building Research Establishment (BRE).

HUNGER, M., ENTROP, A. G., MANDILARAS, I., BROUWERS, H. J. H. & FOUNTI, M. 2009. The behavior of self-compacting concrete containing micro-encapsulated Phase Change Materials. *Cement and Concrete Composites,* 31**,** 731-743.

IP, K., DYBALL, D. & MILLER, A. Thermal behaviour of a wall-lining containing phase change materials. World Sustainable Building Conference, 21-25 Sept 2008 Melbourne, Australia.

IP, K., MILLER, A., CORNER, T. & DYBALL, D. Development of Phase Change Thermal Storage Wallcoverings In Buildings. The CIB 2003 International Conference on Smart and Sustainable Built Environment, 19-21 November 2003 Brisbane, Australia.

IP, K., MILLER, A., CORNER, T. & DYBALL, D. 2005. Development of Phase Change Thermal Storage Wallcoverings In Buildings. *In:* YANG, J., BRANDON, P. & SIDWELL, A. C. (eds.) *Smart and Sustainable Built Environment.* Blackwell Publishers.

KANG, Y. H., KWAK, H. Y., OHM, T. & WANG, Z. 1997. Numerical Heat Transfer Analysis of Heat Storage Board with Microcapsule Using Phase Change Material. *The 1997 ISES Solar World Congress.* Taejon, Korea.

KEDL, R. J. 1991. Wallboard with Latent Heat Storage for Passive Solar Applications. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

KHUDHAIR, A., FARID, M., OZKAN, N. & CHEN, J. 2003. Thermal performance and mechanical testing of gypsum wallboard with latent heat storage. *IEA, ECES IA Annex 17 4th Workshop.* Indore, India.

KIM, J.-S. & DARKWA, K. 2003. Simulation of an Integrated PCM Wallboard System. *International Journal of Energy Research,* 27**,** 215-223.

KISSOCK, K. & LIMAS, S. 2006. Diurnal Load Reductions Through Phase-Change Building Components. *ASHRAE Transactions,* 112**,** 509-517.

KNAUF 2008. Knauf PCM Smartboard - Product Literature. Knauf Gips KG.

KOSCHENZ, M. & LEHMANN, B. 2004. Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. *Energy and Buildings,* 36**,** 567-578.

KOSCHENZ, M., LEHMANN, B. & HOLST, S. 2005. *Thermoactive Wall and Ceiling Element*. United States patent application.

KOSNY, J., YARBOROUGH, D. W. & MILLER, W. A. 2008. Use of PCM Enhanced Insulation in the Building Envelope. *BEST (Building Enclosure Science & Technology) 1 Conference.* Minneapolis.

KUZNIK, F., VIRGONE, J. & JOHANNES, K. 2011. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. *Renewable Energy,* 36**,** 1458-1462.

KUZNIK, F., VIRGONE, J. & NOEL, J. 2008a. Optimization of a phase change material wallboard for building use. *Applied Thermal Engineering,* 28**,** 1291-1298.

KUZNIK, F., VIRGONE, J. & ROUX, J.-J. 2008b. Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation. *Energy and Buildings,* 40**,** 148-156.

LAI, C.-M. & CHAING, C.-M. 2006. How phase change materials affect thermal performance: hollow bricks. *Building Research and Information,* 34**,** 118-130.

LAMBERG, P., JOKISALO, J. & SIRÉN, K. The feasibility of combining phase change materials with building concrete products. Terrastock 2000, 8th International Conference on Thermal Energy Storage, 28 August - 1 September 2000 Stuttgart, Germany. 605-608.

LANE, G. A. 1983. *Background and Scientific Principles,* Florida, CRC Press Inc.

LEE, T., HAWES, D. W., BANU, D. & FELDMAN, D. 2000. Control aspects of latent heat storage and recovery in concrete. *Solar Energy Materials and Solar Cells,* 62**,** 217-237.

LUNGREN, C. J. 2002. Identification of Different Crystalline Forms of Sorbitol by DSC. *www.tainstruments.com/library_downlard.aspx?file=TS82.pdf.* TA Instruments.

MEHLING, H. & SCHOSSIG, P. 2005. Materials Testing for Quality Control. *IEA ECES Annex 17 8th Expert Meeting and Workshop.* Kizkalesi, Turkey.

MEMON, S. A. 2014. Phase change materials integrated in building walls: A state of the art review. *Renewable and Sustainable Energy Reviews,* 31**,** 870-906.

MÉTIVAUD, V., VENTOLA, L., CALVET, T., CUEVAS-DIARTE, M. A. & MONDIEIG, D. 2004. Thermal insulation of buildings using phase change materials. *IEA, ECES IA Annex 17 6th Workshop.* Arvika, Sweden.

MIHASHI, H., NISHIWAKI, T., KANEKO, Y. & NISHIYAMA, N. Development of Smart Concrete. Proceedings of the First FIB Congress, Concrete Structures in the 21st Century, 2002 Osaka, Japan. Japan Prestressed Concrete Association, 165-174.

NAGANO, K., TAKEDA, S., MOCHIDA, T., SHIMAKURA, K. & NAKAMURA, T. 2006. Study of a floor supply air conditioning system using granular phase change material to augment building mass thermal storage--Heat response in small scale experiments. *Energy and Buildings,* 38**,** 436-446.

NEEPER, D. A. 1990. Benefits of Wallboard Impregnated with Phase Change Material for Residential Heating and Cooling. *subcontract report to Solar Energy Research Institute.* Los Alamos.

NEEPER, D. A. 2000. Thermal dynamics of wallboard with latent heat storage. *Solar Energy,* 68**,** 393.

OLAYA, J. M., ALCORTA, O. Z. & CABEZA, L. Free Cooling Concepts for Buildings: Enhanced Thermal Storage Concrete Based on Phase Change Materials. Fifth International Conference on the Environmental and Technical Implications of Construction With Alternative Materials (WASCON), 4-6th June 2003 San Sebastian, Spain. 865-868.

OSTERMAN, E., TYAGI, V. V., BUTALA, V., RAHIM, N. A. & STRITIH, U. 2012. Review of PCM based cooling technologies for buildings. *Energy and Buildings,* 49**,** 37-49.

PASUPATHY, A., VELRAJ, R. & SEENIRAJ, R. V. 2008. Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renewable and Sustainable Energy Reviews,* 12**,** 39-64.

PCP 2006. K-Panel. Phase Change Products Pty Ltd.

PROBE 1998. 14: Elizabeth Fry Building. *Buildings Services Journal.* CIBSE.

RUDD, A. F. 1993. Phase-Change Material Wallboard for Distributed Thermal Storage in Buildings. *ASHRAE Transactions: Research,* 99.

SAKULICH, A. R. & BENTZ, D. P. 2012. Incorporation of phase change materials in cementitious systems via fine lightweight aggregate. *Construction and Building Materials,* 35**,** 483-490.

SALYER, I. O. & SIRCAR, A. K. Development of PCM wallboard for heating and cooling of residential buildings. US Department of Energy Thermal Energy Storage Research Activities Review, 15-17 March 1989 New Orleans, Louisiana. Oak Ridge National Laboratory, 97-123.

SARI, A. 2003. Thermal reliability test of some fatty acids as PCMs used for solar thermal latent heat storage applications. *Energy Conversion and Management,* 44**,** 2277-2287.

SCALAT, S., BANU, D., HAWES, D., PARISH, J., HAGHIGHATA, F. & FELDMAN, D. 1996. Full scale thermal testing of latent heat storage in wallboard. *Solar Energy Materials and Solar Cells,* 44**,** 49.

SCHOSSIG, P., HAUSSMANN, T. & HENNING, H. M. Actively Driven Construction Materials with Latent Heat Storage. *In:* SARI, O., EGOLF, P. W. & KAUFFELD, M., eds. Second Conference on Phase Change Material and Slurry: Scientific Conference & Business Forum, 15-17 June 2005a Yverdon-les-Bains, Switzerland. 40-47.

SCHOSSIG, P., HENNING, H. M., GSCHWANDER, S. & HAUSSMANN, T. 2005b. Micro-encapsulated Phase-Change Materials Integrated into Construction Materials. *Solar Energy Materials and Solar Cells,* 89**,** 297-306.

SHAPIRO, M. M., FELDMAN, D., HAWES, D. & BANU, D. 1987. PCM Thermal Storage In Drywall Using Organic Phase Change Material. *Passive Solar Journal,* 4**,** 419-438.

SHAPIRO, M. M., FELDMAN, D., HAWES, D. & BANU, D. 1988. PCM Wallboard Tempers Passive-Solar Temperature Swings. *SunWorld,* 12**,** 46-47`.

STETIU, C. & FEUSTAL, H. E. 1998. *Phase-change wallboard and mechanical night ventilation in commercial buildings* [Online]. Berkeley, CA: Lawrence

Berkeley National Laboratory. Available: http://epb1.lbl.gov/EPB/thermal/pcm.html [Accessed 26th July 2004 2004].

STOVALL, T. K. & TOMLINSON, J. J. 1992. What are the Potential Benefits of Including Latent Storage in Common Wallboard? Oak Ridge, Tennessee: Oak Ridge National Laboratory.

STOVALL, T. K. & TOMLINSON, J. J. 1995. What are the Potential Benefits of Including Latent Storage in Common Wallboard? *Journal of Solar Energy Engineering - Transactions of ASME,* 117**,** 318-325.

SUALLES, T. D. 2005. Thermal Mass.

TA-INSTRUMENTS 2003a. Default in Software = ICTAC. *DSC Training Course.* Leatherhead, UK.

TA-INSTRUMENTS 2003b. DSC Cell Schematic. *DSC Training Course.* Leatherhead, UK.

TARMAC 2003. Concrete Products - TermoDeck.

TARMAC 2006. TermoDeck - Thermal Mass Benefits.

TURNPENNY, J. R., ETHERIDGE, D. W. & REAY, D. A. 2000. Novel ventilation cooling system for reducing air conditioning in buildings.: Part I: testing and theoretical modelling. *Applied Thermal Engineering,* 20**,** 1019-1037.

VAKILALTOJJAR, S. M. & SAMAN, W. 2001. Analysis and modelling of a phase change storage system for air conditioning applications. *Applied Thermal Engineering,* 21**,** 249-263.

VAN DORP, J. E. 2004. An approach to empirical investigation of performance of passive PCM applications in office buildings based on the T-history method. *IEA, ECES IA Annex 17 6th Workshop.* Arvika, Sweden.

VIRGONE, J. 2010. *Equivalence DuPont™ Energain™ - Concrete* [Online]. DuPont de Nemours. Available: http://energain.co.uk/Energain/en_GB/assets/downloads/documentation/download/energain_Concrete_Relation.pdf 2010].

VOELKER, C., KORNADT, O. & OSTRY, M. 2008. Temperature reduction due to the application of phase change materials. *Energy and Buildings,* 40**,** 937-944.

WEBMASTER 2005. Scanning Electron Microscopy. University of Nebraska.

XU, X., ZHANG, Y., LIN, K., DI, H. & YANG, R. 2005. Modeling and simulation on the thermal performance of shape-stabilized phase change material floor used in passive solar buildings. *Energy and Buildings,* 37**,** 1084-1091.

YINPING, Z., YI, J. & YI, J. 1999. A simple method, the T-history method, of determining the heat of fusion, specific heat and thermal conductivity of phase change materials. *Measurement Science and Technology,* 10**,** 201-205.

ZHANG, Y., DING, J., WANG, X., YANG, R. & LIN, K. 2006. Influence of additives on thermal conductivity of shape-stabilized phase change material. *Solar Energy Materials and Solar Cells,* 90**,** 1692-1702.

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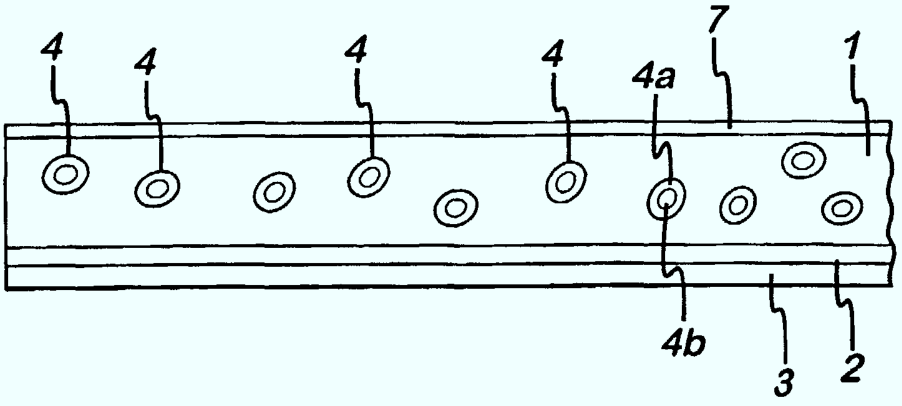

(57) Abstract: A flexible wall lining includes a body layer (1) comprising one or more phase change materials (4) that each exhibit a phase change at a temperature in the range from 5° to 40°C. The wall lining preferably is provided in the form of a sheet that can be attached to a building wall (5) either at the time of construction or, advantageously, at a time when the building is being renovated or redecorated.

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WALL LINING

BACKGROUND INFORMATION

This invention relates to wall linings, especially wall linings that provide enhanced thermal efficiency.

Building walls typically comprise a rigid walling material such as brick or plasterboard covered with a wall lining such as, for example, paint and/or a sheet material like wall paper or a wallcovering.

There is a general desire for buildings to be energy efficient so as to reduce the costs of heating and cooling them. In the case of building walls this is normally addressed by incorporating insulating materials such as rigid foam or heat-reflective metallic sheet into the rigid element of the wall.

Materials commonly known as phase change materials have been used in textiles (for instance for military clothing), surgical bandages and protectors for electronic components. These materials exhibit a phase change at an operational or working temperature, in the course of which they absorb or emit heat. This gives them thermal regulating properties.

It has also been proposed to incorporate phase change materials into plasterboard sheet which could then be used for the rigid elements of walls. Wall boards incorporating phase-change materials have been proposed, for example, in CBS Newsletter, Fall 1997 currently available from http://eetd.lbl.gov/newsletter/CBS_NL/nl16/phase.html and *ASHRAE Transactions: Research*, vol. 99, part 2, paper #3724. These are rigid boards formed of gypsum into which phase change materials have been incorporated with the intention of enhancing the thermal energy storage capacity of buildings whose walls are formed of the boards.

Although gypsum wallboard (due to its highly porous nature) was found to make an ideal supporting medium for phase change materials, the systems that have been developed suffer from a number of problems. The preferred forms of phase change materials in such wall boards have been paraffins and fatty acids. Wall boards incorporating paraffins present flammability issues, and wall boards incorporating fatty acids (which are generally derived from meat by-products and vegetables) have been found to give off unacceptable odor levels.

Additionally, while it might be convenient to use such wall boards when constructing a new building, incorporating them into an existing room would mean replacing the existing walling of the room, which would be inconvenient, messy, and potentially so costly as to outweigh any expected energy savings.

DESCRIPTION OF THE INVENTION

Briefly, there is provided a flexible wall lining that includes one or more phase change materials exhibiting a phase change at a temperature in the range from 5° to 40°C. The wall lining preferably is in the form of a sheet which preferably has an adhesive layer for adhering it to a wall. Alternatively the sheet could be pasted to a wall using an additional adhesive. The adhesive layer may initially be provided with a removable backing sheet on its face opposite the body of the sheet.

The mechanism of the or each phase change is preferably endothermic with increasing temperature and exothermic with reducing temperature. At atmospheric pressure, the or each phase change material preferably has a first phase stable at a temperature below the respective phase change temperature and a second phase stable above the respective phase change temperature. The change from the first to the second phase is preferably endothermic, and the change from the second to the first phase preferably exothermic. Thus the phase change material may act as a temperature buffer about the respective phase change temperature.

Preferably the or each phase change material is in the form of particles. The size of the particles is preferably in the range from 10 to 120 μm, or up to 300 μm. Preferably each particle is encapsulated with an impermeable coating. This coating may be constituted by a structural material of a layer of the coating, or each particle may be individually encapsulated. The coating is preferably flexible.

The particles may be embedded in a layer of the wall coating. That is preferably a polymer layer. Alternatively the particles are adhered to an absorbent layer of the wall lining, for example by impregnating a paper or textile layer of the wall lining with the particles.

Preferably the wall lining comprises from 30 to 60% by weight or alternatively by volume of the phase change material(s). Amounts outside that range could also be used.

Conveniently the or at least one of the phase change materials is hydrated below the temperature at which it exhibits the phase change, and conveniently less hydrated above that temperature. At least one of the phase change materials may be a hydrated metal salt. Phase change materials employing other mechanisms could also be used.

If wall lining comprises two phase change materials, the temperatures at which they exhibit the said phase change may suitably differ by at least 1°C. This can help to broaden the effective buffering range of the wall lining.

The wall lining could be intended to form an exposed surface of a wall to which it is applied. In that case the wall lining could be provided with a cosmetic outer face, for example a printed outer face. Alternatively, the wall lining could be affixed to a wall and then decorated, for instance by painting or by applying a sheet material such as wall paper.

In the accompanying drawings:

Fig. 1 is a cross-section of one form of wall coating;

Fig. 2 is a cross-section of a wall to which the coating of Fig. 1 has been applied; and

Fig. 3 is a cross-section of another form of wall coating; and

The present invention now is described by way of example with reference to the drawings with like reference numerals designating like parts.

Figure 1 shows a cross-section of one form of wall coating. The wall coating of Fig. 1 is a flexible sheet having a structural or body layer 1 and an adhesive layer 2 attached to the body layer and covering one major surface of the body layer. The adhesive layer is backed by a removable backing sheet 3, which protects the adhesive layer until the coating is to be applied to a wall. The body layer 1 comprises at least one phase change material, which in this instance is provided in the form of particles 4 which are embedded in the body layer 1. The phase change material exhibits an exothermic/endothermic phase change at a working temperature. As is conventional with such so-called phase change materials, the material is such that in passing through the phase change from below the working temperature to above the working temperature the material absorbs heat (endothermic) and vice versa. When the wall coating is applied to the wall 5 of a building (see Fig. 2) it can assist in stabilising the temperature of the building around the working temperature, and thus enhance the building's energy efficiency.

The wall coating will now be described in more detail.

The phase change material is preferably present in the wall lining in the form of particles. Figure 1 illustrates one way in which the particles may be integrated with the wall lining. In the wall lining of Fig. 1 the particles 4 are embedded in a polymer material that forms the matrix of the body layer 1. Fig. 2 illustrates another way in which the particles may be integrated with the wall lining. In the wall lining of Fig. 2, the particles have been coated on to an absorbent scrim 6 by soaking the scrim with a liquid bearing the particles, and then drying the scrim so as to leave the particles bound to the scrim. Another option would be to have the particles bound in the adhesive layer 2.

The phase change material could be incorporated in the wall lining in another way than as particles. For example, if the phase change material were in the form of a sheet then it could be laminated to the body layer 1 between the body layer and the adhesive layer 2. The phase change material could be attached to the body layer by an additional adhesive layer.

The phase change material could, for example be a hydrated metal salt such as hydrated aluminium chloride, hydrated magnesium chloride or Glauber's salt (sodium sulphate decahydrate). Alternative materials are listed in the following table.

Material	Approximate melting point (°C)
$CaCl_2 \cdot 6\ H_2O$	27
$Na_2SO_4 \cdot 10\ H_2O$	32
$MgCl_2 \cdot 6\ H_2O$	117
$Na_2S_2O_3 \cdot 5\ H_2O$	48
polyethylene glycol ($M_w > 2000$)	45
$C_{16}H_{34}$	18
$C_{17}H_{36}$	22
$C_{18}H_{38}$	28
$C_{19}H_{40}$	32
$C_{20}H_{42}$	36

Another possible alternative is a PEG/celulose diacetate blend.

To achieve the desired thermal properties, two or more phase change materials could be used in combination.

The working temperature of the phase change material – that is the temperature at which its relevant phase change occurs – should suitably be in the range from 5° to 40°C. One preferred possibility is for the working temperature to be around a desired lower temperature for a building interior, so that it can release heat as the temperature falls to that level: for that purpose the working temperature is suitably in the range from 8° to 14°C. Another preferred possibility is for the working temperature to be around a desired upper temperature for a building interior, so that it can absorb heat as the temperature rises to that level: for that purpose the working temperature is suitably in the range from 26° to 32°C, preferably between 28° and 30°C. Another preferred possibility is for the working temperature to be around a desired ambient temperature for a building interior, so that it can moderate temperature changes in the building: for that purpose the working temperature is suitably in the range from 14° to 26°C. Broader-based effects may be achieved by using combinations of materials from one or more of these temperature ranges.

Many candidates for the phase change materials are hydrated materials, especially hydrated metal salts. In order to maintain such materials in a suitably hydrated state over the lifetime of the wall lining and also during manufacture of the wall lining it is preferred that they are encapsulated in an impermeable coating. This is illustrated in figures 1 and 3, in which the particles 4 comprise a core 4b of phase change material and an impermeable outer coating 4a. The outer coating 4a seals the core 4b so that the composition of the core does not change during use. The encapsulation should be performed below the phase change material's phase change temperature since in that range its degree of hydration will be stable. The encapsulant will typically be a hydrophobic material, and it may be difficult to fully encapsulate hydrated materials with such a material. One way in which this may be achieved is by means of the micro-encapsulation technique described in US 4,675,140. That techniques involves the direction of a suspension of the particles and the encapsulant on to a rotating surface. The surface centrifuges the particles surrounded by the encapsulant into air, which causes the encapsulant to cure around the particles.

Where the particles are loaded into a polymer matrix as in the coating of figure 1, the matrix itself may provide sufficient encapsulation of the particles to keep them stable during use. However, even in that embodiment it is preferred that the particles are individually encapsulated since that diminishes the possibility that the particles will deteriorate when they are loaded into the matrix during manufacture of the wall coating.

To accommodate any volume change accompanying the phase change, any encapsulant and/or matrix holding the phase change material should preferably be flexible.

The phase change material and any encapsulant should be selected to have suitable properties for safe use as a building material. For example, it should preferably be non-flammable and/or non-hazardous.

Where the phase change materials are in the form of particles, it is preferred that the particles are in the size range from 10 to 120 μm. Larger or smaller particles could also be used. Relatively small particles are preferred as they are likely to interfere less with the handling, for example cutting, of the wall lining. The loading of the particles into the wall lining is preferably in the range from 30 to 60% by weight or alternatively by volume. To assist in achieving a relatively high loading of the particles, particles of different sizes may be used.

One preferred arrangement is for the matrix to include particles of two or more sets of sizes, each differing from the others in size by at least an order of magnitude. In this arrangement the particles of smaller sizes can occupy a considerable proportion of the volume between the larger particles. For example, there may be two sets of particles: one having a particle size of approximately 100 μm and one having a particle size of approximately 10 μm. The sizes of particles in each set are preferably tightly controlled to facilitate easy manufacture and to optimise filling. The particles of the largest size set preferably occupy 30 to 60% of the volume of the layer of the wall lining in which they are contained. The particles of the next smallest size preferably occupy up to 60%, and preferably 30 to 60% of the remaining volume, and so on.

The matrix of the body layer 1 is preferably a polymer material, such as a vinyl resin. The scrim 6 could be of paper or fabric.

The wall lining is preferably in the form of a flexible sheet, that can be applied to a wall in a similar way to conventional wall papers and vinyl wall linings. The finished sheet could be put in the form of a roll for shipping and storage, and unrolled for application to a wall. The outer surface of the sheet (e.g., the major surface of the body layer 1 to which the adhesive 2 is not applied, in the embodiment of Fig. 1) could have a decorative aspect. The outer surface could be pigmented by the application of a pigmented layer 7 to the surface, or the incorporation of pigment into the another layer of the sheet (e.g., layer 1). The outer surface could be embossed with a surface relief pattern. Alternatively, it could be intended that the wall lining should be decorated after having been installed. In that case it could have a plain exterior surface.

In summary, the wall linings of Figs. 1 and 3 are multilayer structures. Each embodiment comprises a layer (1,6) that forms the body of the wall lining. Phase change materials are incorporated in that layer: in one instance by being embedded in it and in the other instance by being adhered to its surface. Although it is not essential that an adhesive layer is provided, it is preferred that the wall lining comprises an adhesive layer 2 which coats one major surface of the body layer 1,6. The adhesive layer may be provided with a releasable backing layer 3 over its other major surface. One major surface of the body layer 1,6 may be provided with a decorative coating 7. If the wall lining has an adhesive layer 2, that surface is preferably the surface of the body layer to which the adhesive is not affixed.

The wall lining could include other materials intended to enhance energy efficiency by other mechanisms. For example, it could include reflective materials such as metallic fragments or metallic sheet for heat reflection.

The adhesive layer could be omitted from the coating. The coating could be fixed to a wall by an additional adhesive applied at the time of fixing, or by another means such as tacks.

Although the coating is suitable for application to walls, in practice it could be applied to other elements such as floors or ceilings.

EXAMPLES

Example 1

In a plastic beaker, 118 g Reofos™ 50 flame retardant (Great Lakes Chemical Corp.; Indianapolis, Indiana) was mixed with 1 g Lankromark™ LZB320 PVC stabilizer (Akcros Chemicals Ltd.; Manchester, England) in a using a laboratory mixer. To this mixture was slowly added 50 g Evipol™ MP6852 micro-suspension PVC (EVC (UK) Ltd.; Cheshire, England); after thorough mixing, another 50 g Evipol™ MP6852 PVC was added. After thorough mixing, to the resulting low viscosity liquid was slowly added two 38 g portions (each followed by mixing) of Micronal™ DS 5001 X powdered phase change material so as to give a viscous but pourable liquid.

This liquid was poured onto an A3 sheet of 80 g/m^3 paper and the paper passed through a knife coater with a gap of 2 mm so as to give a thick coating. Immediately after coating the coated paper was put into an oven set at 160°C for 3 minutes. The resultant coating had a coating weight of 1,766 g/m^3.

Using DSC with a heating/cooling rate of 10°C/min, the coating was found to have a melting point and a freezing point very similar to those shown by the powdered phase change material. The cured, flexible coating contained approximately 25.8% (w/w) microencapsulated wax with a melting point of ~23°C and a freezing point of ~13°C.

Example 2

In a plastic beaker, 90 g dioctyl phthalate plasticizer (Hoechst AG; , was mixed with 1 g Lankromark™ LZB320 stabilizer, 3 g Lankroflex™ E2307 epoxidized soya bean oil (Akcros Chemicals), and 2 g Deplastol™ fatty acid polyglycol ester (Cognis Performance Chemicals) using a laboratory mixer. To this mixture was slowly added 50 g Evipol™ MP6852 PVC and, after thorough mixing, 9.32 g Sb_2O_3 and an additional 50 g Evipol™ MP6852 PVC. After thorough mixing, to the resulting low viscosity liquid was slowly added two 40 g portions (each followed by mixing) of Rubitherm™ PX27 silica powder containing a phase change wax (Rubitherm GmbH; Hamburg, Germany) so as to give a viscous but pourable liquid.

This liquid was then poured onto an A3 sheet of 60 g/m^3 non-woven fabric and the coated fabric passed through a knife coater with a gap of 0.5 mm so as to give a thick coating. Immediately thereafter, the coated fabric was put into a oven set at 160°C for 3 minutes. The resultant coating had a coating weight of 450 g/m^3. DSC analysis showed that the coating had a melting point and a freezing point similar to those shown by the phase change material. The cured, flexible coating contained approximately 28.0% (w/w) phase change materials with a melting point of ~9°C and a freezing point of ~0°C.

Example 3

Using the procedure of Example 1, 127 g Reofos™ 50 flame retardant was mixed with 1 g Lankromark™ LZB320 stabilizer. To this mixture was slowly added two 50 g charges of Evipol™ MP6852 PVC. When this had been mixed in thoroughly, a further 50 g of Evipol MP6852 was added. After thorough mixing yielded a low viscosity liquid, two separate portions of 38 g Rubitherm™ PX27 silica powder containing a phase change wax were slowly added, the second of which was accompanied by 9 g Reofos™ 50 flame retardant, and the composition thoroughly mixed so as to give a viscous but pourable liquid.

This liquid was then poured, coated, and heated as described in Examples 1 and 2 (coater gap of 1.5 mm); the resultant coating had a coating weight of 1,300 g/m^3. DSC analysis showed that the coating had a melting point and a freezing point similar to those shown by the phase change material.

The cured, flexible coating contained approximately 25.0% (w/w) of the phase change material with a melting point of ~13°C and a freezing point of ~1°C.

Example 4

Similar to the procedure of Example 2, 71 g dioctyl phthalate plasticizer was mixed with 1 g Lankromark™ LZB320 PVC stabiliser, 3 g Lankroflex™ E2307 epoxidised soya bean oil, 2 g Deplastol™ fatty acid polyglycol ester, and 19 g Cereclor™ S45 chlorinated paraffin (IACC; Thailand). To this mixture was slowly added (separated by thorough mixing) two 50 g charges of Evipol™ MP6852 PVC and 12 g SBP11 solvent (Gelpe and Bate Ltd.) to give a low viscosity liquid. To this was slowly added two charges (each followed by thorough mixing) of 68 g Rubitherm™ GR30 granular diatomaceous earth containing a phase change wax (Rubitherm GmbH) to give a viscous but pourable liquid.

This liquid was then poured, coated, and heated as described previously (80 g/m^3 paper, coater gap of 2.0 mm, 8 minutes of heating); the resultant coating had a coating weight of 2100 g/m^3. DSC analysis showed that the coating had a melting point and a freezing point similar to those of the phase change material. The cured, flexible coating contained approximately 30.1% (w/w) of the phase change material with a melting point of ~6°C and a freezing point of ~ -3°C.

Example 5

Similarly to that described in the prior examples, 64 g Reofos™ 50 flame retardant, 1 g Lankromark™ LZB320 stabiliser, 3 g Lankroflex™ E2307 epoxidized soya bean oil, 2 g Deplastol™ fatty acid polyglycol ester, and 33 g Cereclor™ S45 chlorinated paraffin were mixed. To this mixture was slowly added two 50 g charges of Evipol™ MP6852 PVC, which charges were separated by the addition of 9.32 g Sb_2O_3, 18 g Thermasorb™ 83 microencapsulated wax (Frisby Technologies Inc.; Winston Salem, North Carolina) and 12 g SBP11 solvent. This gave a low viscosity liquid to which was slowly added an additional 46 g Thermasorb™ 83 wax. Mixing was continued so as to give a viscous but pourable liquid.

This liquid was then poured, coated, and heated as described previously (80 g/m^3 paper, coater gap of 2.0 mm, 3 minutes of heating); the resultant coating had a coating weight of 1900 g/m^3. DSC analysis showed that the coating had a melting point and a freezing point similar to those of the phase change material. The cured, flexible coating contained approximately 26.36% (w/w) of phase change material with a melting point of ~17°C and a freezing point of ~1°C.

Example 6

Together were mixed 71 g dioctyl phthalate plasticizer, 1 g Lankromark™ LZB320 stabilizer, 3 g Lankroflex™ E2307 epoxidized soya bean oil, 2 g Deplastol fatty acid polyglycol ester, and 33 g Cereclor™ S45 chlorinated paraffin. To this mixture was slowly added two 50 g charges of Evipol™ MP6852 PVC separated by thorough mixing and the addition of 9.32 g Sb_2O_3. To the resulting low viscosity liquid, 76 g Thermasorb™ 83 microencapsulated wax was slowly added and mixing was continued so as to give a viscous but pourable liquid.

This liquid was then poured, coated, and heated as described previously (80 g/m^3 paper, coater gap of 2.0 mm, 3 minutes of heating); the resultant coating had a coating weight of 1715 g/m^3. DSC analysis showed that the coating had a melting point and a freezing point similar to those of the phase change material. The cured, flexible coating contained approximately 27.02% (w/w) of phase change material with a melting point of ~21°C and a freezing point of ~11°C.

CLAIMS

We claim:

1. A flexible wall lining comprising at least one phase change material, each of said at least one phase change material exhibiting a phase change at a temperature in the range from 5° to 40°C.

2. The wall lining of claim 1 wherein the wall lining is in the form of a sheet, said sheet optionally comprising on one primary side thereof an adhesive layer for securing said sheet to a wall.

3. The wall lining of any of claims 1 and 2 wherein the phase change is endothermic with increasing temperature and exothermic with decreasing temperature.

4. The wall lining of any of claims 1 to 3 wherein said at least one phase change material is in the form of particles.

5. The wall lining of claim 4 wherein said particles have diameters of from 10 to 120 μm.

6. The wall lining of any of claims 4 and 5 wherein each of said particles is encapsulated with an impermeable coating, said coating optionally being flexible.

7. The wall lining of any of claims 4 to 6 wherein said particles are at least one of embedded in a layer of the wall lining and adhered to an absorbent layer of the wall lining.

8. The wall lining of any preceding claim wherein the wall lining comprises from 30 to 60% by volume of said at least one phase change material.

9. The wall lining of any preceding claim wherein said at least one phase change materials is hydrated below the temperature at which it exhibits the phase change.

10. The wall lining of any preceding claim wherein said at least one phase change materials is a blend of at least two such materials, the temperatures at which each exhibits a phase change differing by at least 1°C.

Fig. 1

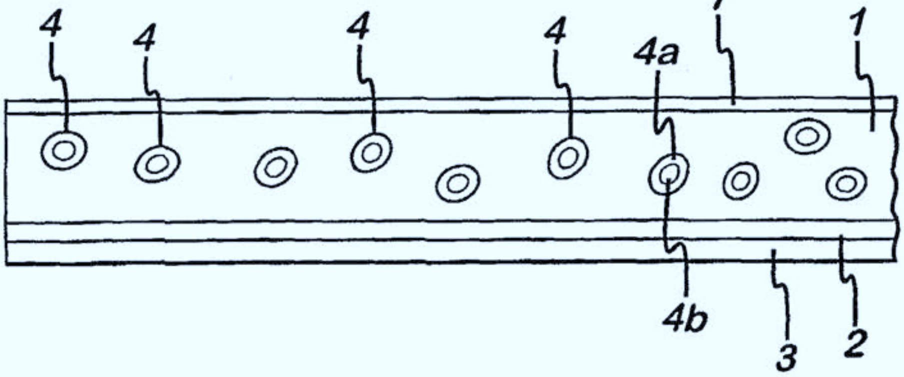


Fig. 2

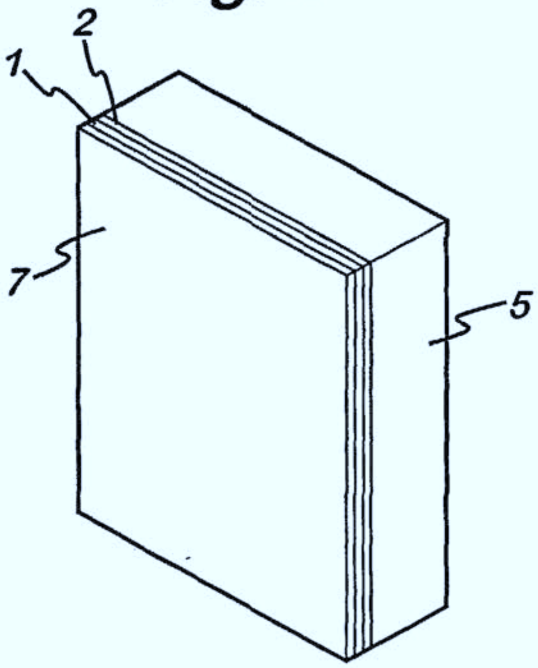
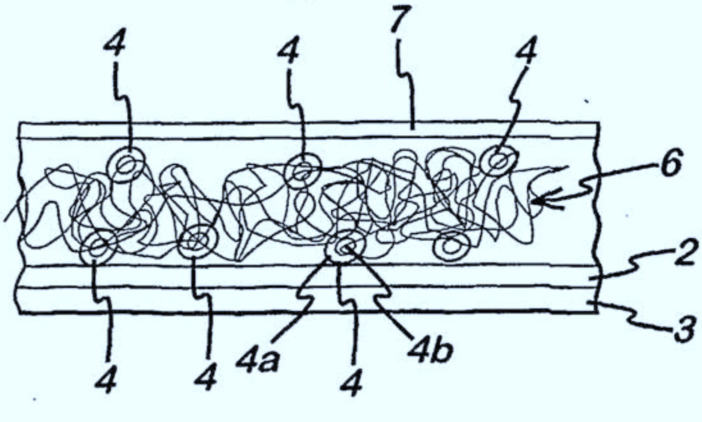


Fig. 3



INTERNATIONAL SEARCH REPORT

Internat[illegible] Application No
PCT/US 03/09902

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F28D20/02 C09K5/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 F28D C09K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 003 442 A (ARCHITECTURAL RES CORP) 8 August 1979 (1979-08-08) page 3, line 24 -page 4, line 9 page 7, line 4 - line 23 page 8, line 8 - line 26; figures 1-4 ---	1,4,5,10
X	WO 98 42929 A (PAUSE BARBARA ;OUTLAST TECHNOLOGIES INC (US)) 1 October 1998 (1998-10-01) page 5, line 27 -page 6, line 22 page 8, line 14 -page 9, line 9 page 10, line 14 -page 11, line 21; figures 1-5 ---	1-4
A	US 4 367 788 A (CORDON WILLIAM A) 11 January 1983 (1983-01-11) column 2, line 22 -column 3, line 68; figures 2A-5 --- -/--	1-10

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search 19 June 2003	Date of mailing of the international search report 26/06/2003
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Beltzung, F

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 747 240 A (VOISINET WALTER E ET AL) 31 May 1988 (1988-05-31) column 1, line 61 -column 2, line 9 column 3, line 23 -column 4, line 6 ---	1-10
A	US 4 259 401 A (CHAHROUDI DAY ET AL) 31 March 1981 (1981-03-31) column 10, line 64 -column 11, line 43 column 22, line 10 - line 47; figures 3,3A,10B,11 ---	1-10
A	US 4 587 279 A (SALYER ET AL) 6 May 1986 (1986-05-06) column 3, line 58 - line 64 column 4, line 32 - line 42 column 4, line 64 -column 5, line 11 ---	1-10
A	US 5 501 268 A (STOVALL THERESE K ET AL) 26 March 1996 (1996-03-26) column 3, line 45 -column 4, line 65 -----	1-10

INTERNATIONAL SEARCH REPORT

ion on patent family members

Internati[illegible] Application No
PCT/US 03/09902

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0003442 A	08-08-1979	US 4178727 A	18-12-1979
		DE 2965171 D1	19-05-1983
		DK 35679 A	02-08-1979
		EP 0003442 A1	08-08-1979
		FI 790272 A ,B,	02-08-1979
		NO 790262 A	02-08-1979
		SE 7811286 A	02-08-1979
WO 9842929 A	01-10-1998	DE 981675 T1	14-09-2000
		EP 0981675 A1	01-03-2000
		JP 2001507420 T	05-06-2001
		WO 9842929 A1	01-10-1998
		US 6230444 B1	15-05-2001
US 4367788 A	11-01-1983	US 4482010 A	13-11-1984
US 4747240 A	31-05-1988	NONE	
US 4259401 A	31-03-1981	NONE	
US 4587279 A	06-05-1986	NONE	
US 5501268 A	26-03-1996	NONE	

Appendix B: Published Papers

Development of Phase Change Thermal Storage Wallcoverings In Buildings.

2003

The CIB 2003 International Conference on Smart and Sustainable Built Environment

Brisbane, Australia.

DEVELOPMENT OF PHASE CHANGE THERMAL STORAGE WALLCOVERINGS IN BUILDINGS

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Abstract

Energy saving wallcoverings that incorporate phase change materials (PCMs) as the thermal storage media is currently under development between the University of Brighton and OMNOVA Wallcovering (UK) Ltd. The PCM in the wallcovering functions to reduce the heating and cooling requirements by shifting the peak cooling/heating demand. This will, not only result in the reduction of annual overall energy consumption, but also smaller installed heating/cooling plant capacity. Initial evaluation indicated that energy saving of over 25% on a design day for a typical air conditioning office in the UK is possible. Dynamic computer simulation was used to provide some preliminary guidance on the optimum quantities of phase change materials to be embedded in the wallcoverings in different perimeter zones of a model building. There is a number of development issues identified that need to be addressed before the commercial production of the PCM wallcoverings.

Keywords: Thermal storage, phase change materials, wallcoverings, energy saving innovation

1. Introduction

A phase change material (PCM) stores the sensible heat as the temperature increases, but more importantly, it can store or release large quantities of latent heat during the phase transition. This can be illustrated by using a common building material such as concrete, which has a sensible heat capacity of approximately 1.0 kJ/kgK whereas a phase change material such as calcium chloride hexahydrate can store/release 193 kJ/kg of heat on phase transition. The potential for peak load shifting, reduced space temperature fluctuations and small volume make PCMs very attractive means of energy saving media. There are numerous applications of PCMs in buildings including PCMs embedded in concrete blocks and boards [1], PCM modules for underfloor heating [2] and 'CoolDeck' for night cooling [3].

A novel developing application of latent thermal storage described in this paper is the incorporation of phase change materials in wallcoverings. Wallcoverings are widely used in offices, hospitals, hotels and domestic buildings. With an estimated demand in new wallcovering area of three billion square metres per year in North

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America alone [4], the PCM wallcovering can have significant impacts on the energy consumptions and installed capacities of the heating and cooling plants in buildings. A three-year research programme, supported under the UK government's Teaching Company Scheme [5], was set up in 2002 between University of Brighton and Omnova Wallcovering (UK) Ltd. to develop wallcoverings embedded with phase change materials. The research programme involves the evaluation of the potential applications for PCM wallcoverings, the testing and development of prototypes and the marketing of the product.

This paper reports on some of the initial outcomes of the research. The concept of incorporating PCMs in wallcoverings and a simple evaluation of the energy saving potentials are summarised. An eight-zone computer model representing a typical office building has been developed and adapted in a computer simulation program to assess the effective latent heat storage capacities in each zone. The development team has identified a number of development issues that ought to be addressed before the commercial production of the PCM wallcoverings.

2. Wallcoverings with PCM

PVC (Vinyl) wallcoverings are usually made by one of two manufacturing processes. Perhaps the most commonly used is the "plastisol" route. The term plastisol is used to describe a suspension of finely divided PVC polymer made by emulsion or microsuspension polymerisation, in a plasticiser. Typically, plastisols are modified by the addition of stabilisers, inert fillers, pigments and rheology control agents prior to coating a continuous fabric or paper substrate with the resultant paste. Coating can be achieved by various methods but direct coating of the substrate with a knife coater is most common. Once the continuous substrate is coated to the desired thickness, usually between 100 – 500 μm, the plastisol is transformed into a solid substance by passing the coated substrate through an oven heated to an elevated temperature for several minutes. As the temperature of the plastisol is raised, the plasticiser penetrates the PVC particles that then swell. The plasticised particles eventually coalesce to give homogeneous plasticised PVC. Whilst still hot, the softened PVC can be embossed. On cooling this material solidifies after which it can be printed to give rise to the familiar PVC wallcovering.

The second most common manufacturing route to Vinyl wallcoverings is the calendering route. Here, porous PVC granules made by suspension polymerisation are mixed with plasticiser, stabilisers, fillers, etc in a blender to produce pre-compounded PVC in powder form. The resultant powder is usually dry because the plasticiser is absorbed within the pores of the PVC granules. Next, the PVC compound is fed into a melt-compounder or extruder to convert the powder into a plastic material that can then be fed into a set of heated rollers, the calender. As the plastic compound is fed through successive heated sets of rollers, it is converted into a hot, homogeneous sheet of plasticised PVC. This hot molten sheet can be used to coat continuous substrates such as paper and fabric or it can be laminated with other sheets of materials by hot rolling. The resultant materials can be embossed and/or decorated as described above. In general, the thicknesses of PVC sheets made by calendering lie in the range 100 – 800 μm, although sheets up to 1.5 mm can be produced.

A number of organic and inorganic PCMs are being evaluated on their suitability for use in wallcoverings. Organic PCMs are mainly products of petroleum refinement such as paraffin wax although it is possible to use fatty acids from renewable sources [6]. Inorganic PCMs are mainly salts and salt hydrates such as sodium sulphate decahydrate. Most inorganic PCMs have high volumetric energy storage capacities [7] but smaller changes in volume in comparison to organic PCMs [8].

Omnova Wallcovering (UK) Ltd filed a UK patent application in April 2002 and a PCT application in April 2003 that describe wall linings containing phase change materials. The wall linings can be used to reduce the amount of energy required to heat and cool buildings and to produce a more comfortable environment by minimising temperature fluctuations.

3. Energy saving potential

A simple steady state thermal model representing a typical office was established to evaluate the energy saving potential of the wallcovering due the latent heat of PCM embedded in it. The model office has the dimensions of 5m by 5 m by 2.5m high with a south facing window of 10 m^2. Taking into account the furniture and other furnishing of the room, the net wall area available for the storage of latent heat is approximately 31 m^2. The wallcovering selected in this analysis has a thickness of 4mm comprising of 35% by volume of inorganic PCM, which has a latent heat capacity of 150 kJ/kg and phase change temperature of 21ºC. The PCM wallcovering in this model would have an average latent thermal storage capacity of 641 kJ/m^2 or a total of 19,800 kJ. The room is assumed to be occupied 250 days a year that splits between 166 winter days and 84 summer days.

For the summer cycle, the model assumes that for each day the air conditioning is used, the PCM releases its heat by night cooling and the wall lining absorbs its “full quota” of heat during the occupancy hours. The total energy saving due to the latent heat of the phase change process alone is the product of the area of wallcovering available for the storage of latent heat, the average thermal storage capacity and the number of days when air conditioning is used

For the winter cycle, the low angle sun allows deep penetration of direct solar radiation on the wallcovering. As the direct solar gains far exceeds the total latent heat capacity of PCM wallcovering, the model assumes that the air temperature swing would allow the wall lining to absorb its “full quota” of heat in the early part of the day and the PCM releases this heat into the room in the late afternoon. The energy saving due to the latent heat transfer of the PCM alone is the product of the area of wallcovering available for latent heat storage, the average thermal storage capacity and the number of days when useful solar gain is available.

Using the solar data information from the CIBSE Guide A [9], the reduction in maximum energy consumption for the model room due to the latent heat of the PCM on the design heating and cooling days are summarised in table 1. The energy consumption for a typical air-conditioned office, based on the energy consumption data from the UK Energy Efficiency Best Practice Programme [10], is 79,704 kJ in winter and 96,444 kJ in the summer. Higher energy savings are expected if specific heat transfers are included in the calculations. The results show that savings, depending on the PCM wallcovering area, are between 17% to 31% for heating and 14% to 25% for cooling.

PCM wallcovering applied to	Energy Storage Capacity (kJ)	Heating Only	Cooling Only
		Percentage reduction	Percentage reduction
1 m^2	641	0.81%	0.67%
21 m^2	13,712	17%	14%
31 m^2	19,674	25%	20%
38 m^2	24,480	31%	25%

Table 1: Energy reduction on design days due to PCM wallcovering

4. Preliminary dynamic thermal analysis

A validated computer thermal model representing the interaction between the PCM wallcoverings, the thermal behaviour of the room, the mechanical heating and cooling systems being used and the external climate has yet to be developed. The computer thermal model developed at this stage aims to provide an initial assessment of the optimum quantity of PCM to be used in different parts of a building. The optimum quantity of PCM allows the best use of latent heat on a daily cycle basis.

The program used in this assessment is a dynamic thermal simulation software Virtual Environment (VE) produced by the Integrated Environmental Solutions Ltd. Virtual Environment is a simulation program that can perform dynamic thermal analyses and energy evaluation of buildings [11]. The program allows users to specify the physical environmental parameters of each room, the external weather climate and the operation of the heating and cooling systems. As the thermal simulation of a room with PCM paper is not available, a special PCM room component was adapted to emulate the thermal performance of the PCM wallcovering.

The simulation model consists of an intermediate floor of an office building, which is divided into 8 perimeter zones and one internal zone. Each zone is 5m x 5m x 2.5m high. The corner zones have two 4m x 1.25m low-E double glazed windows while the middle zone in each façade have only one 4m x 1.25m low-E double glazed window. The construction materials used for the floor, roof, external walls and windows of the building are those that meet the UK Building Regulations 2002. The wallcovering is assumed to have a thermal resistance of 0.177m^{2}K/W and conductivity of 0.5W/mK. An organic and an inorganic PCMs were used in the simulation.

4.1 Simulation process

The computer simulation to find the optimum quantity of PCM is based on the principle that the daily cycle of heat gain during the charging period is balanced by the heat loss during the discharging period.

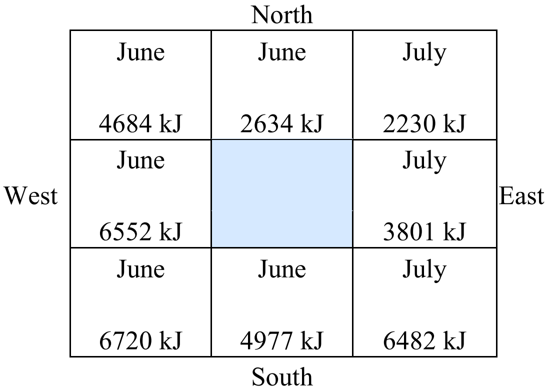
To simulate the latent heat gain of the phase change material, a cooling cycle would be specified in the PCM room that emulated the PCM wallcovering. The phase change material starts to melt once the room reaches phase change temperature and begins to absorb heat. The simulation software would determine the amount of energy that is required to keep the room at that temperature, which represents the amount of energy absorbed by the phase change material.

To simulate the phase change material releasing the latent heat, a heating cycle would be specified. This means that heating is required should the temperature drop below phase change temperature. The amount of energy required to keep the room 'warm' shows the amount of heat that could be released by a phase change material.

The simulations were repeated, with adjustments to the charging and discharging periods of the melting and solidification processes, until the heat gain by the PCM was balanced by the heat it released. Further simulations were carried out for each month in a year, of every zone in the model building.

4.2 Results

The results representing the maximum amount of energy that can be utilised by phase change materials in the perimeter offices on four sides of the square model building are shown in figures 2 to 5. The results indicated that the PCM performs best in the summer months of June and July. Each box in figure 2, representing a building zone, shows the maximum energy involved in the latent heat transfer process.



North

	June 4684 kJ	June 2634 kJ	July 2230 kJ	
West	June 6552 kJ		July 3801 kJ	East
	June 6720 kJ	June 4977 kJ	July 6482 kJ	

South

Figure 2: Maximum PCM latent heat transfer

Figures 3 and 4 show the amount of inorganic and organic phase change materials that are required in each zone to absorb and release the latent energy indicated in figure 2.

The amount of organic phase change material required in the model building ranges from 0.37 kg/m^2 to 1.12 kg/m^2 whereas 0.31 kg/m^2 to 0.93 kg/m^2 would be required using inorganic phase change materials. Due to the current limitations of the simulation model, such as disregard of specific heat transfer and direct solar gains, the results can only be considered as useful indications of the effective quantity of PCM to be used.

		North		
	31.23 kg 0.78 kg/m^2	17.56 kg 0.39 kg/m^2	14.87 kg 0.37 kg/m^2	
West	43.68 kg 0.97 kg/m^2		25.34 kg 0.56 kg/m^2	East
	44.80 kg 1.12 kg/m^2	33.18 kg 0.74 kg/m^2	43.21 kg 1.08 kg/m^2	
		South		

Figure 3: Optimum quantity of organic PCM (latent heat storage capacity of 150 kJ/kg)

		North		
	26.02 kg 0.65 kg/m^2	14.64 kg 0.33 kg/m^2	12.39 kg 0.31 kg/m^2	
West	36.40 kg 0.81 kg/m^2		21.12 kg 0.47 kg/m^2	East
	37.34 kg 0.93 kg/m^2	27.65 kg 0.61 kg/m^2	36.01 kg 0.90 kg/m^2	
		South		

Figure 4: Optimum quantity of inorganic PCM (latent heat storage capacity of 180 kJ/kg)

5. Development issues

OMNOVA's patent application describes how wallcoverings containing phase change materials can be made. The effectiveness of such wallcoverings in absorbing and then releasing heat is to be studied in a test room environment and later in "thermally matched" houses. There are, however, many technical issues that need to be addressed prior to a commercial launch of wallcoverings containing PCMs. These include:

- Will the microencapsulated PCMs retain their recycling capabilities with respect to melting and freezing after experiencing the processes involved during the manufacture of wallcoverings?
- Can high loadings of PCMs in wallcoverings be obtained so that high thermal mass is achieved at modest and acceptable thicknesses?
- Can heat in a room be readily transferred to and from the PCM containing wallcoverings?

- Will, for example, the fire resistance properties of PCM containing wallcoverings be good enough for wide application within both commercial and domestic buildings?

Other issues that are being addressed include:

- Marketing - How should wallcoverings containing PCMs be marketed and sold?
- Sustainability - There are various environmental issues to be addressed:
    - Recycling of PVC - This is possible with some forms of PVC and recycling plants are being built in Europe using the "Vinyl Loop" process developed by Solvay Industries [12]. Would PVC wallcoverings containing PCMs be recyclable?
    - Life cycle energy analysis - Would the manufacture of wallcoverings containing PCMs consume more or less energy than they would save through reduced heating and cooling energy?
    - CO_2 emissions - Air conditioning is becoming more prevalent and it generates large amounts of CO_2. What role could wall linings containing PCMs play in mitigating the proliferation of air conditioning systems and thence the reduction of CO_2 emissions?
    - Healthy buildings - What is the value of providing a "more comfortable" environment by reducing the difference between the upper and lower temperatures attained in a room?

6. Conclusions

Novel energy saving wallcoverings that utilise the latent thermal storage technique are currently being developed jointly between University of Brighton and OMNOVA Wallcovering (UK) Limited. Initial 'snapshot' analyses indicate there is potential for energy saving. Further dynamic analyses to assess the annual energy savings and plant size reduction are necessary to provide more detailed and accurate data. A number of development issues have already been identified, these have to be addressed before the PCM wallcovering can be manufactured commercially.

With the energy saving feature and environmental sustainability principles embedded in their production, the PCM wallcoverings can help to minimise the environmental impact of existing and new buildings.

References

[1] **Zalba, B., Marin, J. M., Cabeza, L. F. and Mehling, H.** (2003) "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications." *Applied Thermal Engineering*, 23(3), 251-283.

[2] **Ip, K. C. W.** (1998) "Solar thermal storage with phase change materials in domestic buildings." *CIB World Congress*, Gavle, Sweden, 1265-1272.

[3] **Maunsell, F. (2003)** "Stevenage Borough Council Case Study" Faber Maunsell, Available from http://www.fabermaunsell.com, [Accessed 2 May 2001]

[4] **Dyball, D. L.** (2003) "Plasterboard market report." OMNOVA Wallcovering (UK) Ltd., UK.

[5] **TCS (2003)** "Teaching Company Scheme Homepage" Available from http://www.tcsonline.org.uk/, [Accessed 2 June 2003]

[6] **Feldman, D., Banu, D., and Hawes, D.** (1995) "Low chain esters of stearic acid as phase change materials for thermal energy storage in buildings." *Solar Energy Materials and Solar Cells*, 36, 311-322.

[7] **Dincer, I.** (1999) "Evaluation and selection of energy storage systems for solar thermal applications." *International Journal Of Energy Research*, 23, 1017-1028.

[8] **Hawes, D. W., Banu, D. and Feldman, D.** (1992) "The stability of phase change materials in concrete." *Solar Energy materials and Solar Cells*, 27, 103-118.

[9] **CIBSE** (1986) *Guide A2 Weather and Solar Data*, The Chartered Institution of Building Services Engineers, London.

[10] **BRESU** (2000) *Energy consumption guide 19: Energy consumption in offices*, BRE, London, UK.

[11] **IES (2003)** "APACHE Virtual Environment Software" Integrated Environmental Solutions Ltd, Available from http://www.ies4d.com/ [Accessed 20th May]

[12] **Solvay.com (2003)** "Plastics Sector Strategy" Available from http://www.solvay.com/strategy/sectorsapproach/plastics/0,7123,781-1-0,00.htm#Essentials [Accessed 10th June 2003]

Development of Phase Change Thermal Storage Wallcoverings In Buildings.

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Development of phase change thermal storage wallcoverings in buildings

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Abstract

Energy saving wallcoverings that incorporate phase change materials (PCMs) as the thermal storage media is currently under development between the University of Brighton and OMNOVA Wallcovering (UK) Ltd. The PCM in the wallcovering functions to reduce the heating and cooling requirements by shifting the peak cooling/heating demand. This will, not only result in the reduction of annual overall energy consumption, but also smaller installed heating/cooling plant capacity. Initial evaluation indicated that energy saving of over 25% on a design day for a typical air conditioning office in the UK is possible. Dynamic computer simulation was used to provide some preliminary guidance on the optimum quantities of phase change materials to be embedded in the wallcoverings in different perimeter zones of a model building. There is a number of development issues identified that need to be addressed before the commercial production of the PCM wallcoverings.

Keywords: Thermal storage, phase change materials, wallcoverings, energy saving innovation

1. Introduction

A phase change material (PCM) stores the sensible heat as the temperature increases, but more importantly, it can store or release large quantities of latent heat during the phase transition. This can be illustrated by using a common building material such as concrete, which has a sensible heat capacity of approximately 1.0 kJ/kgK whereas a phase change material such as calcium chloride hexahydrate can store/release 193 kJ/kg of heat on phase transition. The potential for peak load shifting, reduced space temperature fluctuations and small volume make PCMs very attractive means of energy saving media. There are numerous applications of PCMs in buildings including PCMs embedded in concrete blocks and boards [1], PCM modules for underfloor heating [2] and 'CoolDeck' for night cooling [3].

A novel developing application of latent thermal storage described in this paper is the incorporation of phase change materials in wallcoverings. Wallcoverings are widely used

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in offices, hospitals, hotels and domestic buildings. With an estimated demand in new wallcovering area of three billion square metres per year in North America alone [4], the PCM wallcovering can have significant impacts on the energy consumptions and installed capacities of the heating and cooling plants in buildings. A three-year research programme, supported under the UK government's Teaching Company Scheme [5], was set up in 2002 between University of Brighton and Omnova Wallcovering (UK) Ltd. to develop wallcoverings embedded with phase change materials. The research programme involves the evaluation of the potential applications for PCM wallcoverings, the testing and development of prototypes and the marketing of the product.

This paper reports on some of the initial outcomes of the research. The concept of incorporating PCMs in wallcoverings and a simple evaluation of the energy saving potentials are summarised. An eight-zone computer model representing a typical office building has been developed and adapted in a computer simulation program to assess the effective latent heat storage capacities in each zone. The development team has identified a number of development issues that ought to be addressed before the commercial production of the PCM wallcoverings.

2. Wallcoverings with PCM

PVC (Vinyl) wallcoverings are usually made by one of two manufacturing processes. Perhaps the most commonly used is the "plastisol" route. The term plastisol is used to describe a suspension of finely divided PVC polymer made by emulsion or microsuspension polymerisation, in a plasticiser. Typically, plastisols are modified by the addition of stabilisers, inert fillers, pigments and rheology control agents prior to coating a continuous fabric or paper substrate with the resultant paste. Coating can be achieved by various methods but direct coating of the substrate with a knife coater is most common. Once the continuous substrate is coated to the desired thickness, usually between 100 – 500 μm, the plastisol is transformed into a solid substance by passing the coated substrate through an oven heated to an elevated temperature for several minutes. As the temperature of the plastisol is raised, the plasticiser penetrates the PVC particles that then swell. The plasticised particles eventually coalesce to give homogeneous plasticised PVC. Whilst still hot, the softened PVC can be embossed. On cooling this material solidifies after which it can be printed to give rise to the familiar PVC wallcovering.

The second most common manufacturing route to Vinyl wallcoverings is the calendering route. Here, porous PVC granules made by suspension polymerisation are mixed with plasticiser, stabilisers, fillers, etc in a blender to produce pre-compounded PVC in powder form. The resultant powder is usually dry because the plasticiser is absorbed within the pores of the PVC granules. Next, the PVC compound is fed into a melt-compounder or extruder to convert the powder into a plastic material that can then be fed into a set of heated rollers, the calender. As the plastic compound is fed through successive heated sets of rollers, it is converted into a hot, homogeneous sheet of plasticised PVC. This hot molten sheet can be used to coat continuous substrates such as paper and fabric or it can be laminated with other sheets of materials by hot rolling. The resultant materials can be embossed and/or decorated as described above. In general, the thicknesses of PVC sheets made by calendering lie in the range 100 – 800 μm, although sheets up to 1.5 mm can be produced.

A number of organic and inorganic PCMs are being evaluated on their suitability for use in wallcoverings. Organic PCMs are mainly products of petroleum refinement such as paraffin wax although it is possible to use fatty acids from renewable sources [6]. Inorganic PCMs are mainly salts and salt hydrates such as sodium sulphate decahydrate. Most inorganic PCMs have high volumetric energy storage capacities [7] but smaller changes in volume in comparison to organic PCMs [8].

Omnova Wallcovering (UK) Ltd filed a UK patent application in April 2002 and a PCT application in April 2003 that describe wallcoverings containing phase change materials. The wallcoverings can be used to reduce the amount of energy required to heat and cool buildings and to produce a more comfortable environment by minimising temperature fluctuations.

3. Energy saving potential

A simple steady state thermal model representing a typical office was established to evaluate the energy saving potential of the wallcovering due the latent heat of PCM embedded in it. The model office has the dimensions of 5m by 5 m by 2.5m high with a south facing window of 10 m^2. Taking into account the furniture and other furnishing of the room, the net wall area available for the storage of latent heat is approximately 31 m^2. The wallcovering selected in this analysis has a thickness of 4mm comprising of 35% by volume of inorganic PCM, which has a latent heat capacity of 150 kJ/kg and phase change temperature of 21°C. The PCM wallcovering in this model would have an average latent thermal storage capacity of 641 kJ/m^2 or a total of 19,800 kJ. The room is assumed to be occupied 250 days a year that splits between 166 winter days and 84 summer days.

For the summer cycle, the model assumes that for each day the air conditioning is used, the PCM releases its heat by night cooling and the wallcovering absorbs its “full quota” of heat during the occupancy hours. The total energy saving due to the latent heat of the phase change process alone is the product of the area of wallcovering available for the storage of latent heat, the average thermal storage capacity and the number of days when air conditioning is used

For the winter cycle, the low angle sun allows deep penetration of direct solar radiation on the wallcovering. As the direct solar gains far exceeds the total latent heat capacity of PCM wallcovering, the model assumes that the air temperature swing would allow the wallcovering to absorb its “full quota” of heat in the early part of the day and the PCM releases this heat into the room in the late afternoon. The energy saving due to the latent heat transfer of the PCM alone is the product of the area of wallcovering available for latent heat storage, the average thermal storage capacity and the number of days when useful solar gain is available.

Using the solar data information from the CIBSE Guide A [9], the reduction in maximum energy consumption for the model room due to the latent heat of the PCM on the design heating and cooling days are summarised in Table 3.1. The energy consumption for a typical air-conditioned office, based on the energy consumption data from the UK Energy Efficiency Best Practice Programme [10], is 79,704 kJ in winter and 96,444 kJ in the summer. Higher energy savings are expected if specific heat transfers are included in the calculations. The results show that savings, depending on the PCM wallcovering area, are between 17% to 31% for heating and 14% to 25% for cooling.

PCM wallcovering applied to	Energy Storage Capacity (kJ)	Heating Only	Cooling Only
		Percentage reduction	Percentage reduction
1 m^2	641	0.81%	0.67%
21 m^2	13,712	17%	14%
31 m^2	19,674	25%	20%
38 m^2	24,480	31%	25%

Table 3.1: Energy reduction on design days due to PCM wallcovering

4. Preliminary dynamic thermal analysis

A validated computer thermal model representing the interaction between the PCM wallcoverings, the thermal behaviour of the room, the mechanical heating and cooling systems being used and the external climate has yet to be developed. The computer thermal model developed at this stage aims to provide an initial assessment of the optimum quantity of PCM to be used in different parts of a building. The optimum quantity of PCM allows the best use of latent heat on a daily cycle basis.

The program used in this assessment is a dynamic thermal simulation software Virtual Environment (VE) produced by the Integrated Environmental Solutions Ltd. Virtual Environment is a simulation program that can perform dynamic thermal analyses and energy evaluation of buildings [11]. The program allows users to specify the physical environmental parameters of each room, the external weather climate and the operation of the heating and cooling systems. As the thermal simulation of a room with PCM paper is not available, a special PCM room component was adapted to emulate the thermal performance of the PCM wallcovering.

The simulation model consists of an intermediate floor of an office building, which is divided into 8 perimeter zones and one internal zone. Each zone is 5m x 5m x 2.5m high. The corner zones have two 4m x 1.25m low-E double glazed windows while the middle zone in each façade have only one 4m x 1.25m low-E double glazed window. The construction materials used for the floor, roof, external walls and windows of the building are those that meet the UK Building Regulations 2002. The wallcovering is assumed to have a thermal resistance of 0.177m^{2}K/W and conductivity of 0.5W/mK. An organic and an inorganic PCMs were used in the simulation.

4.1 Simulation process

The computer simulation to find the optimum quantity of PCM is based on the principle that the daily cycle of heat gain during the charging period is balanced by the heat loss during the discharging period.

To simulate the latent heat gain of the phase change material, a cooling cycle would be specified in the PCM room that emulated the PCM wallcovering. The phase change material starts to melt once the room reaches phase change temperature and begins to absorb heat. The simulation software would determine the amount of energy that is required to keep the room at that temperature, which represents the amount of energy absorbed by the phase change material.

To simulate the phase change material releasing the latent heat, a heating cycle would be specified. This means that heating is required should the temperature drop below phase change temperature. The amount of energy required to keep the room 'warm' shows the amount of heat that could be released by a phase change material.

The simulations were repeated, with adjustments to the charging and discharging periods of the melting and solidification processes, until the heat gain by the PCM was balanced by the heat it released. Further simulations were carried out for each month in a year, of every zone in the model building.

4.2 Results

The results representing the maximum amount of energy that can be utilised by phase change materials in the perimeter offices on four sides of the square model building are shown in figures 3.1 to 3.3. The results indicated that the PCM performs best in the summer months of June and July. Each box in Figure 3.1, representing a building zone, shows the maximum energy involved in the latent heat transfer process.

		North		
	June 4684 kJ	June 2634 kJ	July 2230 kJ	
West	June 6552 kJ		July 3801 kJ	East
	June 6720 kJ	June 4977 kJ	July 6482 kJ	
		South		

Figure 3.1: Maximum PCM latent heat transfer

Figures 3.2 and 3.3 show the amount of inorganic and organic phase change materials that are required in each zone to absorb and release the latent energy indicated in figure 3.1.

The amount of organic phase change material required in the model building ranges from 0.37 kg/m^2 to 1.12 kg/m^2 whereas 0.31 kg/m^2 to 0.93 kg/m^2 would be required using inorganic phase change materials. Due to the current limitations of the simulation model, such as disregard of specific heat transfer and direct solar gains, the results can only be considered as useful indications of the effective quantity of PCM to be used.

		North		
	31.23 kg 0.78 kg/m^2	17.56 kg 0.39 kg/m^2	14.87 kg 0.37 kg/m^2	
West	43.68 kg 0.97 kg/m^2		25.34 kg 0.56 kg/m^2	East
	44.80 kg 1.12 kg/m^2	33.18 kg 0.74 kg/m^2	43.21 kg 1.08 kg/m^2	
		South		

Figure 3.2: Optimum quantity of organic PCM
(latent heat storage capacity of 150 kJ/kg)

North

	26.02 kg 0.65 kg/m^2	14.64 kg 0.33 kg/m^2	12.39 kg 0.31 kg/m^2	
West	36.40 kg 0.81 kg/m^2		21.12 kg 0.47 kg/m^2	East
	37.34 kg 0.93 kg/m^2	27.65 kg 0.61 kg/m^2	36.01 kg 0.90 kg/m^2	
		South		

Figure 3.3: Optimum quantity of inorganic PCM
(latent heat storage capacity of 180 kJ/kg)

5. Development issues

OMNOVA's patent application describes how wallcoverings containing phase change materials can be made. The effectiveness of such wallcoverings in absorbing and then releasing heat is to be studied in a test room environment and later in "thermally matched" houses. There are, however, many technical issues that need to be addressed prior to a commercial launch of wallcoverings containing PCMs. These include:

- Will the microencapsulated PCMs retain their recycling capabilities with respect to melting and freezing after experiencing the processes involved during the manufacture of wallcoverings?
- Can high loadings of PCMs in wallcoverings be obtained so that high thermal mass is achieved at modest and acceptable thicknesses?
- Can heat in a room be readily transferred to and from the PCM containing wallcoverings?
- Will, for example, the fire resistance properties of PCM containing wallcoverings be good enough for wide application within both commercial and domestic buildings?

Other issues that are being addressed include:

- Marketing - How should wallcoverings containing PCMs be marketed and sold?
- Sustainability - There are various environmental issues to be addressed:
    - Recycling of PVC - This is possible with some forms of PVC and recycling plants are being built in Europe using the "Vinyl Loop" process

developed by Solvay Industries [12]. Would PVC wallcoverings containing PCMs be recyclable?

- Life cycle energy analysis - Would the manufacture of wallcoverings containing PCMs consume more or less energy than they would save through reduced heating and cooling energy?
- CO_2 emissions - Air conditioning is becoming more prevalent and it generates large amounts of CO_2. What role could wallcovering containing PCMs play in mitigating the proliferation of air conditioning systems and thence the reduction of CO_2 emissions?
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6. Conclusions

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References

[1] **Zalba, B., Marin, J. M., Cabeza, L. F. and Mehling, H.** (2003) "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications" *Applied Thermal Engineering*, 23(3), 251-283.

[2] **Ip, K. C. W.** (1998) "Solar thermal storage with phase change materials in domestic buildings" *CIB World Congress*, Gavle, Sweden, 1265-1272.

[3] **Maunsell, F.** (2003) "Stevenage Borough Council Case Study" Faber Maunsell, Available from http://www.fabermaunsell.com [accessed 2 May 2001].

[4] **Dyball, D. L.** (2003) "Plasterboard market report." OMNOVA Wallcovering (UK) Ltd., UK.

[5] **TCS** (2003) "Teaching Company Scheme Homepage" Available from http://www.tcsonline.org.uk/, [accessed 2 June 2003].

[6] **Feldman, D., Banu, D., and Hawes, D.** (1995) "Low chain esters of stearic acid as phase change materials for thermal energy storage in buildings." *Solar Energy Materials and Solar Cells*, 36, 311-322.

[7] **Dincer, I.** (1999) "Evaluation and selection of energy storage systems for solar thermal applications." *International Journal of Energy Research*, 23, 1017-1028.

[8] **Hawes, D. W., Banu, D. and Feldman, D.** (1992) "The stability of phase change materials in concrete." *Solar Energy materials and Solar Cells*, 27, 103-118.

[9] **CIBSE** (1986) *Guide A2 Weather and Solar Data*, The Chartered Institution of Building Services Engineers, London.

[10] **BRESU** (2000) Energy consumption guide 19: Energy consumption in offices, BRE, London, UK.

[11] **IES** (2003) "APACHE Virtual Environment Software" Integrated Environmental Solutions Ltd, Available from http://www.ies4d.com/, [accessed 20th May].

[12] **Solvay.com** (2003) "Plastics Sector Strategy" Available from http://www.solvay.com/strategy/sectorsapproach/plastics/0,7123,781-1-0,00.htm#Essentials, [accessed 10th June 2003].

Development of Phase Change Wall-linings to Enhance Thermal Storage of Buildings.

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DEVELOPMENT OF PHASE CHANGE WALL-LININGS TO ENHANCE THERMAL STORAGE OF BUILDINGS

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Keywords: phase change materials, thermal storage, wall-lining, thermal comfort, latent heat

Summary

Research collaboration between University of Brighton and OMNOVA Wallcovering (UK) Ltd has successfully developed a thermal interactive wall-lining utilising sensible and latent heat storage through the inclusion of phase change materials. The current use of lightweight construction can result in large temperature swings and overheating in the summer. The PCM wall-lining functions to reduce overheating in buildings by storing the excess heat principally in the form of latent heat. By minimising overheating the PCM wall-lining can reduce and, in some climates, eliminate the need for air-conditioning. A direct result of the reduced overheating is the improved thermal comfort for the occupants.

A test laboratory has been set up at the University of Brighton, comprised of two thermally matched chambers, to evaluate the performance of the PCM wall-lining in a controlled environment. This paper describes the results of the experimental work which demonstrates the reduction of peak temperatures and improvement in thermal comfort. Factors affecting PCM wall-lining performance and future work to optimise the test facilities to enable greater analysis of the PCM wall-lining are also discussed.

1. Introduction

Global temperatures have increased by around 0.6°C over the last 100 years and there is continually new evidence showing most of the global warming that has occurred over the last 50 years is a direct result of human activities. The Intergovernmental Panel on Climate Change (IPCC) has predicted that during the 21st Century global temperatures will increase by between 1.4°C and 5.8°C, and that sea levels will rise by between 0.09 and 0.88 metres. This is an unprecedented rate of global warming, which is largely caused by the increased amount of man-made greenhouse gas emitted into the atmosphere (UNFCC 2004).

Buildings are responsible for over 40% of Europe's total energy consumption and consequently produce a huge amount of carbon dioxide (CO_2) emissions. In the UK almost half of all CO_2 emissions are from buildings, the largest proportion is a result of space heating (CIBSE 2004). The continuing trend of lightweight construction has not only reduced the thermal capacity for the storage of beneficial solar gain in winter, but also increases the occurrence of temperature swing and overheating in the summer. Innovative design and materials need to be developed that can work in conjunction with existing technologies to reduce the amount of overheating in summer by improving the thermal capacity of lightweight buildings. Appropriate use of energy saving design such as the PCM wall-lining being developed in the current research can reduce the need for energy intensive cooling systems, which has grown by 10% from 2000 to 2004 (BSRIA 2002). The application of PCM wall-lining can have significant impact to reduce global energy consumption, a preliminary analysis of the quantity of wall-lining products installed in new and refurbished buildings globally suggests there is the potential for installing up to 440 million square metres of PCM wall-lining in domestic and non-domestic buildings (Dyball 2004).

The aim of this research is to determine if PCM wall-linings can improve thermal comfort through the reduction of peak internal temperatures. The research has reviewed the use of thermal energy storage technologies for use in buildings and identified the environmental benefits of PCM wall-linings. This paper reports on the experimental setup, monitoring procedure and the preliminary results of the experimental investigations to determine the temperature reductions achievable by the prototype PCM wall-lining. The limitation and inference of the results to the future development are also summarised.

2. Development of Phase Change Wall-linings

Research collaboration between University of Brighton and OMNOVA Wallcovering (UK) Ltd has resulted in a project to develop a thermal interactive wall-lining, utilising OMNOVA's manufacturing technology, that can improve the thermal storage capacity of buildings, reduce overheating and reduce the demand for conventional cooling systems. This has been realised by including phase change materials in wall-linings.

2.1 Phase Change Technology

Phase Change Materials (PCMs) are materials that not only absorb sensible heat as the temperature increases but also absorb latent heat when melting and release the stored heat when freezing, both at an almost constant temperature. PCMs have a high latent heat storage capacity, high energy densities and are relatively low in cost. PCMs can be used in buildings to significantly improve the thermal mass as they have a much greater ability to store heat than conventional building materials such as concrete. Concrete has a sensible heat storage capacity of 1.0 kJ/kgK, whereas an inorganic phase change material such as calcium chloride hexahydrate can store up to 193 kJ/kg during phase transition. PCMs are able to reduce peak temperatures in buildings by absorbing excess heat during the day and releasing the heat at night when it is cooler. The storage and release of excess heat results in a narrower temperature band over a diurnal period therefore improves thermal comfort for the occupants.

A significant development in phase change technology is the ability to microencapsulate PCMs. Microencapsulation is the packaging of micron-sized materials (both liquids and solids) in the form of capsules, ranging from less than 1μm to more than 300μm. Microencapsulated PCMs can be used to introduce high thermal storage capacity into conventional building materials. Examples of research developments using microencapsulated PCMs include gypsum plaster (Schossig et al. 2004), concrete (Cabeza et al. 2004), and wallboard (Hummel 2004; Khudhair et al. 2003).

An advantage of using a PCM wall-lining instead of the other developing products is its direct exposure to heat exchange within the room. Most PCM materials are located deep within the construction of a wall or ceiling and would have less effective heat transfer.

2.2 PCM Wall-linings

OMNOVA Wallcovering (UK) Ltd has undertaken laboratory experiments to develop a vinyl formulation that included microencapsulated organic PCMs in the wall-lining. Vinyl formulations are developed using the plastisol route, a suspension of finely divided polymer held within a plasticiser and modified using stabilisers, pigments and rheology control agents. The plastisol formulation is coated out and passed through a high temperature oven for a few minutes where the heated plasticiser penetrates the polymer and the plasticised polymers coalesce to produce a homogeneous wall-lining. A successful formulation was developed and a prototype PCM wall-lining was manufactured using the knife-over-roll coating technique. A 6mm PCM wall-lining was produced containing 20% microencapsulated organic PCM.

2.3 Preliminary Investigation

A theoretical analysis was conducted to determine the quantity of PCM that would be required in a standard office to prevent it from overheating. Dynamic thermal simulations were conducted of an intermediate floor in an office building that had north, east, south and west facing orientations. The maximum amount of PCM required in each office to absorb all of the excess heat in the day and be able to release the stored heat during the night in the UK was determined. The maximum amount of inorganic PCM with a latent heat storage capacity of 180 kJ/kg required in an office was 0.93 kg/m^2 and the maximum amount of organic PCM (150 kJ/kg) required was 1.12 kg/m^2 (Ip et al. 2003). The prototype PCM wall-lining developed contains 1.5 kg/m^2 microencapsulated organic PCM which indicates the PCM wall-lining would be able to reduce overheating in a standard office.

Detailed thermal analysis of the PCM wall-lining prototype was performed to determine its latent heat storage capacity and the melting point. A common method used to analyse the properties of PCMs is Differential Scanning Calorimetry (DSC). DSC measures the temperatures and heat flows associated with phase transitions in materials as a function of time and temperature in a controlled atmosphere. A DSC analysis of the microencapsulated PCM and an analysis of the PCM wall-lining were carried out. Theoretically the PCM wall-lining should have the same melting point as the microencapsulated PCM if it was undamaged during the manufacturing process. As the PCM wall-lining contains 20% PCM then the latent heat storage capacity of the PCM wall-lining should be around a fifth of the microencapsulated PCM result. The results of the DSC analysis during the heating and cooling cycles are shown in Figures 1 and 2 respectively.

The phase change temperature of the microencapsulated PCM and the PCM wall-lining is 25°C. This is the onset point of the melting transition that is displayed in Figure 1. The larger peak illustrates the quantity of latent heat absorbed during the phase change of the microencapsulated PCM and when integrated with respect to time gives the latent heat capacity of 95 J/g. The PCM wall-lining peak, the smaller peak, also has a melt point of 25°C and the latent heat capacity is 16 J/g. The same results were obtained for the thermal properties during the cooling cycle, Figure 2. The DSC results have demonstrated that a PCM wall-lining does change phase at the phase change temperature and is able to absorb and release latent heat under controlled conditions.

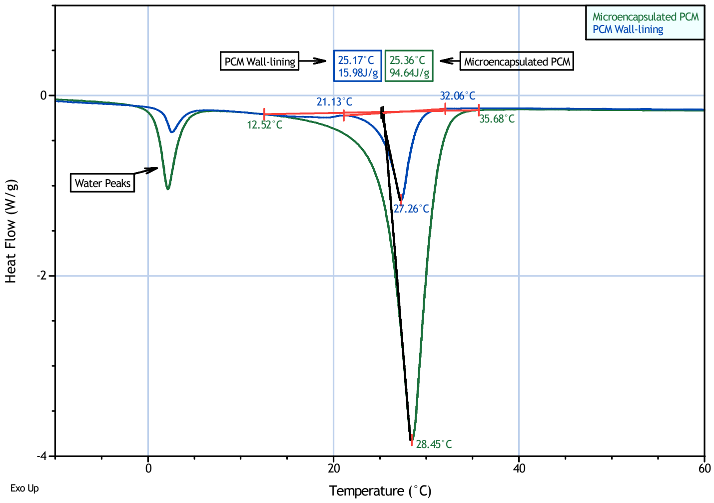

Figure 1 Thermal properties of PCM and PCM wall-lining during heating cycle

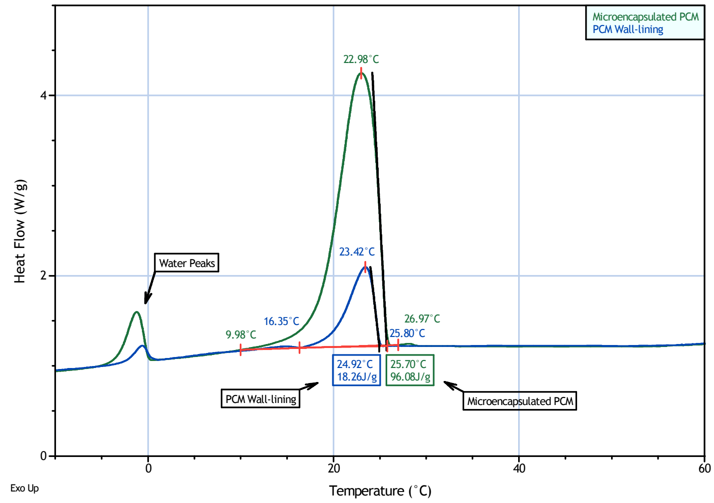

Figure 2 DSC cooling curve of PCM and PCM wall-lining

3. Experimental Investigation

The experimental investigation aims to determine the ability of the PCM wall-lining to reduce internal temperatures of a room to improve thermal comfort. To do this two identical chambers were constructed; the first chamber is fitted with PCM wall-lining while the second chamber is used as a reference chamber for comparison. The chambers were heated and measured using different amounts of heat input and air flow conditions.

3.1 Test Chambers

Two highly insulated, identical chambers, 2.4m^3, were constructed within a laboratory at the University of Brighton. The chambers were fitted with a total of 18 surface temperature sensors, 6 air temperature probes and 2 room temperature sensors, as illustrated in Figure 3. The room radiant temperature, as part of the indication of thermal comfort, is measured using a 36mm black globe thermometer (Humphreys 1978).

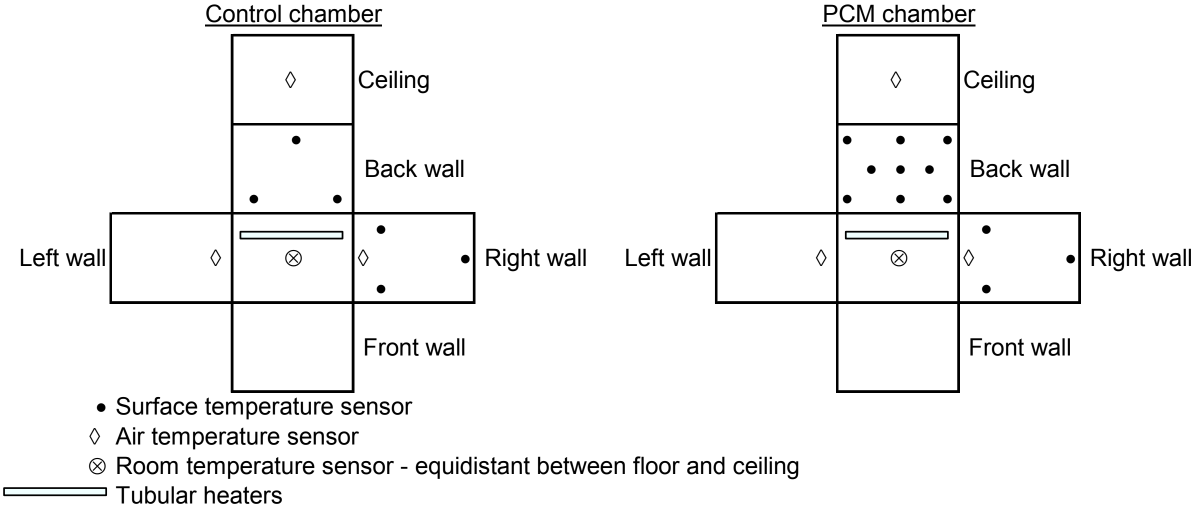

Figure 3 Layout of temperature sensors in test chambers

The heaters used to supply heat to the test chambers were connected to power meters to ensure the heat input to each chamber was identical. All the monitoring devices were wired to an Agilent Benchlink data logger and the data were recorded at timed intervals.

The PCM wall-lining was fitted to the walls of the first chamber, as shown in Figure 4, providing a latent heat storage capacity of 1663 kJ. No materials were fitted to the walls in the Control chamber, so latent heat was only available in the PCM chamber.

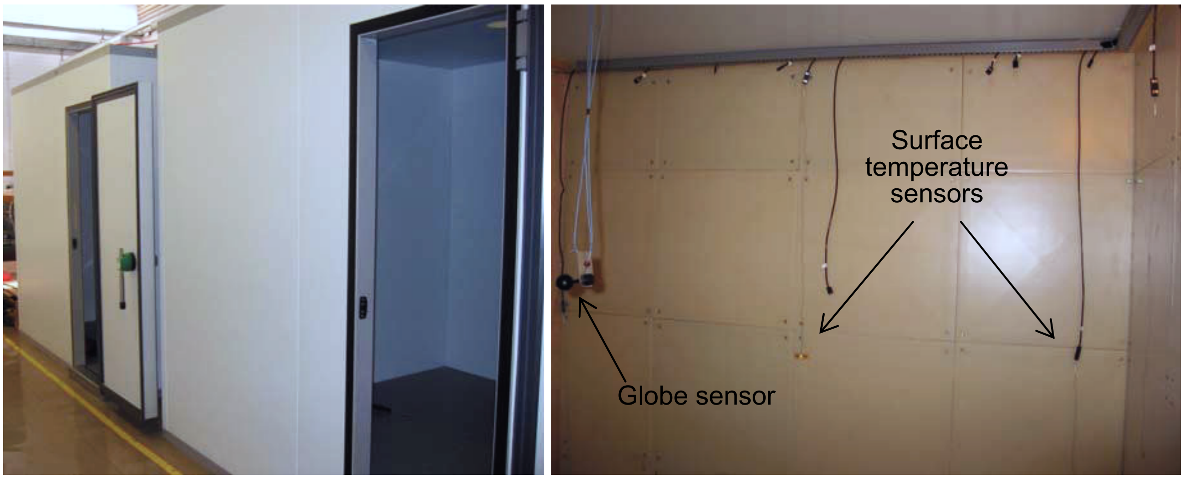

Figure 4 Test chambers (left) and fitted PCM wall-lining with temperature monitoring sensors (right)

3.2 Experimental Procedure

A range of experiments were conducted in the test chambers using different amounts of internal heat inputs and air supply rates. The results reported focus on two experiments, one with ventilation and one without, to quantify the temperature reduction that can be achieved using the PCM wall-lining under two test conditions. The test chambers were heated using a 360W heat source in each chamber and programmed to operate from 14:00 to 22:00 hours. The temperature data were recorded every 5 minutes for at least one heating and cooling cycle.

3.3 Results and Discussion

The room temperature results after heating the test chambers for 8 hours and allowing to cool without refrigeration are shown in Figures 5 and 6. Figure 5 shows the room temperature results when using no ventilation and Figure 6 shows the results using constant ventilation.

The different slopes of the two curves in Figures 5 and 6 shows the different rates of temperature changes of each chamber when both are subjected to the same amount of heat input. In both experiments, without and with ventilation, the PCM chamber heats up at a slower rate than the Control chamber and the final temperature achieved is lower in the PCM chamber.

3.3.1 Without mechanical ventilation

Figure 5 shows that after heating the test chambers for 8 hours the PCM wall-lining kept the room temperature of the PCM chamber almost 4°C cooler than the Control chamber. This is due to the PCM wall-lining absorbing the heat and storing it in the PCMs. At the beginning of the heating cycle the graphs (section a-b) show the rooms began to heat at the same rate until 21°C was reached. This is due to the rapid sensible heating of the air in both chambers. After 21°C the heating rates of each chamber changed as a result of the different heat transfer processes. The temperature rise in the PCM chamber was clearly slower than in the Control chamber.

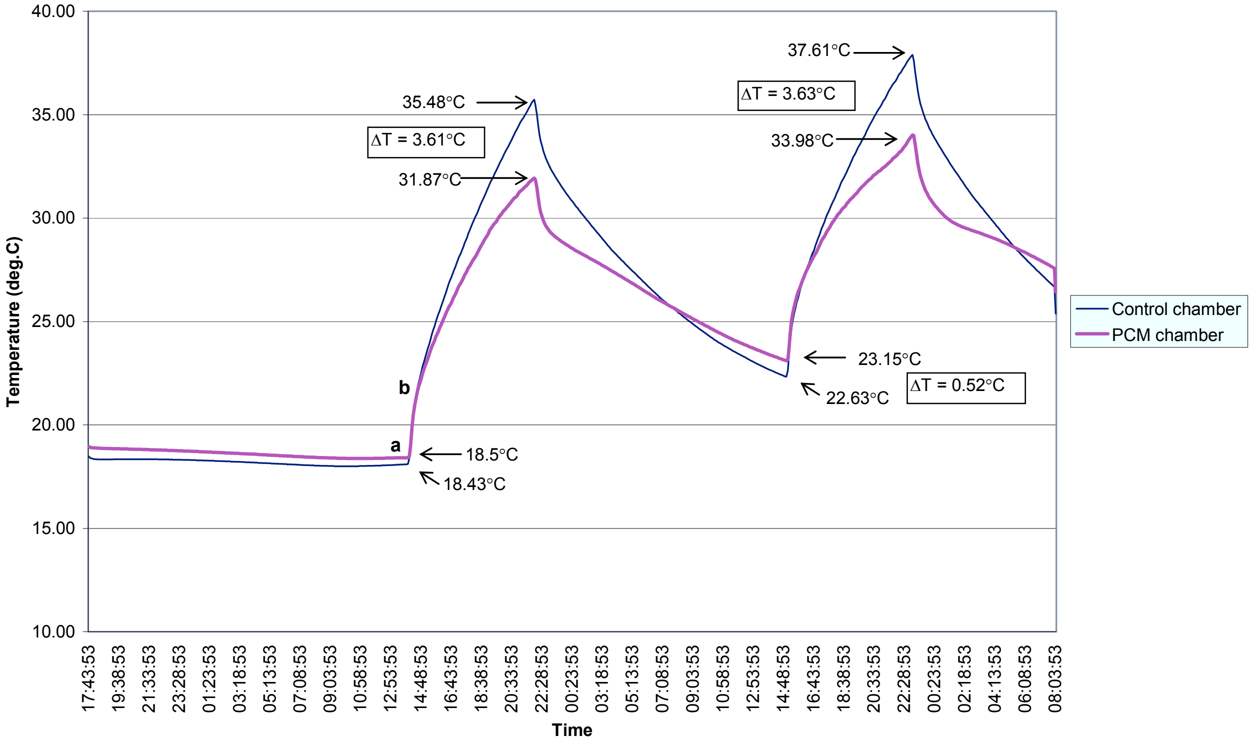

Figure 5 Room temperature results of testing PCM wall-lining with 8 hour heating cycles and no air flow

When the heaters were switched off in both chambers at 22:00 the chambers began to cool naturally. The initial sharp temperature drop of the cooling curve in Figure 5 is due to the rapid cooling of the air in the chambers. The room temperature in the Control chamber drops by 1.75°C whereas the PCM chamber only has a temperature reduction of 1.58°C during the 30 minutes after the heaters were switched off. The subsequent change in the curves is related to the thermal capacity of the materials in the chambers. The PCM wall-lining cools at a significantly slower rate, due to the release of latent heat from the PCMs. As the chambers were not ventilated the internal temperature in both chambers remained high during the cooling cycle.

After 9 hours and 50 minutes both chambers reached 25.65°C, illustrated in Figure 5 where the curves cross. Although the chambers have reached the same temperature the PCM Room only reduced 6.22°C whereas the Control Room cooled by 9.83°C, a much larger temperature range.

At the end of the cooling period there was a 0.5°C difference in room temperatures between the two chambers; such difference will increase if the cooling cycle continues. It can be estimated from the graph that it would take an additional 3 hours for the PCM Room to cool to the same temperature of the Control Room at 14:00.

3.3.2 With mechanical ventilation

The room temperature results of the test chambers when ventilation was used, in Figure 6, show that a smaller temperature reduction is achieved in the PCM chamber than when no ventilation was used, Figure 5. As a result of using ventilation in the chambers the room temperatures do not rise as quickly or as high as the experiment with no air flow.

Section a-b in Figure 6 demonstrates the initial heating of the air in each chamber from the start at 19.9°C to 21°C. There is a deviation in the heating rate due to the thermal capacity of materials in the chambers. The use of mechanical ventilation resulted in lower room air temperatures than the previous experiment and consequently a much lower surface temperature on the PCM wall-lining. The difference in surface temperatures of the PCM wall-lining and the plain wall in the Control chamber is only 0.89°C, whereas the surface temperature difference of the experiment without ventilation is 4.5°C. As the heat transfer is related to the air mass flow rate, surface heat transfer coefficient and the temperature difference, the results indicated that an optimum balance of ventilation and room temperature is necessary to achieve best heat transfer performance in a real building room.

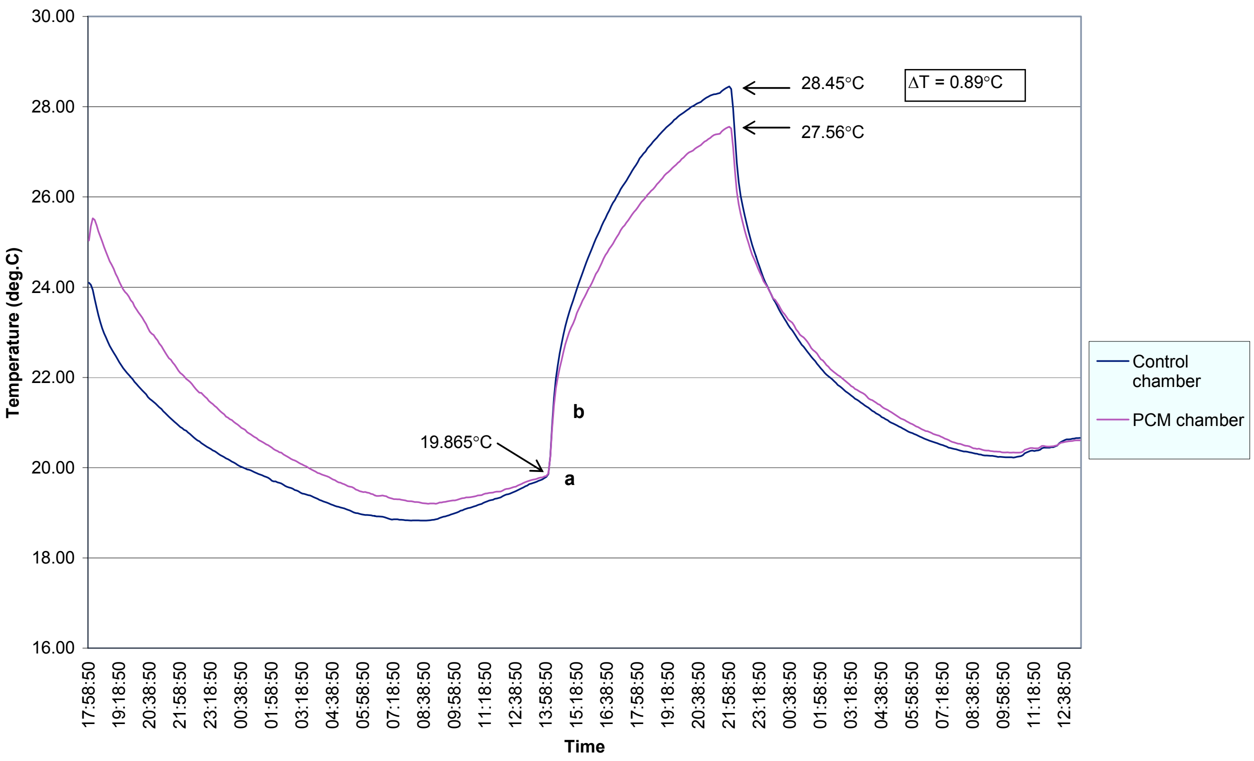

Figure 6 Room temperature results of ventilated test chambers after 8 hours heating

Figure 6 shows after the heating in both chambers is turned off at 22:00 the temperatures in both chambers immediately begin to reduce. The slope of the cooling curve is steeper than in Figure 5 demonstrating the effective removal of heat from the chambers when mechanical ventilation is used. During cooling it took only 1 hour and 50 minutes for the two chambers to reach the same temperature of 23.75°C, although the Control Room had a larger temperature range to reduce.

The experiments described have shown that a PCM wall-lining can successfully reduce the temperature of a room and improve the thermal comfort conditions. The results showed that the non-ventilated chamber with PCM wall-lining is more effective in minimising the temperature swing. It may be necessary to have a variable flow ventilation system to improve the PCM wall-lining's performance such as a low ventilation rate during the heating period to enable the heat to transfer into the PCM wall-lining and a high ventilation rate to discharge the PCM wall-lining during the cooling cycle.

3.3.3 Limitations

The experimental investigations are limited in the ability to simulate conditions consistent with real office environments. Whilst every effort is made to subject the PCM wall-lining to realistic temperature and ventilation conditions it is not possible to simulate a real in-use room environment.

The temperature of the PCM wall-lining may not be the accurate phase change temperature to keep a room 'comfortable'. The results of the experimental investigation showed the room temperature of the test chambers became much higher than would be comfortable for an occupant, even when the PCM wall-lining successfully reduced the peak temperature. A microencapsulated PCM with a lower melting point may be required to maintain lower room temperatures or a blend of PCMs with different phase transition points.

4. Conclusions

The experimental investigation has shown that the PCM wall-lining prototype can reduce the internal temperatures of the test chamber. The PCM wall-lining also delays the time taken to reach the extreme temperatures, which results in a narrower temperature band for the room throughout a 24 hour period. A reduction in peak temperature fluctuations by the PCM wall-lining could improve the thermal comfort environment for the occupants.

The difference in the PCM wall-lining's performance dependent on air flow and air temperature across the surfaces demonstrates that further work needs to be done to understand how optimal heat transfer into the PCM wall-lining can be achieved.

The successful development of PCM wall-linings will play a significant role in tackling the growing problem of overheating in buildings due to global warming, leading to a global reduction of energy consumption and demand for air-conditioning.

5. Future Work

Further work needs to be done to quantify the variables that affect the thermal performance of the PCM wall-lining. An air-conditioning system is currently being installed in the test chambers so air temperatures and air flows can be controlled more accurately than currently available. This will enable the heat transfer rates into and out of the PCM wall-lining to be determined and how they are affected by temperature and the air exchange rate.

The temperature monitoring of the chambers needs to be more sophisticated. The next phase of experiments will have surface temperature sensors located at every layer of the wall so the heat transfer rate and amount of heat stored in the PCM wall-lining during experiments can be quantified. These results will be used in finite element analysis along with air flows and conductivity of PCM wall-lining to determine the optimum thickness of the PCM wall-lining to operate at maximum efficiency.

The results from experiments in the upgraded test chambers will be used to validate the developing thermal simulation models in TRNSYS, a building simulation program. This program will help to identify if the phase change temperature of the PCM wall-lining is correct, to be able to absorb the necessary heat from an office in different buildings, and to evaluate the dynamic thermal performance of PCM wall-lining under different climatic and operating conditions.

References

BSRIA. 2002. World Market for Air-Conditioning. BSRIA.

Cabeza, L. F., Nogues, M., Roca, J. & Ibanez, M. 2004. PCM research at the University of Lleida (Spain). IEA, ECES IA Annex 17 6th Workshop. Arvika, Sweden.

CIBSE. 2004. Guide F Energy Efficiency in Buildings. London. CIBSE. pp 1-2

Dyball, D. L. 2004. The Practical Opportunities for Use of Phase Change Materials in Buildings. Brighton, UK. University of Brighton.

Hummel, H.-U. 2004. Leichtgewichte mit Massivem Wärmespeichervermögen: Gipsplatten mit Inkorporiertem PCM. ZAE Symposium. Munich, Germany.

Humphreys, M. A. 1978. The Optimum Diameter for a Globe Thermometer For Use Indoors. Watford, UK. BRE.

Ip, K., Miller, A., Corner, T. & Dyball, D. L. 2003. Development of Phase Change Thermal Storage Wallcoverings In Buildings. The CIB 2003 International Conference on Smart and Sustainable Built Environment. Brisbane, Australia.

Khudhair, A. M., Farid, M. M., Özkan, N. & Chen, J. J. 2003. Microencapsulated Phase Change Materials in Building Materials. ISES Solar World Congress. Göteborg, Sweden.

Schossig, P., Henning, H. M. & Haussmann, T. 2004. Microencapsulated Phase Change Materials Integrated into Construction Materials. 5th ISES Europe Solar Conference: EuroSun. Freiburg, Germany.

UNFCC. 2004. Essential Background - Feeling the Heat [Online]. Available at: <http://unfcc.int/essential_background/items/2877.php>. [Accessed 11 November 2004].

Thermal behaviour of a wall-lining containing phase change materials.

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THERMAL BEHAVIOUR OF A WALL-LINING CONTAINING PHASE CHANGE MATERIALS

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Summary

In temperate climates like UK, buildings constructed with high thermal mass materials have the intrinsic capacity to alleviate the effect of overheating in the summer. Phase change materials (PCMs), which have a high latent heat capacity to volume ratio is a potential effective means to improve the thermal capacity of light-weight or existing buildings. The feasibility of applying PCMs in buildings was investigated through a research and development collaboration between University of Brighton and OMNOVA Wallcoverings (UK) Ltd. The aim was to develop a PCM wall-lining which can reduce energy consumption of buildings, by minimising the use of air-conditioning, and improve the thermal comfort during periods of extreme climate conditions.

This paper reports on the measured experimental findings of the thermal performance of a prototype phase change wall-lining developed and manufactured. Samples of the prototypes were tested using Differential Scanning Calorimeter (DSC) in the laboratory which provided evidence of the projected and actual sensible-latent heat transfer behaviour of the micro-encapsulated PCM. In order to evaluate the thermal performance in actual installed conditions, the prototype wall-linings were subject to a regime of cyclic environmental conditions in a 13.8m^3 chamber. The results were compared with a control chamber that was subject to the same conditions but without the phase change wall-lining. The experiments provided measured data on the effect of different supply air conditions to the charging and discharging behaviour of the wall-lining, the amount of energy stored and the moderation of peak temperatures. These experimental results enabled the evaluation of the effectiveness of the latent heat storage by the PCMs within the wall-lining and are analysed and discussed.

1. Introduction

Research collaboration between University of Brighton and OMNOVA Wallcoverings (UK) Ltd has resulted in a project to develop a thermally interactive wall-lining, utilising OMNOVA's manufacturing technology, that can improve the thermal storage capacity of buildings, reduce overheating and reduce demand for conventional cooling systems. This has been realised by the inclusion of phase change materials in wall-linings.

Phase Change Materials (PCMs) are materials that not only absorb sensible heat as the temperature increases but also absorb latent heat when melting and release the stored heat when freezing, both at an almost constant temperature. PCMs can be used in buildings to significantly improve the thermal mass as they have a much greater ability to store heat than conventional building materials such as concrete. Concrete has a sensible heat storage capacity of 1.0 kJ/kgK, whereas an inorganic phase change material such as calcium chloride hexahydrate can store up to 193 kJ/kg during phase transition. PCMs are able to reduce peak temperatures in buildings by absorbing excess heat during the day and releasing the heat at night when the surrounding temperature is cooler. The storage and release of excess heat results in a narrower temperature band over a diurnal period therefore improves thermal comfort for the occupants.

A significant development in phase change technology is the ability to microencapsulate PCMs. Microencapsulation is the packaging of micron-sized materials (both liquids and solids) in the form of capsules, ranging from less than 1μm to more than 300μm. Microencapsulated PCMs can be used to introduce high thermal storage capacity into conventional building materials. Examples of research developments using microencapsulated PCMs include gypsum plaster (Schossig et al., 2004), concrete (Cabeza et al., 2004), and wallboard (Hummel, 2004); (Khudhair et al., 2003).

An advantage of using a wall-lining containing phase change materials is its direct exposure to heat exchange within the room. Other PCM materials are located deep within the construction of a wall or ceiling and would have less effective heat transfer.

2. Phase Change Wall-lining Development

Initial investigations to incorporate microencapsulated phase change materials into a vinyl wall-lining were successful using microencapsulated phase change materials supplied by BASF. This preliminary phase change wall-lining was tested and the results showed it successfully slowed the temperature rise and reduced peak room temperatures, as reported at SB05 (Dyball, 2005).

To progress the development of a phase change wall-lining to a prototype stage it was desirable to increase the thermal storage capacity of the wall-lining. Outlast Technologies Inc, specialists in the research of phase change materials, was approached to develop microencapsulated phase change materials specially formulated for inclusion in a vinyl wall-lining.

Outlast supplied a range of their microencapsulated PCMs, known as Thermocules®, with different particle sizes for joint development work. Analysis of the Thermocules® determined the larger the particle size the larger the heat storage capacity. Extensive experiments were undertaken to develop a plastisol formulation containing the highest possible loading of the largest Outlast Thermocules, referred to as XXL(2). The resulting formulation was coated out and cured and a vinyl wall-lining containing 46% by weight of microencapsulated phase change materials was produced.

Differential Scanning Calorimeter (DSC) analysis of the lab prepared phase change wall-lining revealed the phase transition temperature has shifted from 24°C phase change temperature of XXL(2) Thermocules) to 23°C. This raised concern that the shell of the Thermocules may have ruptured during processing and the wax core contaminated. If the wax core was contaminated it is likely that after thermal cycling (repeated heat then cool cycles) each phase transition would show a different profile in the DSC graph as the phase change material would be unable to perform in the same manner as the wax composition would have changed. The results, illustrated in Figure 1 showed that repeated heating and cooling of the phase change wall-lining did not affect the phase transition temperatures. The shape of all the peaks remained the same after 22 cycles confirming the Thermocules performance had not been compromised and they were robust enough to withstand the manufacturing process.

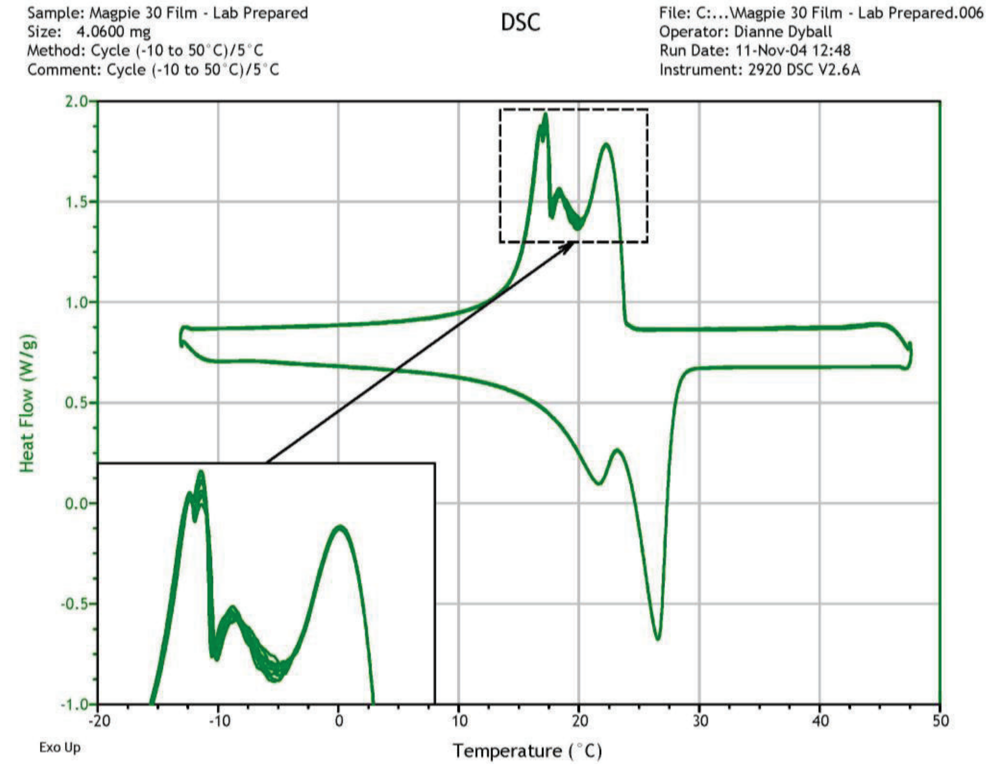

Figure 1 Results of thermal cycling lab prepared phase change wall-lining

A successful pilot scale trial was undertaken and manufactured 50m of 700mm wide, 6mm thick phase change wall-lining. The wall-lining contained 45% by weight of Outlast XXL(2) Thermocules. The thermal performance of the trialled manufactured phase change wall-lining was thermally analysed and the results are shown in figure 2. The DSC results of the manufactured phase change wall-lining show the phase transition temperature is 23°C and the latent heat storage capacity is 87 J/g. This latent heat capacity equates to 503 kJ/m^2.

The graph also includes the DSC results of the Outlast XXL(2) Thermocules used in the phase change wall-lining. This makes it easy to identify any change in the peak profiles and highlight any problems that may have occurred to the microcapsules during manufacture. From the graph in Figure 2 it is clear the melt point has shifted from 24°C to 23°C as occurred in the lab prepared sample. As this is consistent with the inclusion of XXL(2) into vinyl wall-linings there is no need for concern. There is no other significant change to the profiling of the Thermocules within the phase change wall-lining therefore the inclusion was a success.

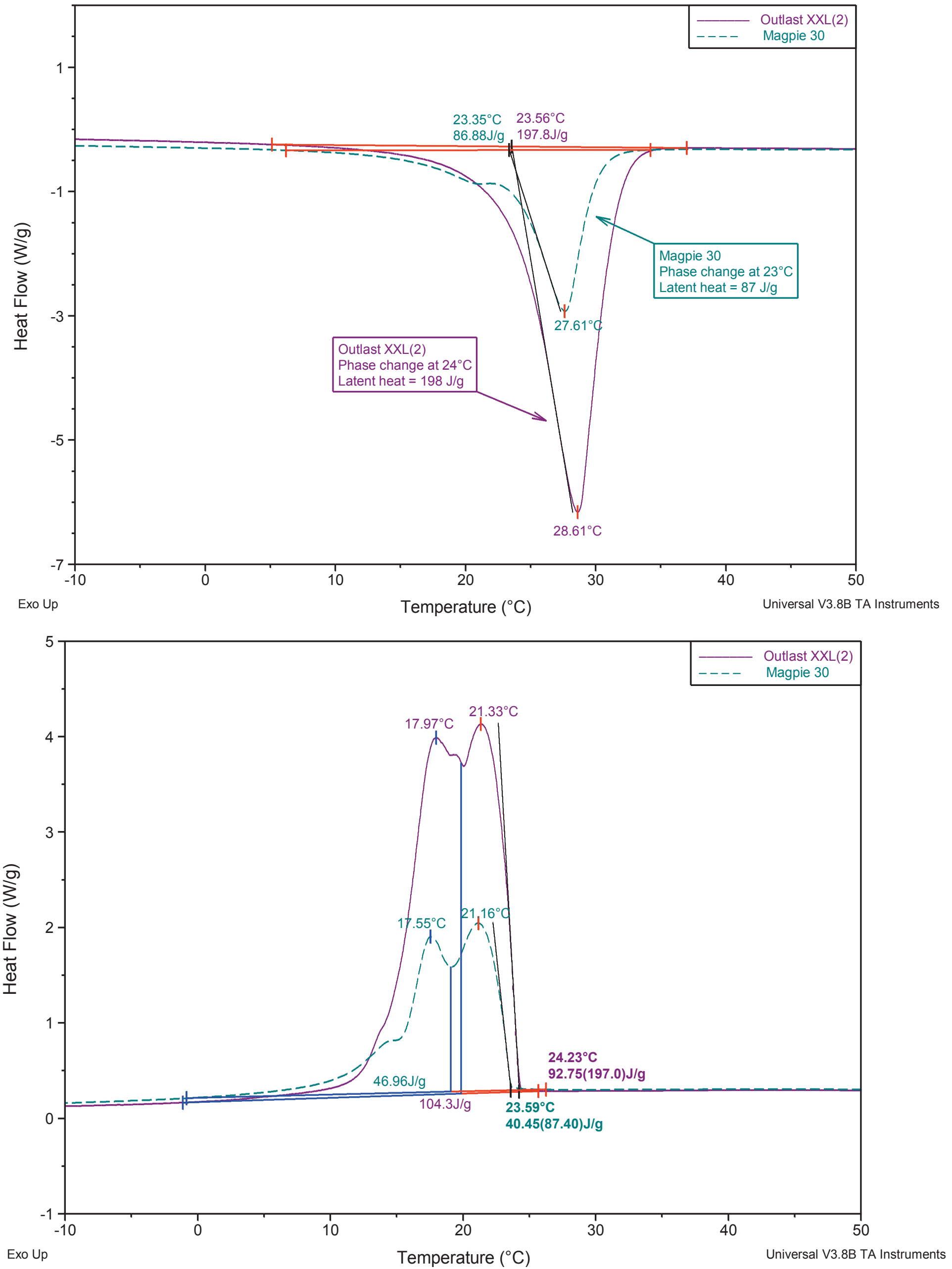

Figure 2 Thermal analysis results of trial manufactured phase change wall-lining during heating cycle (upper) and cooling cycle (lower)

The prototype phase change wall-lining was tested by Gearing Scientific Ltd to determine the conductivity value. The thermal conductivity value of a material is important as it is a measure of the rate at which heat can pass through a material.

The phase change wall-lining was tested using a LaserComp Fox 200 thermal conductivity instrument which conforms to ISO 8301. The tests were conducted at temperature intervals from 20°C to 30°C to ensure before, during and after phase changes were included. The results showed the thermal conductivity value of the prototype phase change wall-lining is 0.12 W/mK.

3.0 Experimental Setup and Measurements

To evaluate the thermal performance of the phase change wall-lining using realistic room conditions two environmental test chambers were proposed. To determine the variables that need to be considered a mathematical model was first developed. A one dimensional finite element heat transfer network through a chamber wall with phase change wall-lining and timber board was then established and simulated to predict the performance. The different elements to be considered for the heat transfer in a chamber with air supply and exhaust are illustrated in Figure 3. The proposed environmental chambers would be used to evaluate the thermal performance of the phase change wall-lining when subjected to different supply air conditions.

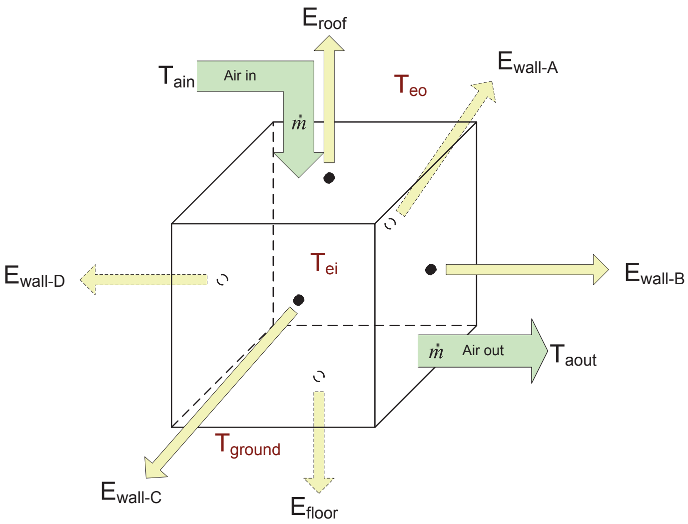

Figure 3 Heat transfer of Environmental Chamber

Two highly insulated, identical chambers, 13.8m^3, were constructed in an open laboratory space that has relatively stable thermal conditions at the University of Brighton, see Figure 4.

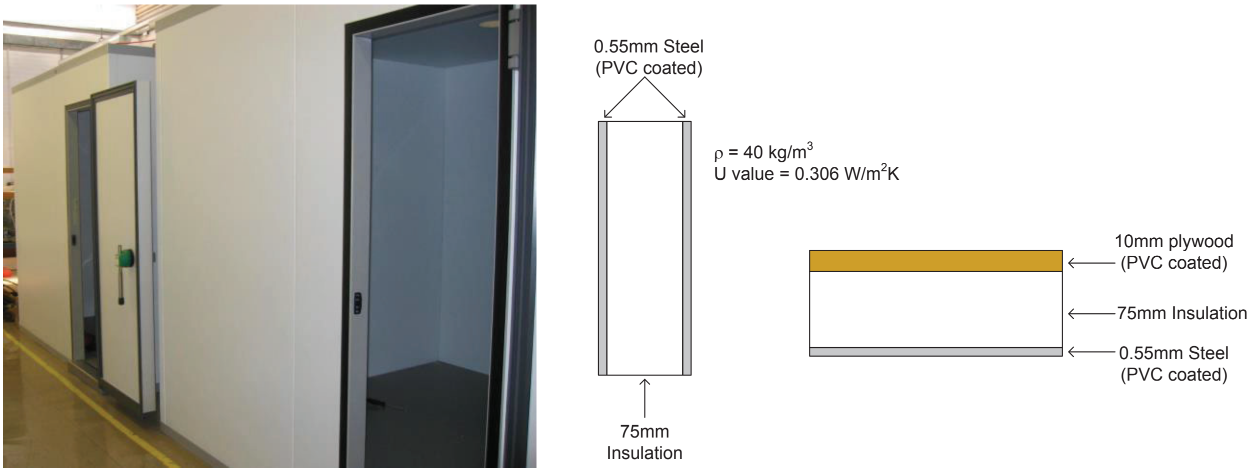

Figure 4 External view of test chambers (left) & schematic showing construction of walls, ceilings and floor (right)

The temperature and air flow inputs to the chambers are set by an Excel programme that operates the air-conditioning system via a programmable logic controller (PLC) in a control panel. The system can operate to provide supply air temperature between 15 - 30°C and air flow of 1.5 – 10 air changes per hour (ach).

The supply temperature is monitored by two air temperature probes, both located in the ductwork prior to air inlet as shown in Figure 5, which feeds back to the PLC and enables the program to adjust the amount of heating or cooling necessary to maintain the temperature set-point.

The test chambers were fitted with extensive surface, air and room temperature sensors which were all connected to a data logger for data acquisition at timed intervals.

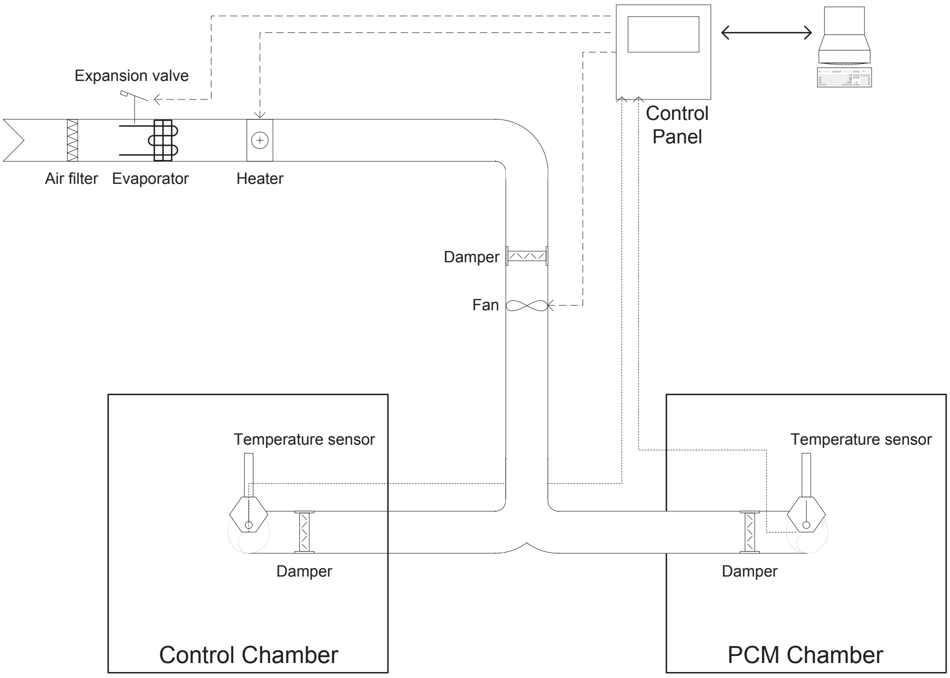

Figure 5 Schematic of air-conditioning system supplying test chambers

The test chambers were heated and subsequently cooled to a fixed temperature. Each experiment used a different air supply rate, which remained constant throughout the duration of the experiment. The experiment continued until steady state conditions were reached.

4.0 Results and Discussion

The aim of the experiments was to evaluate the effect of supply air conditions to the thermal behaviour and storage capability of the phase change wall-lining. Two sets of results are illustrated to demonstrate the charging and discharging behaviour. Figures 6 and 7 show the PCM charging process when air at 30°C was supplied whereas Figures 8 and 9 show the PCM discharging process when the air supply temperature was set at 15°C.

4.1 Heating cycle

The graphs have been divided into 'zones' to represent different stages of the heat transfer process. Figure 6 showing the heating cycle in the Control Chamber has been divided into Zones A, B and S. Zone A is the initial stage when warm air begins entering the chamber. The curve in Zone B shows the effect of sensible heat storage of the chamber walls, which is proportional to the rate of change of temperature. The steady state heat transfer occurs in Zone S where heat contributing to thermal storage gradually diminishes. The charging time (Zone B) is affected by the air change rates; the use of 9 ach reduced the charging time by nearly 50% in comparison with the 3 ach air flow rate.

In Figure 7, heating results for the PCM Chamber, an additional zone has been created. For the PCM Chamber Zone B exhibits the phase change characteristics of the wall-lining where the rate of air temperature increase is reduced in comparison with Figure 6. As the microencapsulated PCM is evenly distributed within the wall-lining, the thermal behaviour is similar to a wall with high thermal capacity that slows the change in temperature, in particular more evidently in the temperature region where phase change occurs. The phase change processes appear to occur mainly between the first 6 to 9 hours. A comparison of the time for the air temperatures to reach a reference temperature of 24°C for the experiments in each test chamber show significant difference from 100, 250 and 880 minutes to 230, 540 and 1740 minutes. Zone C exhibits the sensible heat transfer characteristics similar to Zone B of the Control Chamber (Figure 6) whilst Zone D shows the more gradual temperature rise, due to the additional thermal capacity of the phase change wall-lining, until steady state conditions are reached in Zone S.

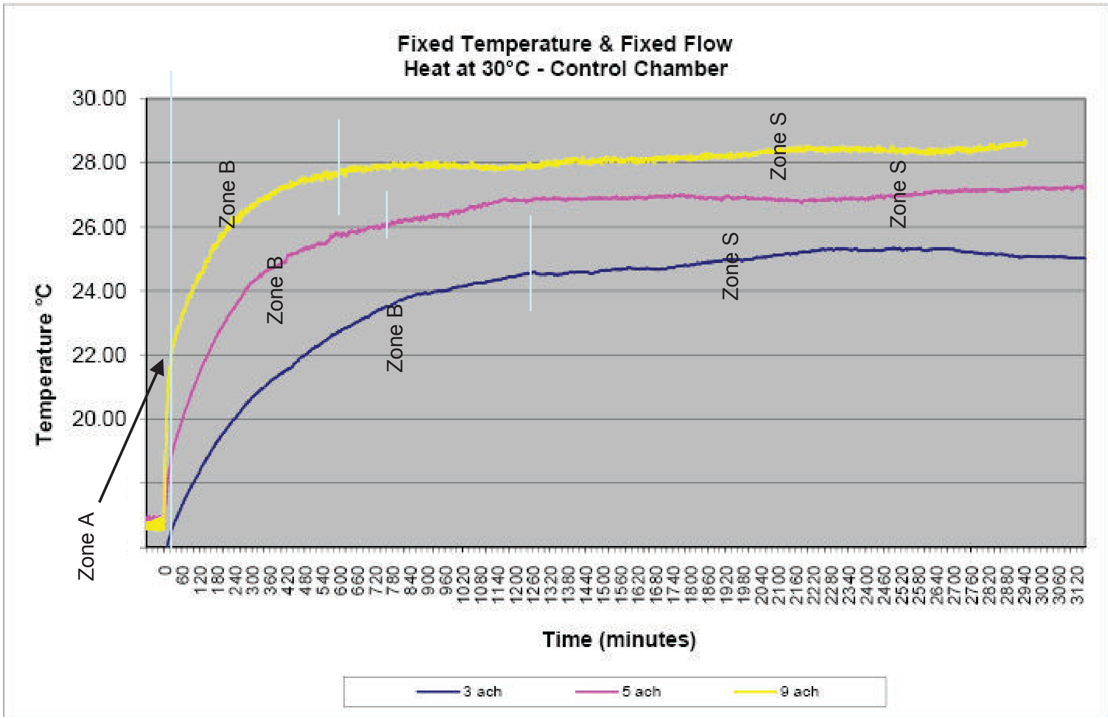

Figure 6 Results of Control Chamber during heat cycle

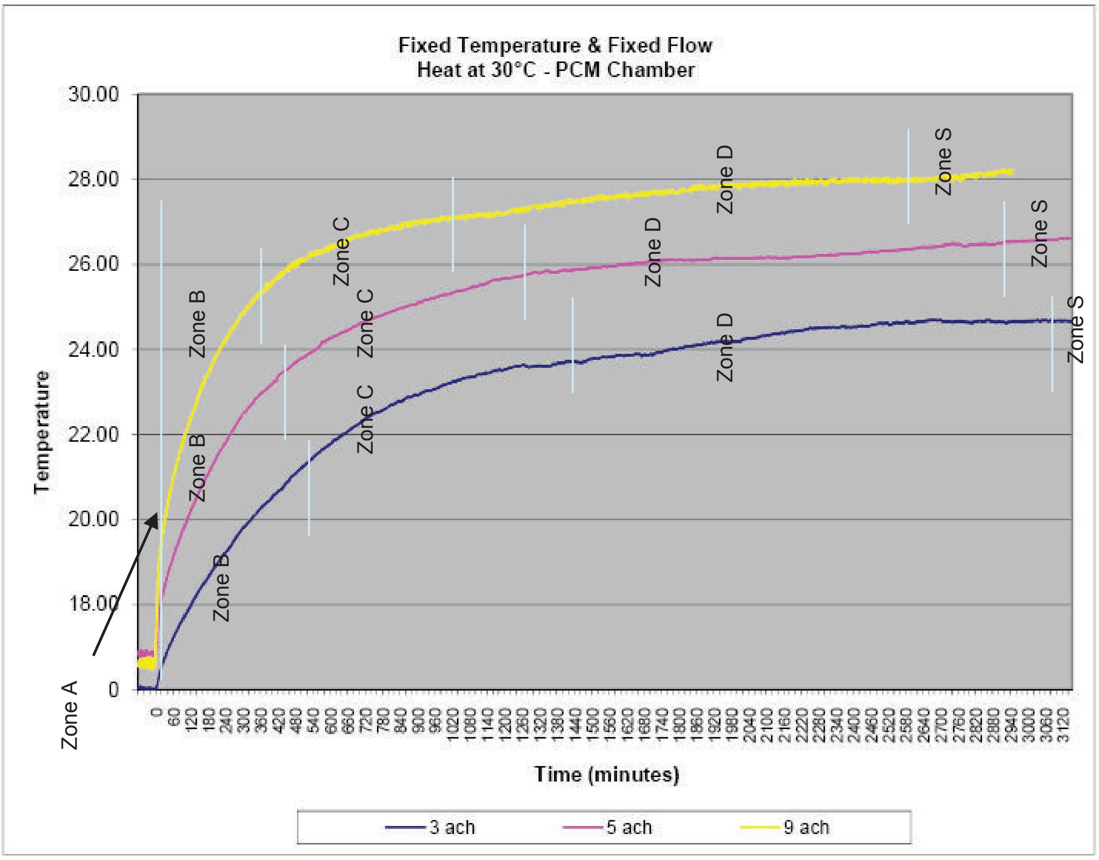

Figure 7 Results of PCM Chamber during heat cycle

4.2 Cooling cycle

For the cooling cycle where the supply air was maintained at 15°C for the three different air change rates in the test chambers the results have also been zoned using the same format as for the heating cycle results.

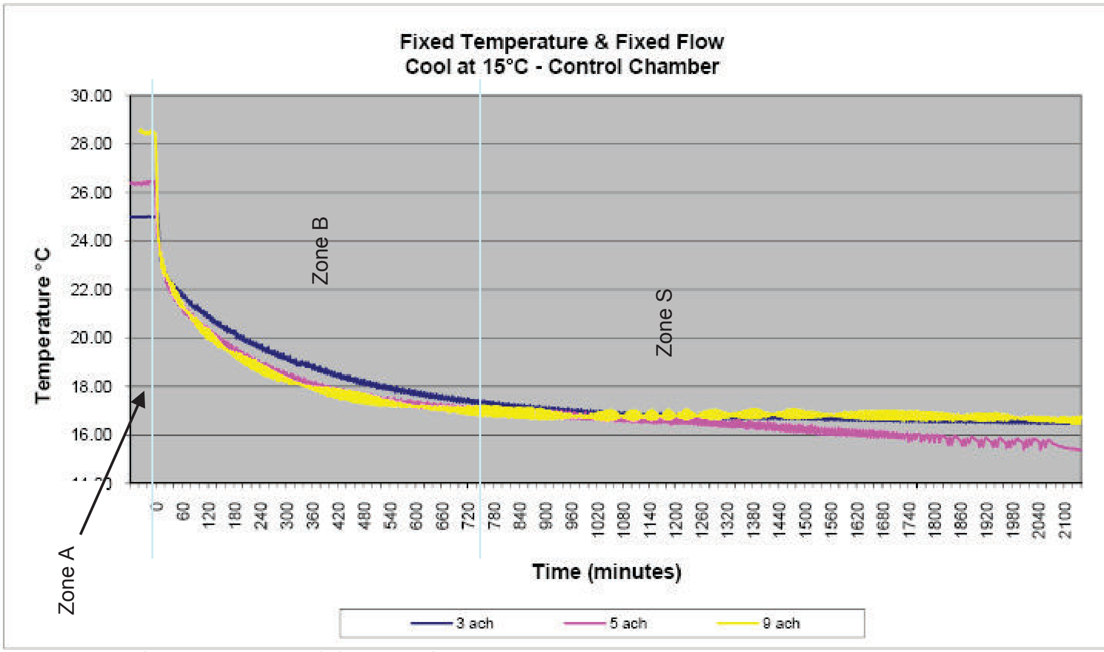

Figure 8 Cooling cycle of Control Chamber

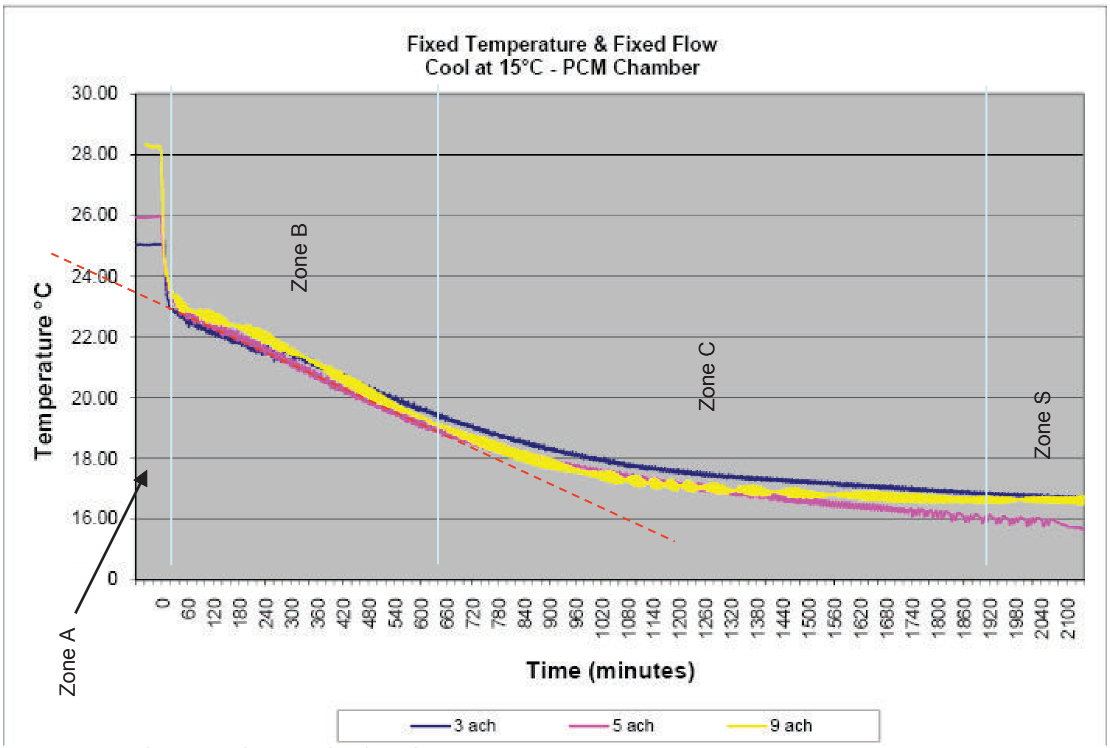

Figure 9 Cooling Cycle of PCM Chamber

The graphs for the cooling cycle in Figures 8 and 9 show the temperature variations are less distinctly separated than those in the heating cycle. This can be attributed not only to the relatively smaller temperature differences between supply air and the external air but also the supply air and the phase change temperatures when the experiments were performed.

Zone A in Figures 8 and 9 show the warm air of the chamber being replaced by the 15°C supply air. The temperature drops quickly as the thermal capacity of air is low. Zone B in the Control Chamber (Figure 8) exhibits the non-linear characteristics of the sensible heat transfer process, therefore illustrating the heat being removed by the chamber wall as the temperature drops. It took about 12 hours to reach steady state.

Zone B in Figure 9 exhibits a linear temperature profile of a constant rate of change of temperature. Such characteristic is in contrast to the results for Zone B of the Control Chamber. It illustrates the rate of change of temperature is maintained by the latent heat released from the PCM in the wall-lining. Zone C shows a non-linear reduction in temperature when most of the PCM in the phase change wall-lining has solidified and the sensible heat transfer process dominates. Zone S again represents the steady state conditions in the chambers.

As the supply air temperature is only 7°C below the phase change temperature, the air change rates do not appear to have significant effects on the temperature during the cooling cycles. This suggests the lower flow rate may be used to save fan energy.

5. Conclusions

This research investigates the potential of applying phase change materials contained within wall-linings to enhance the thermal capacity of buildings. The research has successfully developed and manufactured wall-lining prototypes containing micro-encapsulated phase change materials. The laboratory tests showed the PCM wall-lining has a latent heat capacity of 503 kJ/m^2 with a phase change temperature of 23°C. The dynamic thermal behaviour of the wall-lining as installed in a room has been evaluated using two identical environmental test chambers. Analysis of results for this part of the research is still on-going. Initial comparison of results between the PCM and Control Chambers provided information on the cyclic charging and discharging behaviour of the phase change wall-lining. Future work will focus on establishing the energy stored and detailed performance data to enable the prediction of the daily and seasonal thermal performance with the UK climate.

References

Cabeza, L. F., Nogués, M., Roca, J. and Ibañez, M. 2004, PCM research at the University of Lleida (Spain). *IEA, ECES IA Annex 17 6th Workshop.* Arvika, Sweden.

Dyball, D.L. 2005, Development of Phase Change Wall-linings to Enhance Thermal Storage of Buildings. In Proceedings of The 2005 World Sustainable Building Conference. Tokyo, Japan.

Hummel, H.-U. 2004, Leichtgewichte mit Massivem Wärmespeichervermögen: Gipsplatten mit Inkorporiertem PCM. *ZAE Symposium.* Munich, Germany.

Khudair, A. M., Farid, M. M., Özkan, N. and Chen, J. J. 2003, Microencapsulated Phase Change Materials in Building Materials. *ISES Solar World Congress.* Göteborg, Sweden.

Schossig, P., Henning, H. M. and Haussmann, T. 2004, Microencapsulated Phase Change Materials Integrated into Construction Materials. *5th ISES Europe Solar Conference: EuroSun.* Freiburg, Germany.