University of Strathclyde
Engineering

PCM performance optimisation in buildings using active cooling systems

---

A thesis presented in fulfilment of the requirements for the degree of

MSc in Energy Systems and the Environment

DEPARTMENT OF MECHANICAL ENGINEERING

Anastasios Markopoulos

September 2008

Copyright declaration

Contents

List of Tables

List of Figures

Acknowledgements

First of all I would like to thank my supervisor Dr Nick Kelly for his guidance and knowledge which helped me during the completion of this project.

I want to thank my family for the continual support and encouragement they gave me throughout the duration of this course.

My sincerest gratitude goes to the gang of 322; they know who they are!

I would especially like to thank my girlfriend Magdalen for the constant support and understanding she has given me during the course.

Abstract

The aim of this project was to discover if the thermal energy storing potential of three different types of PCM (phase change material) could be utilised and optimised in order to help moderate internal peak temperatures and reduce the cooling load consumption of commercial buildings. The study involved modelling and simulating two identical constructions in a Mediterranean climate for both passive and active cooling conditions using ESP-r between June and September. A PCM-gypsum composite wallboard was allocated to a single vertical wall within one of the zones for each simulation; and a PCM-concrete combination located in a multilayer ground surface was also simulated.

The results of the study showed that small temperature moderations, approximately 1 degree centigrade on average, were achievable at the beginning of the monitored period under passive cooling conditions when using each of the PCMs selected; however the internal temperatures exceeded the human comfort range by more than 7^{o}C. The resultant latent heat capacity of the PCM was adversely affected during melting and solidification with the incorporation of scheduled air-conditioning operating in the models. The results of a proposed PCM showed that with a wider phase change temperature range (4^{o}C), integrated into the floor, showed more energy savings could be made as the resultant cooling was significantly decreased (~10% saving); proving that further analysis of the thermal properties of PCM is required to increase their effectiveness in an actively cooled environment.

1 Introduction

The potential risk of energy shortages, more frequently occurring blackouts and further increases in energy costs, grows rapidly on a daily basis as the global economy expands at an alarming rate; and in parallel the demand for the availability of energy increases. Generating more energy to meet the rising demands of both developed and developing nations is the key solution being utilised by numerous governments around the world to secure a more reliable supply. As a result, the competition and urgency to discover more sources of fossil fuels is heightening; with attention turning towards various renewable technologies and nuclear energy generation in the form of financial investment and development in order to achieve this goal.

The increased interest in renewable technologies and nuclear energy is driven by the aim of reducing the current level of greenhouse gas emissions being produced. However in order to achieve these targets and to be able to sustain them, it is vital to recognise that greater efforts must be placed in improving the efficiency and effectiveness of our energy generation systems and ultimately the way in which energy is utilised on commercial and domestic levels.

This project has been carried out to investigate the potential economic and environmental benefits which can be achieved through the integration of Phase Change Materials (PCMs) into a building envelope material. Three PCMs with varying thermal characteristics have been selected and integrated into a typical residential construction located in Spain. The model has been simulated in a Spanish climate over a summer period using a building energy simulation package called ESP-r. This type of thermal testing enabled quantitative thermodynamic results to be collected from a realistic modelling situation which could not be easily recreated in experimental conditions. The main results being focussed on in this study are the electrical load reductions which can be made in an actively cooled environment by the PCMs; and additionally the thermal moderation attainable in both actively and passively cooled internal climates again through the use of PCM. The independent simulation variable was the surface selected to apply the phase change material.

The level of temperature moderation which can be achieved from integration of a latent heat storage material with a high thermal mass, into the construction of a building, can have a substantial impact on reducing the required cooling loads necessary to achieve comfortable thermal conditions. The use of energy will vary dramatically over the course of the daytime and night time periods and with this in mind, the ability to improve the effectiveness of our energy use successfully is a difficult problem to tackle. This problem is mainly due to the unpredictability and poor management of the demand. One example where the fluctuations in our use of energy is clearly visible is within building environments; where significant amounts of electrical energy are consumed in a wide range of industrial, commercial and residential activities; with the majority of this energy being utilised for either domestic space heating or air conditioning units. This type of behaviour is exacerbated when buildings are located in extremely hot or cold climatic conditions.

In addition to the variable external climatic conditions e.g. wind velocity, solar radiation, outdoor temperature, the heating and cooling demand of a building will also be dependent on several other internal factors. Some of these include the buildings occupancy; and the casual energy gains induced within the building through a variety of different means e.g. lighting, electrical appliances, etc; which will all impact on the overall thermal comfort of the internal environment. The graphical representation in Fig.1 below indicates the comfort range for indoor environments.

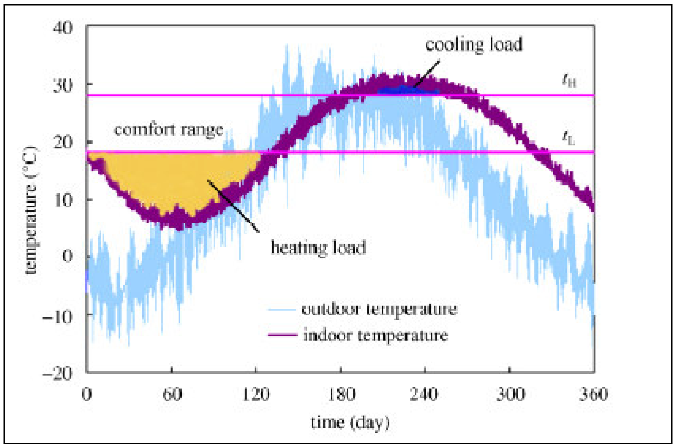

Figure 1 Heating and Cooling load profile in a building environment;[1]

---

[1] Zhang Y et al, (2007), Application of latent heat thermal energy storage in buildings: State of the art and outlook, *Building and Environment,* p2198.

Increasing the thermal comfort conditions of a building, whilst at the same time reducing the rate of air temperature variation and electrical energy demand necessary to achieve this, is an important factor involved in the design and construction phases of a building. Fig.1 demonstrates that the amount of heating or cooling required within a space is dictated by the difference between the actual indoor air temperature and the optimum thermal comfort range. (Zhang Y et al 2007: 2198) Reducing peaks in power consumption and shifting portions of the load from periods of maximum demand are achievable targets being set in sustainable housing design.

This has been a continually growing area of interest with increased research and development going into technologies attempting to conserve energy and reduce the dependency on fossil fuels. Economic and environmental benefits can also be gained when implementing these changes in various areas. For example the operating efficiency and rational use of available resources can be increased thus reducing emission rates and non-renewable energy generation; and the incorporation of more available renewable energies within a building will add further savings. (Zalba et al 2003: 252) One of the prospective technologies being developed to achieve these targets is the development of latent heat energy storage systems incorporating Phase Change Materials in the wallboards of building envelope materials.

2. Background Review

2.1 Thermal Energy Storage

Thermal energy storage devices have been seen as a promising solution to helping manage the mismatch between energy demand and supply; and achieve acceptable levels of thermal comfort, in accordance with human comfort levels, within a building envelope. The additional benefits that are gained from these devices are the performance enhancement and increased reliability of energy generating systems producing high concentrations of waste heat, as well as getting the most out of zero-greenhouse-gas emission options for electrical power generation (Suppes et al 2003 1751); which have the potential to work more effectively in off peak demand periods. Ultimately these types of devices will play an important role they in building energy conservation. (Sharma et al 2007: 2)

Since their initial discovery in the early twentieth century, extensive research has been carried out on various heat storage devices for a variety of potential applications. The systems that have been tested incorporate either one, or a combination of the different types of storage method available. These are as follows:

2.1.1 Sensible Heat Storage

Thermal energy is stored in this system by raising the temperature of a solid or liquid; and thus utilising the heat capacity of the storage material during the charging and discharging phases. The storage capacity of the material used in this type of system is dependent on the rate of temperature change required in the applied circumstance, and the volume of material used.

High material cost is the most significant factor preventing the sensible heat storage technique from operating effectively in newly constructed buildings. A much larger material mass, when compared to materials used in other storage methods, is usually required; and is dependent on the rate of absorption and rejection of heat necessary to produce the desired temperature swing and hence thermal comfort level. The liquids most commonly used in sensible heat storage systems are water and thermal oil. Frequently used solids include rocks, brick, concrete, iron and dry and wet earth.

2.1.2 Thermo-chemical Heat Storage:

These types of system rely on the absorption and release of thermal energy as a result of the break down and reformation of a molecular bond in a completely reversible chemical reaction. The amount of heat made available to store from the reaction will be dependent on the volume of material; the endothermic heat in the reaction; and the extent of the change in the materials structure. (Sharma et al 2007: 3)

2.1.3 Latent Heat Storage:

This method of energy storage is based on the absorption or discharge of heat which takes place during the phase change period of the storage material being used. The types of transition include solid to solid, where the stored energy will be transferred from one crystal to another; and little volume change will be experienced providing more flexibility to the designers of the PCM containers. This type of phase change however yields a smaller amount of latent heat, which makes it less desirable when trying to maximise thermal energy storage in a small volume. (Regin et al 2007: 2) Solid to liquid phase changes produce comparatively smaller latent heat than liquid to gas transformations; but they have proved to be more economically viable as a smaller volume change results from the phase transition. All of these phase changes are reversible with near enough isothermal transition. (Sharma S D 2005: 3)

Presently the solid to liquid phase transition is the preferred latent heat storage method under development for introducing phase change material; due to both its low volume and enthalpy variations encountered. (Pincemin et al 2008: 604) Solid to gas and liquid to gas phase changes in fact produce higher latent heat during transition in comparison, but their increased volume changes during this process create problems with respect to the storage space required and additionally the type of containment required. (Sharma et al 2007: 4)

Latent heat storage is considered to be a very effective thermal storage method; and this is down to several performance enhancing characteristics. It is becoming an increasingly attractive option as a method of space heating and cooling. Its ability to provide high thermal storage capacity with a lower working temperature variation during the transition phase of the storage material, are very attractive features of this system.

The earliest studies carried out on latent heat storage systems, were just after World War II. (Khudhair et al 2003: 264) Investigations were carried out on new solar space heating technology which required a more volume efficient approach to its design. This was the critical design factor which led to the majority of the research being focused on latent heat storage systems using phase change materials (PCMs). These types of material meet the design criteria required for low volume variation, and they can be manipulated to suit medium to long term energy storage; and will operate effectively within the human comfort temperature range (~16-25^{o}C).

However there are existing technical problems associated with phase change materials which are affecting their widespread practical application. The main issues of concern are the large surface areas required to achieve their optimal performance; incongruent melting and solidification during phase transition; degradation of the PCM after repeated cycling; and compatibility between storage material and phase change material.

2.2 Phase Change Materials

Phase change material is a latent heat storage material but can also store sensible heat. (Sharma et al 2007:4) Each PCM has a melting temperature at which point it will transform from a solid to a liquid or a liquid to a vapour state; retaining the latent heat of fusion produced from the endothermic process. When the temperature falls below this melting point, the material will solidify again releasing the stored thermal energy into the surrounding environment at a constant rate.

Some of the first PCMs to be studied were inorganic salt hydrates integrated into solar energy storage systems; these were readily available, and at a low cost. The development of storage systems using these substances soon became limited by poor performance reliability. Incongruent phase transition and phenomena such as super-cooling became apparent. (Khudhair et al 2003: 264) Decomposition and corrosion problems also limited the lifespan of these substances; preventing further advances from being made and hampering their potential application.

In light of these inherent problems associated with inorganic materials, interest once again turned towards organic phase change materials. They were found to possess advantageous properties both physically and chemically; reliable thermodynamic behaviour; and adjustable phase transition temperatures. Additionally to the organic materials available, other substances such as paraffin waxes, fatty acids and eutectics have been studied over the last 40 years. (Farid et al 2004: 3)

During the last two decades, research has provided results highlighting the promising impact that different phase change materials can have when integrated into various types of heating systems. These include solar water-heating systems; solar air-heating systems; solar cookers; and solar greenhouses. Another area which was studied with the intention of improving energy conservation was the inclusion of PCM within building constructions; and especially for lightweight constructions where there is low thermal inertia and protection; and increasing energy efficiency is vital.

It has been an area of intense research during this time. Various porous building materials impregnated with phase change materials, such as gypsum wallboard, plaster, concrete, glass, and numerous others, which will be discussed at a later stage, have shown potential in helping solve issues concerning security of energy supply and the efficient use of energy in buildings. Benefits such as peak load shifting; 5-14 times more heat per unit volume storage compared to sensible storage materials (Sharma et al 2007: 4); and increases in the availability of energy between its production and consumption, are all being gained specifically through the incorporation of PCM in thermal energy storage systems.

Many substances have been studied as potential PCMs, although very few of them have been developed and produced to a commercial standard. Most of the attempts that have been made to introduce these substances into building material have been through macro-capsulation and immersion techniques; which have both presented several drawbacks; with micro-encapsulation showing more positive results. These techniques will be discussed in a later section. (Schossig et al 2005: 298)

In order to overcome the apparent obstacles to their commercial success, it is important that PCM candidates are able to fulfil a number of desirable criteria; and possess suitable properties for their intended application. The properties observed during testing and when selecting the appropriate material during the building design phase, are as follows:

2.2.1 Thermo-Physical

It is important that the phase transition temperatures of the PCM i.e. for heating or for cooling are in the required operating temperature range suitable for its application. The melting process that takes place at this temperature must produce a high latent heat of fusion per unit volume in order to minimise the containment required for the volume change of the PCM; high material density and low vapour pressures at the operating temperature are preferable in aiding to achieve this. In addition to the latent heat stored, significant sensible heat produced from the phase change must also be stored.

Selecting a suitable PCM for a potential application is dependent on several factors. One of these is the efficiency at which energy is absorbed and discharged from the PCM. Maximising this capability is possible by selecting a substance with good thermal conductivity. A high thermal conductivity is beneficial as it can help avoid instability in the material during these processes.

2.2.2 Kinetic

Congruent and complete phase transition during charging and discharging of energy is vital in gaining the maximum storage capacity available. A problem that has been recognised in the behaviour of some phase change materials is that of super-cooling. This phenomenon interferes with the exothermic transition phase of the substance and prevents the complete crystallisation of the storage material (Tyagi et al 2005: 1150); and the total release of the heat stored if the super-cooling is in the range of 5-10 degrees centigrade. It is important to select a phase change material with a high rate of crystal growth so that the demand of heat recovery is met by the storage system. (Tyagi et al 2005: 1150)

Methods to prevent this situation from occurring have been created. Nucleating agents have been introduced as catalysts within the PCM mixture to help increase the rate of crystal growth.

2.2.3 Chemical

Safety is paramount when PCM is being considered in the construction of a building. The long term chemical stability of a phase change material will be assessed before introducing it to the structure of a building; minimal deterioration of the material and complete reversibility is a high priority as it will undergo a number of phase change cycles in its lifetime.

The substance must be compatible with the surrounding materials so as not to induce or cause any structural damage. Equally the substance must not be toxic, flammable or explosive so that occupants of the building are not be put at risk at any point in the building s lifetime.

2.2.4 Economic

The availability of the different types of phase change materials will be the major factor influencing their integration in future and current building design; as well as the financial implications associated with them. The potential use of PCMs in several thermal control applications is limited mainly due to the extent of the costs; and present research and development has not involved industrial scale testing due to the low thermal conductivity property of available PCMs. However the performance of thermal control for space applications is critical in developing sustainable building design and needs to be addressed comprehensively in order to tackle the issue of energy conservation, no matter what the cost. (Zalba et al 2003: 262)

2.3 Analysis of Phase Change Materials

It is important that a comprehensive study of all of these characteristics is carried out before selecting the most appropriate PCM for its intended application. The thermal reliability of a PCM is potentially at risk when undergoing numerous thermal cycles, so the longevity of the material can only be verified through testing. The methods most commonly used to assess the thermal characteristics of a PCM are Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC).

Both of these techniques involve measuring the latent heat of fusion and melting temperature characteristics of PCMs. The analysis uses a recommended reference material, Al_2O_3, and a PCM sample, which are both heated at a constant rate. The temperature difference recorded between the two materials is proportional to the rate of heat flow in either material. The result is presented on a DSC graph, where the latent heat of fusion is calculated from the area under the curve; and the melting temperature is estimated from the gradient at the steepest point on the curve. (Sharma et al 2007: 10)

2.4 Classification of available PCMs

There are a wide range of available PCMs produced to perform in a variety of temperature ranges. It is extremely difficult to find a phase change material which exhibits all of the properties described prior. For this reason thermal storage systems need to be designed to maximise the potential of the inherent qualities found in the chosen PCM; and incorporate additional means of improving the performance of the system e.g. using metallic fins to increase the thermal conductivity of the system; metal dispersion with the PCM mixture will also enhance the conductive performance of the substance (Pincemin et al 2008: 604); or by mixing nucleating agents into the PCM to limit super-cooling.

The groups of PCM available are described below:

2.4.1 Inorganic

As already mentioned, inorganic substances were initially used to investigate latent heat storage using phase change material. They were classified as either salt hydrates or metallic; and consist of a salt and water which combine in a crystalline matrix during the solidification process. They displayed promising performance characteristics in a wide range of thermal conditions with relatively high latent heat of fusion per unit volume; high thermal conductivity when compared to other PCMS; were readily available at low cost; and were not seen as a safety hazard i.e. non-flammable and only slightly toxic. (Sharma et al 2007: 8)

Certain disadvantages were identified by using inorganic materials though. One behavioural characteristic of salt hydrates is that of incongruent melting. The phase change process that occurs at the melting and freezing temperatures involves the hydration and dehydration of the substance using water. The water released during the melting phase of the transition is sometimes found not to be sufficient to dissolve the crystalline structure of the phase change material; and the difference in densities between the solid and liquid material results in the less hydrated salt settling at the bottom of the container.

A similar situation is observed during the solidification phase of the substance; where poor nucleating properties lead to super-cooling and thus a reduction in the release of latent heat stored. If these problems are not addressed, the problem becomes irreversible rendering the system ineffective. (Hawes et al 1992: 105)

There are very few salt hydrates which melt completely during the phase change cycle. Successful integration of salt hydrates in a thermal storage system will involve using one of the following methods:

- Mechanical stirring;
- Encapsulation of the PCM in order to reduce the separation of the PCM molecules;
- Adding thickening agents to the phase change material to prevent the solid salts from settling at the bottom of its container;
- Using excess water to prevent melted crystals from producing a supersaturated solution;
- Better design of containers so as not to leak out any of the water in the mixture; (Sharma et al 2005: 10)
- Altering the chemical composition of the PCM to enhance congruency in the phase transition periods. (Sharma et al 2007: 8)

2.4.2 Organic

The advantages associated with organic materials have been known for a long time. Research within the last twenty years has shown the positive impact they can have in building materials. They are classified as paraffin and non-paraffin, with organic paraffin being the preferred substance as it is cheaper, more chemically stable and readily available.

2.4.3 Paraffin

Paraffin wax is composed of a chain of alkenes. The normal paraffins of type C_nH_{2n+2} are a family of saturated hydrocarbons with similar properties. Paraffins in the range C_5 to C_{15} are liquids and the rest are waxy solids. (Sharma et al 2005: 5) When the chain crystallises during the cooling phase of the thermal cycle, a large amount of latent heat is released. The latent heat stored can be varied by altering the melting point of the substance which for commercial grade paraffin waxes is in the range of 23-67^{o}C, and by increasing the number of alkanes in the chain. There is a wide selection of these substances available, each of which operating in a different temperature range. They are considered reliable and predictable materials as they melt congruently; do not portray super-cooling characteristics; and are safe during operation with appropriate containment.

When considering paraffin waxes for application in a building environment, there is need for a sealed containment strategy to be designed as they oxidise when exposed to oxygen. Another benefit of using organic paraffin is the long duration of phase change cycles. (Sharma et al 2007: 6) This time delay can help shift the peak loads in buildings energy consumption to off-peak times; reducing costs and improving energy conservation.

There are unfortunately some drawbacks with this material. High thermal conductivity is not a property found in all organic paraffins; they have a higher volume change in comparison to inorganic paraffins; and they are not compatible with all building materials. (Hawes et al 1992: 106)

2.4.3.1 Non-paraffin

Organic non-paraffin is the most readily available PCM of all. Numerous types are produced e.g. esters, fatty acids, alcohols, and glycols, each with varying performance and properties independent of each other. Low thermal conductivity is also a feature of non-paraffins and this requires using metallic fillers to improve their conductivity and thermal diffusivity. If exposed to high temperatures, flames or oxidising agents (Sharma et al 2005: 9), non-paraffins become very unstable and flammable; and additionally have fluctuating toxicity levels.

Reliable organic non-paraffins are found in the fatty acid subgroup; showing reproducible phase change cycles with high latent heat of fusion. This type of success though is achieved at a high cost, resulting in only technical grade non-paraffins and paraffins being utilised in building integrated latent heat storage systems. (Sharma et al 2007: 7)

2.4.4 Eutectics

A eutectic is a mixture of two or more substances which both possess reliable melting and solidification behaviour; and results in a congruent crystallisation process with consistency in the crystalline composition. The effects of repeated thermal cycling in eutectics does not appear to present performance degradation, such as super-cooling; and rarely does the solid to liquid transition phase produce uneven liquidity in the mixture as a result of the strong chemical composition; which experimental techniques used, such as Fourier Transform Infrared (FT-IR) spectroscopy, have shown that the accelerated phase changes during repeated cycling, fall in the same frequency band. (Sari, A 2006: 1218)

Recent studies have looked at binary phase change material composition, consisting of fatty acids. These substances have shown promise in their ability to maintain performance reliability for reasons such as suitable phase change temperature; high latent heat capacity; none or little observable volume change during phase change; and readiness in availability due to the common manufacturing materials i.e. vegetable and animal oils, necessary for their production. Several positive results were obtained from studying fatty acid eutectics. One concern was that the limited degradation that did occur within the chemical structure of some of these substances was mainly a consequence of specific impurities that were used during the preparation of the PCM mixtures. (Sari et al 2008: 906)

2.5 PCM applications

Two very important advantages have been discovered by using phase change material as a thermal storage media. These are:

- Increased magnitude of storage capacity;
- Discharge process is approximately isothermal. (Khudhair et al 2004: 268)

The advantageous characteristics provided by PCM are being put into affect in a variety of different applications. Their use can be either passive or active, where a passive system can utilise the thermal characteristics of a PCM to store and release solar energy and help reduce the level of electrical demand; and an active system involves using a PCM source container, which operating as a heat exchanger with either a fluid or air, can circulate to either absorb or release thermal energy.

2.5.1 Solar Water Heating System

This type of system has become very popular in research incorporating phase change materials. They are relatively inexpensive and simple to construct and maintain. During the daylight hours, the PCM melts and absorbs the thermal energy stored in the water as latent heat. This heat is released as the PCM changes from its liquid state to a solid state as a result of the hot water being replaced by cold water in the evening, so that the cold water temperature is increased. The problem with this system is that poor heat transfer between the water and the PCM prevents the cold water from being heated effectively.

Various studies have looked at ways to improve the rate of heat transfer between the water and the PCM. The most promising results have been achieved by using the salt hydrate PCMs, zinc nitrate hexahydrate, disodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate and sodium sulphate decahydrate; which showed 2-3 times better heat storage than conventional water heating systems. In addition to this result, it was found using a newly proposed solar water heating design, that by introducing water mass flow through a PCM store the heat transfer would increase; and thus increase the useful heat gain. (Sharma et al 2007: 12)

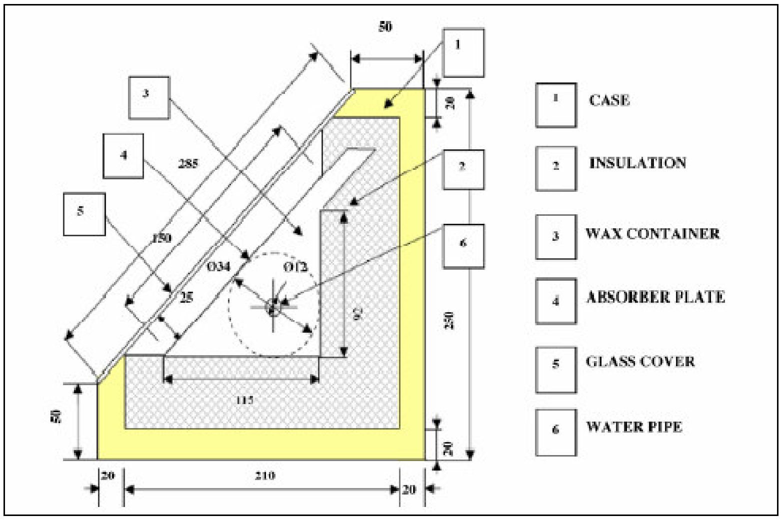

Figure 2 *Proposed Solar water heating system design using a Paraffin Wax PCM.*[2]

2.5.2 Solar Air Heating System

The application of PCM in solar air heating system has been researched experimentally to identify its effect on the thermal performance. Generally, solar air heaters show lower heat transfer efficiencies as a result of lower density and conductivity, and inadequate thermal volumetric capacity. The main outcomes of the studies carried out have shown that the phase change material should be selected based on its melting point rather than the latent heat produced; and that the storage volume in this type of system is considerably reduced.

The first commercial products incorporating PCM did not provide sufficient surface area for energy storage; and therefore the release of heat from the phase change as a result of solar heat gains and cooling, was not adequate to meet the corresponding demands of its environment.

---

[2] Sharma A et al, (2008), Review on thermal energy storage with phase change materials and applications, *Renewable and Sustainable Energy Reviews, p12.*

2.6 PCM application in buildings

The surface area available in building constructions for heat transfer however is far greater in comparison to encapsulated products; and for a passive building heating system, was found to be adequate relative to the demands. (Khudhair et al 2004: 266) The two main advantages listed above, highlight the integral role PCM could play as a component of building designs and applications; where large amounts of energy can be stored with minimal fluctuations in the transition temperature. As a result of the improved thermal performance gained from PCM incorporation, lighter and thinner building elements can be manufactured to take full advantage of this.

The three main areas that PCM has been introduced in building design are (i) Wallboard and concrete impregnation (using both macro and micro techniques of encapsulation); (ii) Components other than walls including window shutters and double glazing; (iii) Heat and cold storage units e.g. under-floor heating systems, night time cooling ventilation systems.

2.6.1 Trombe Wall

Applying a PCM in a buildings construction can utilise both the heat from external and internal solar energy gains and the energy produced by artificial heating and cooling systems. Effective storage of this energy is then required in order to match the energy demand of the building sufficiently and at the appropriate time.

Research has been carried out on various building applications to determine the effectiveness of PCM latent heat storage. The Trombe wall is an example of an indirect gains approach to passive heating which has been tested both experimentally and theoretically with the integration of phase change material. The working principal of a Trombe wall is based on sensible heat storage and can be seen in the diagram below. A piece of glass is placed on the exterior surface of a masonry wall with a thin air gap separating the two materials. The face of the wall is painted black so as to absorb the solar energy; which is then stored and conducted through the wall over the period of the day. As the evening approaches and the internal temperature of the building drops, heat will radiate into the building from the wall over several hours.

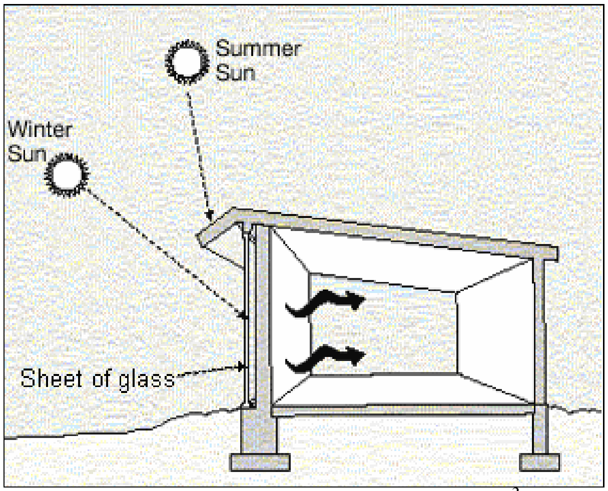

Figure 3 *Schematic of a Trombe Wall.*[3]

Trombe walls are generally built using either masonry or water in order to deliver the appropriate thermal energy from sensible heat storage. This requires large areas of space in order to construct the walls. For this reason, the greater heat storage per unit mass provided by PCM is seen as the ideal property which can replace or be incorporated into the existing systems; and optimise the space for other practical uses. Thinner phase change material walls are also much lighter in weight in comparison to the traditional materials used. These factors offer convenience and attractive reductions in the construction costs associated with retrofit applications (Tyagi et al 2005: 1153); which should be considered as an intrinsic method of improving energy conservation in older existing buildings.

Investigations have reported that the integration of thin layers of PCM in this type of application are more effective than thicker masonry walls; with an exemplar 8.1cm wall showing improved thermal performance when compared to a 40cm wall. (Sharma et al 2007: 17)

---

[3] Trombe wall image, www.apps1.eere.energy.gov

2.6.2 PCM Wallboards

During the last decade interest has again been shown in the energy saving potential achieved when combining PCMs into the wallboard materials of building construction. Wallboards are capable of capturing a large proportion of incident solar radiation falling on building surfaces. They are also cheap and are used in a wide variety of applications, but limited analytical studies of PCM wallboard have been conducted; and have not provided enough insight into the thermodynamic behaviour of the products available. (Neeper 2000: 393) Some studies of wallboard materials impregnated with PCM have shown promising results in terms of thermal performance but also in the effectiveness of the manufacturing processes used to build these types of components.

Most of the studies originally carried out focused on macro-encapsulated PCM wallboards or wallboard that had been immersed into a molten PCM store; which as already mentioned proved ineffective. However more recent developments have shown improved structural and thermal performance reliability. The three main types of process used to incorporate PCM into building materials are described below:

2.6.3 Macro-encapsulation

The effective containment of PCM in building materials has always been an important design parameter. Ensuring the structural reliability i.e. the PCM does not adversely affect the primary function of the construction material, and safety of the occupants within the building envelope is a key issue considered during the container design and PCM selection phase. In addition to these factors, balancing the cost of designing safe and effective encapsulated PCM systems has always been a difficult process.

Macro-encapsulation integrates the phase change material in some form of packaging, usually tubes, pouches, panels or some other type of receptacle; and then incorporated into the chosen building material or simply to act as a direct heat exchanger in an active heating system. (Khudhair et al 2004: 271) This is an expensive method of encapsulation as it requires energy intensive methods of integration into building materials; and protection from external factors such as building maintenance. (Zhang et al 2007: 2204)

The thermal performance of macro-encapsulated PCMs studied has shown poor heat transfer efficiency mainly due to the inherently poor conductivity associated with several phase change substances; and incongruent solidification during the cooling process which would prevent complete thermal discharge during the overnight period. (Schossig et al 2005: 298)

2.6.4 Immersion

Porous building material such as gypsum and plasterboard, brick, or concrete block is dipped into a molten PCM source, absorbing the material into pores by capillary action. The building material is then removed from the PCM source and is cooled, allowing the PCM to set. The great advantage of this method is that it enables ordinary wallboard to be converted to PCM wallboard simply, inexpensively, and when it is required i.e. imbibing the material either prior to installation or at the building site. Despite these benefits, the problem of leakage of the PCM in the housing material has been observed as a potential problem after repeated thermal cycling. (Zhang et al 2007: 2203) Empirical study has examined the potential of developing and using absorption constants for PCM impregnation in concrete, in order for the correct amount of PCM to be utilised and help prevent this problem.

2.6.5 Micro-encapsulation

This approach to encapsulation is similar to the macro type with the difference being in the dimensions of the PCM packaging. Smaller spherical or rod-shaped particles are enclosed in a thin, high molecular weight polymeric film; with a diameter of a few micro-metres (average of 8μm). (Zhang et al 2007: 2204)

Micro-encapsulation is an economical process in comparison to macro-encapsulation, as the technical difficulty associated with integrating the capsules into the wall construction material is reduced. The type of material used to encapsulate the PCM must be compatible with the PCM and building material; and additionally it must not impact on the mechanical strength of the building structure.

These issues are being resolved progressively with the development of new capsule materials. Formaldehyde free micro-encapsulation of paraffins enables easy integration into conventional construction materials and removes concerns of incompatibility. (Schossig et al 2005: 298)

The effectiveness of the heat transfer is improved using a micro-encapsulated method of impregnation due to the easier distribution of smaller capsules. (Cabeza et al 2007: 114) The heat exchange can take place over a larger surface area mainly by conduction; and incomplete phase change in the material can be avoided, preventing the potential problem of super-cooling. Below is a diagram illustrating the construction of a lightweight wallboard using micro-encapsulated PCM:

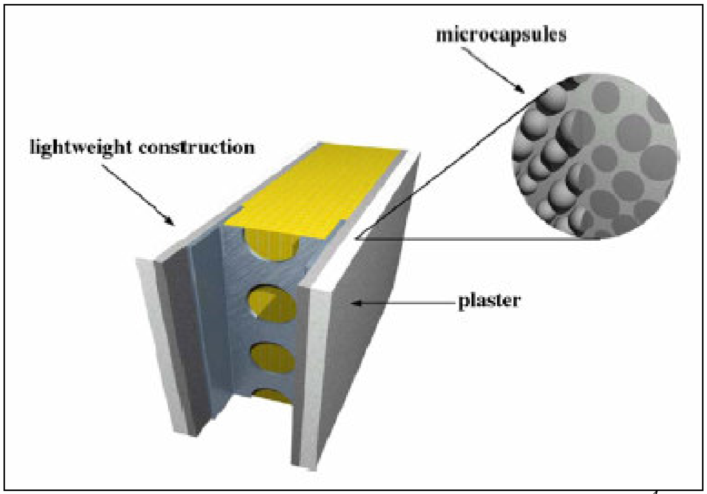

Figure 4 *Schematic of a lightweight PCM wallboard.*[4]

---

[4] Schossig P et al, (2005), Micro-encapsulated phase change materials integrated into construction materials, *Solar Energy Materials and Solar Cells,* p299.

3 Description of Investigation

Provision of comfortable indoor thermal conditions is commonly achieved by employing either passive cooling strategies or active cooling mechanisms such as air conditioning systems or fans. Attaining and sustaining human thermal comfort conditions through the use of electrical cooling is a process taking place on a daily basis in the warm summer conditions experienced in the Mediterranean climate.

From the literature review carried out, studies which have looked at the influence that PCM impregnated walls have in helping to achieve the preferred human comfort conditions, have mainly focussed on their incorporation in passively cooled environments located in milder climates; with night time ventilation utilising off-peak electricity to displace the stale warm air with fresher, cooler air. This method of 'air conditioning' relieves the pressure on generation plants during the day described earlier; and assists in making savings in terms of greenhouse gas emission reductions, and at the domestic level where lower electricity tariffs will be charged.

This type of system however does not operate as effectively in much warmer climates. Higher indoor air temperatures resultant from greater solar gains and the natural infiltration of warmer air during the course of the day are not countered as successfully from the use of the night time ventilation process described above. This is mainly due to the night time outdoor ambient air temperature not decreasing sufficiently to allow this forced convection method to operate optimally in reducing the internal dry bulb temperature. With higher ambient air temperatures being experienced during the summer period in these locations, partly as a result of ongoing human induced climate change, more and more building occupants are turning to air conditioning system installations to provide the required cooling. Consequently, the constant rise in peak time electricity demand observed from the use of this technology is resulting in more frequent blackouts and energy shortages in these regions.

This project has been carried out essentially to investigate the ability of phase change materials, with a range of thermal properties, to moderate peak internal room temperatures and cooling loads when they are integrated into a buildings wallboard material. Simulating the chosen materials in passively cooled conditions initially will determine the overall impact that the PCM has on reducing the internal dry bulb temperatures. Comparisons can then be made between the thermal performance of the material in naturally cooling conditions and those observed in a mechanically cooled environment to assess whether or not the original performance can be sustained or improved upon. The incorporation of PCMs into a model operating an actively cooled environment under Mediterranean climatic conditions is proposed in this investigation as a solution to help reduce the required diurnal cooling loads.

3.1 Description of Model

In order to identify the benefits of integrating phase change materials into the wallboard of a building, a testing model was developed on the building energy simulation package ESP-r. The model consists of two detached zones with identical structural and operational features. The idea was to incorporate the phase change material into one of the zones, whilst the other would serve as a reference zone in order to gauge the effect of the PCM on cooling load reductions and moderating internal room dry bulb temperature.

The simulations were carried out to observe the impact of the PCM when both of the zones were operating either under passively or actively cooled environments. The following factors listed below have been identified as the possible sources which would have the greatest impact on the internal dry bulb temperatures experienced in a passively cooled environment:

- Fluctuations of the ambient outdoor air temperature;
- Direct and indirect solar heat gains absorbed by the building structure;
- Casual heat gains produced by the occupants' activities.

For the case of an actively cooled building, the internal air temperature of the room is to be maintained at a constant set point which for the purposes of this investigation is 24^{o}C. The load that is necessary to maintain this temperature is equally dependent on the factors listed above.

3.1.1 Operational Details

The model was designed so that air would filter into and out of the zones naturally, and this process has been accounted for in the simulations by setting the number of expected air changes per hour (ac/h). The daytime period infiltration rate, considered to be during the occupied hours in both of the zones (0900hrs – 1800hrs) was set at 1 ac/h; and for the hours outside of the daytime period, a night time infiltration rate was set at 4 ac/h.

The active cooling system comes into effect when the internal dry bulb temperature of a zone exceeds 24^{o}C; and operates during the occupied hours previously specified. The maximum cooling capacity has been set at 10kW.

3.1.2 Climate Boundary Conditions

The climate data for Madrid in 2001 was selected to define the environmental conditions for the simulations. The simulation period chosen was between 1st June and 30th September. From the initial climate analysis carried out on the selected weather data, this was the period displaying the highest peak ambient air temperatures and was deemed a suitable period for simulating. For the four months specified, the peak ambient temperatures are as follows:

June= 33.9$^{\mathbf{o}}$**C**;
July= 39$^{\mathbf{o}}$**C**;
August= 40.3$^{\mathbf{o}}$**C**;
September= 30.7$^{\mathbf{o}}$**C**;

A graphical representation of the Madrid climate in 2001 is shown below.

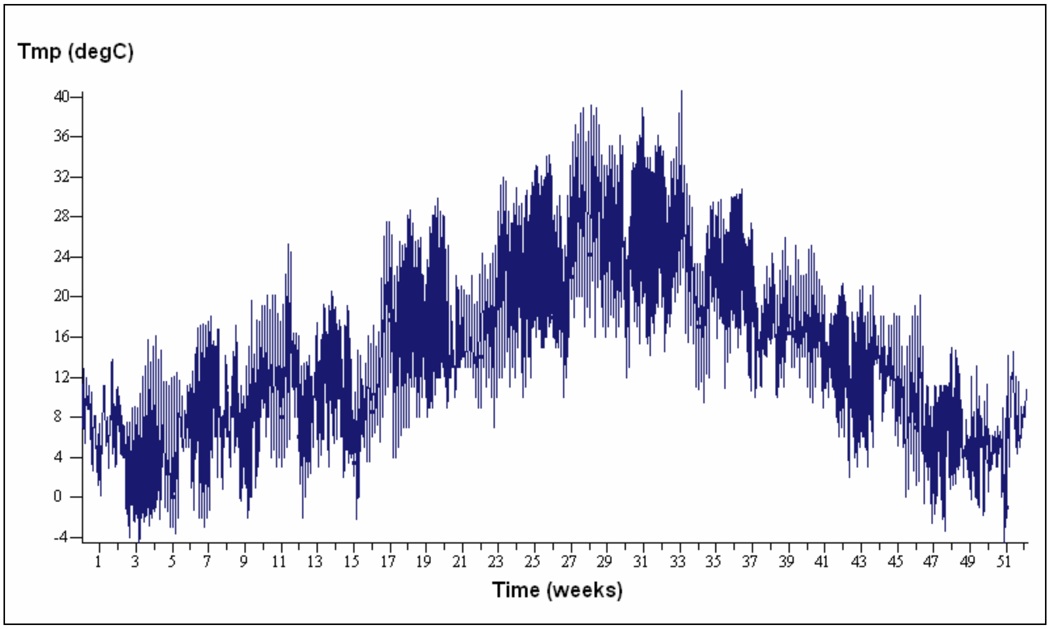

Figure 5 *Annual Ambient db Temperatures; Madrid 2001.*

Residential and commercial buildings would have air-conditioning units operating at their highest rate during this period and hence this is an ideal time to observe the level of impact that a latent heat storage system has on reducing cooling loads in air conditioned buildings. Additionally in a passively cooled environment, the differences produced in internal dry bulb temperatures for both zones would be most prominent here as well; and would highlight the basic advantages of latent heat storage systems in comparison to simply using sensible heat storage materials. For both the passive and active cooling scenarios, the thermal characteristic modifications which may be necessary to help improve certain aspects of the thermal performance of the phase change material will become apparent during this period.

3.1.3 Model Construction Materials

The construction of both zones was based on a typical Spanish residential construction. The material specification for the external walls can be seen in the cross sectional diagram below; and the material specification of the ceiling and floor surfaces of the modelled zone can be found in **Table 1** and **Table 2** below.

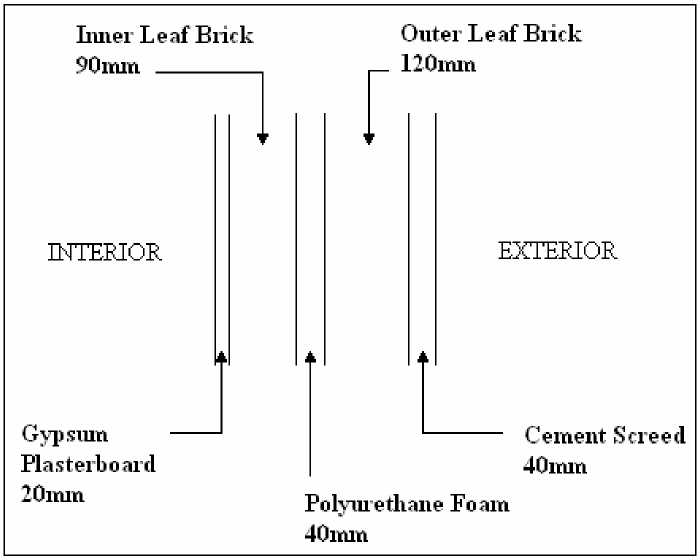

Figure 6 *Cross-section of external wall.*

Layer	Material	Thickness (mm)
1	Floor Tiles	15
2	Cement Screed	90
3	Heavy Mix Concrete	150
4	Gravel	150
5	Earth	250

Table 1 Floor construction for Zones A and B.

Layer	Material	Thickness (mm)
1	Clay Tile	30
2	Asphalt	30
3	Polyurethane Foam	40
4	Softwood	25

Table 2 Ceiling construction for Zones A and B.

The diagram below shows a schematic of the model design.

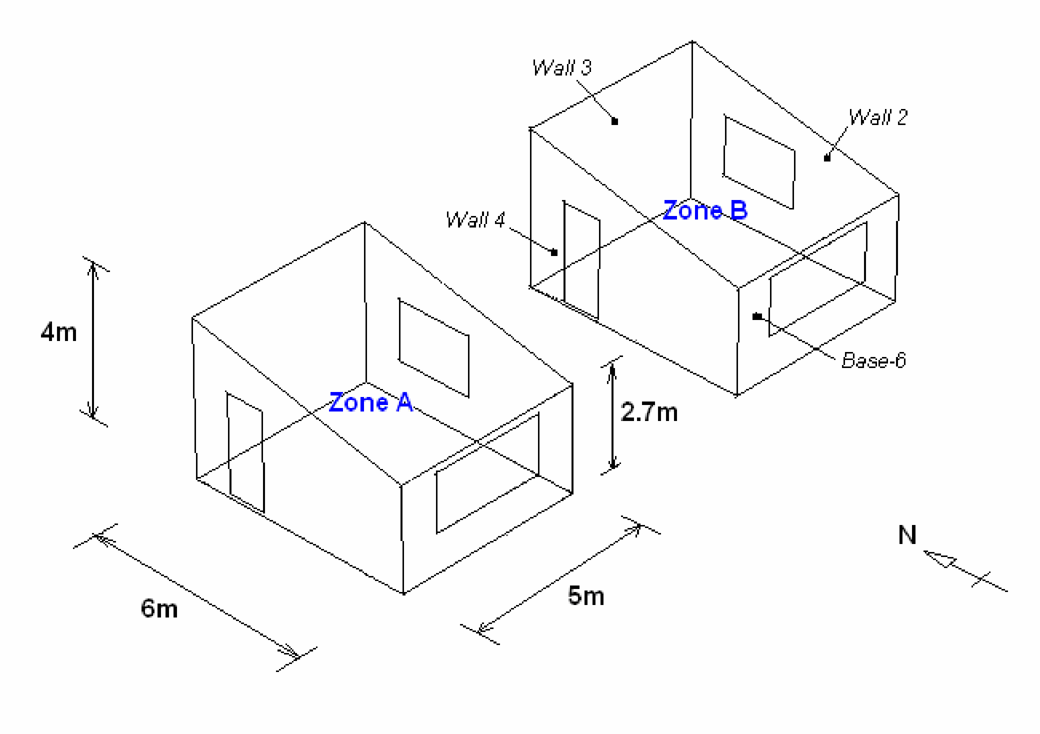

Figure 7 *Schematic diagram of ESP-r model.*

3.2 Simulation Process

Phase Change Materials are incorporated into the ESP-r programme using the *Active Materials* option, found within the section defining the *Composition* of the model construction. The process of integrating a phase change material into the construction of the model requires entering specific information on that material. The data required for the simulation is listed below:

T_m (^oC): Temperature at which the PCM begins to melt;
T_s (^oC): Temperature at which PCM is fully charged;
k_m (W/mK): Thermal conductivity at T_m;
k_s (W/mK): Thermal conductivity at T_s;
C_s (J/kgK): Specific Heat Capacity;

The final pieces of data requested by ESP-r require entering the thermal gradient of the phase change process; and the latent heat of the material during the transition temperature range. During this temperature range the latent heat of fusion of the material can be constant or vary linearly as a result of the thermal gradient produced during the transition temperature range of the material. These parameters are represented by ESP-r in the equation shown below:

$$\rightarrow \textit{Latent Heat} = a(x) + b$$

a = J/kg.K^2

b = J/kg.K

The method referred to by ESP-r for calculating the thermal gradient and the latent heat generated during the transition phase of the PCM is the Effective Heat Capacity Method. This method requires several thermal properties of the chosen PCM for solid and liquid states, such as the specific heat capacity; and the corresponding temperatures at these points.

Another existing method used to calculate the latent heat stored as a result of the PCM changing state is known as the Additional Heat Source Method. This assumes a heat flux in the PCM impregnated surface relevant to the latent heat stored or released. This flux is negative when the energy is stored and positive when the latent heat energy is released. (Heim 2005: 398) The graphical representations below highlight the two different methods that have been described.

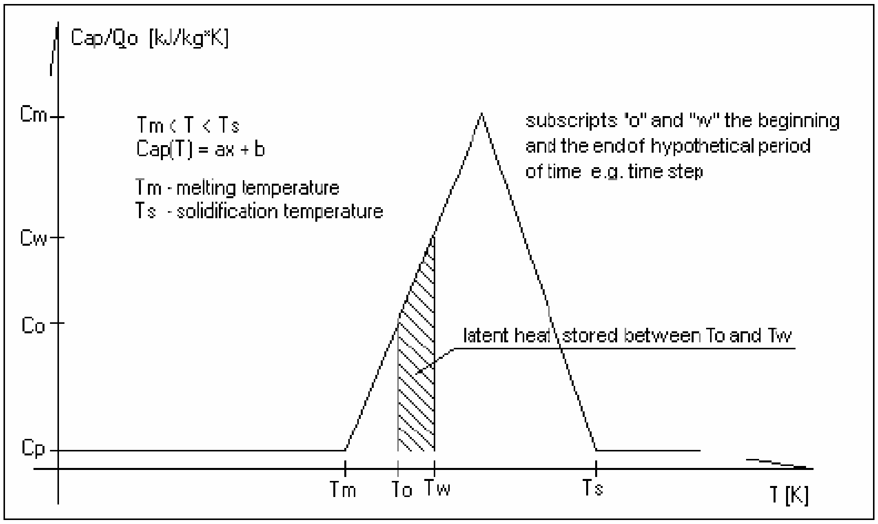

Figure 8 *Effective Heat Capacity Method.*

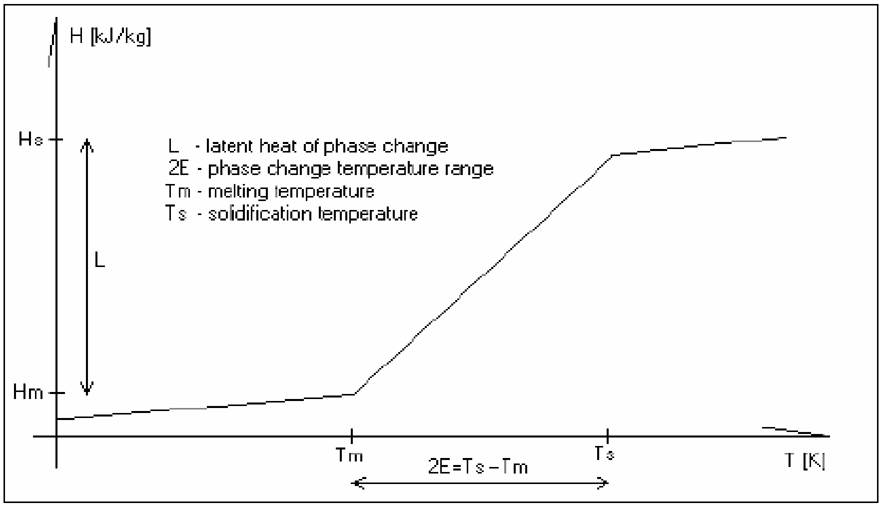

Figure 9 *Additional Heat Source Method.*[5]

As already mentioned the phase change material is incorporated into the building construction as an *active material*; and applied to a specific node in a selected layer of the building envelope construction. The node chosen is then subject to a time variation in its defined thermal properties in order to accommodate the phase change behaviour. (Heim et al 2004: 797) The internal surface lining of the zone construction was chosen to apply the active material characteristics of the PCM in this investigation. The PCM-gypsum plasterboard composite could only be associated with a single layer of a specified surface per zone. The location of the PCM was

---

[5] Heim D, (2005), Two solution methods of heat transfer with phase change within whole building dynamic simulation, *Building Simulation,* p2.

varied during the simulation process in order to identify if the material operated more effectively in certain parts of the zone i.e. ceiling, floor.

Three PCMs were selected from the literature review that was carried out and their thermal properties are tabulated below. PCM1 was an organic material; PCM2 was an inorganic substance; and PCM3 was an inorganic eutectic.

Name	**T_m (^oC)**	**T_s (^oC)**	**k_m(W/mK)**	**k_s (W/mK)**	**C_s (J/kgK)**	**Latent heat of fusion (kJ/kg)**
PCM 1	*25*	*27*	*0.2*	*0.2*	*2450*	*116000*
PCM 2	*27*	*29*	*0.79*	*0.48*	*1800*	*103500*
PCM 3	*26*	*28*	*1.1*	*0.54*	*1440*	*94000*

Table 3 Properties of PCMs used in simulations.

ESP-r allows one phase change material at a time to be applied to a particular node in a specified multilayer surface; and can only be incorporated into one zone every time a simulation is run. Each PCM composite was assumed to have a constant latent heat of fusion value.

The lining of gypsum plasterboard in the surfaces labelled Wall-2, Wall-3 and Wall-4 in Zone A has been selected for applying the PCMs during all of the simulations. Surface Base-6 was also chosen for applying the PCM. Most of the internal surfaces of buildings are not illuminated directly by the sun, and therefore these surfaces were chosen due to their larger surface areas where the PCM is considered to be more effective. The thermodynamic behaviour of each zone would then be monitored in terms of the fluctuations of internal dry bulb temperature with and without mechanical cooling; and as a result of the heat transfer by convection and radiation within the zones. The results produced from the simulations were recorded using a 15 minute time step.

4 Simulation Results and Analysis

4.1 Results: PCM 1 applied to surfaces in Zone A; Zones cooled passively;

The initial simulations were conducted to analyse the difference in the internal zone temperatures achieved under passive heating and cooling conditions; which demonstrate the thermal buffering effect achieved when incorporating one of the PCMs into the wall lining. The maximum resultant room temperatures experienced for each month of the period simulated; and the resultant mean temperature differences between the surface incorporating PCM and the equivalent surface in the other zone, is shown in the tables below for the period of simulation.

PCM applied Surface: *Wall-2*

Period:	**June**		**July**		**August**		**September**	
Zone:	A	B	A	B	A	B	A	B
Max Tmp	34.19	34.86	38.19	38.77	38.55	38.82	34.57	35.39
Mean Tmp Diff	-0.59		-0.85		-0.79		-0.23	

Wall-3

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
34.17	34.86	38.19	38.77	38.55	38.82	34.57	35.39
-0.61		-0.84		-0.77		-0.2	

Wall-4

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
34.2	34.86	38.19	38.77	38.55	38.82	34.58	35.39
-0.61		-0.84		-0.8		-0.2	

Floor

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
33.68	34.85	38.17	38.77	38.51	38.82	33.7	35 39
-0.46		-0.96		-0.76		-0.38	

Table 4 Maximum db Temperatures in zones; Average db temperature difference.

4.1.1 Impact of Climate on Internal Temperature fluctuations

The effect the PCM has on reducing the internal zone temperature in Zone A is relatively small during the months of June and September. The average of the mean zone temperature differences found for each of the monitored surfaces in June and September are -0.57 and -0.25 respectively. Direct solar radiation absorbed by the internal surfaces in the zones is low between June and September and therefore is not influencing the thermal behaviour of the PCM greatly.

From the initial climate graph for Madrid, it is seen that June and September are the transitional periods between seasons and the ambient outdoor temperature range is much lower than in July and August. The simulation results up until the mid-point of June showed that the PCM was not activated fully due to the surface temperature not reaching the melting point of the material; and both zones performed identically. The average diurnal ambient air temperature for June was 20.61^{o}C and thus the internal zone temperatures remained below 25^{o}C on average. Cooler night time air ventilated into the zones and low absorption of solar radiation helped to maintain these conditions.

Fig.10 presents a comparison between the internal temperature profiles of the two zones; and Fig.11 shows a comparison between the surface temperature profile of Wall-4 (for PCM1 applied in Wall-4 in Zone A) during the last week of June at which point the thermal response of the PCM has already commenced.

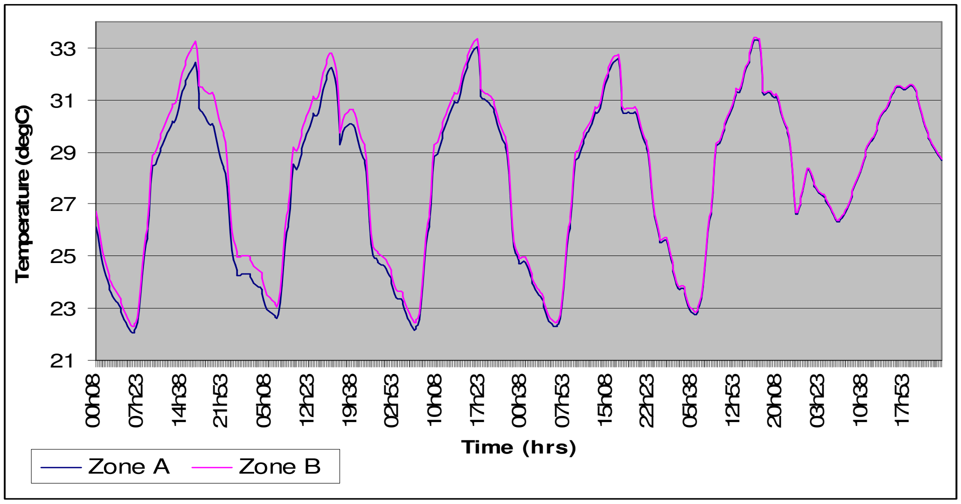

Figure 10 *Graph representing the internal room temperatures in Zone A and B.*

Fig.10 shows how the thermal effect of the PCM impacts on the zone temperatures. Although the room temperatures have surpassed the human comfort temperature range of 16-25^{o}C, additional night time ventilation could be introduced to improve this situation. The higher daytime temperatures are a combined result of the casual internal gains during the occupied hours and primarily as a result of increased outdoor temperatures; which on average was 3 degrees centigrade higher than at the beginning of June. As this warmer air is circulated into the zones, the average internal temperatures rise accordingly. For the period of July the average temperature was 29.5^{o}C and in August this was 28.5^{o}C. The higher internal zone temperatures were sustained during the day and night time periods during July and August and prevented surface temperatures falling to the solidification point of the PCM.

4.1.2 Internal Zone Temperature impact on Surface Temperatures

This rise in ambient temperature gradually starts to prevent the optimum performance of the PCM. The natural ventilation occurring during the day increases the internal temperatures of the zones to a maximum 34^{o}C; and with higher outdoor temperatures in the evening, the cooler air that passes through the zones does not reduce the internal dry bulb temperature sufficiently before the outdoor temperatures increase again. This prevents effective heat transfer by free convection from the PCM lined surface to the air. The small temperature difference between the air and wall surface reduces the rate of heat flux from the wall to the air. From Fig.11 below, it can be seen that the surface temperature will not drop below 25^{o}C to enable the PCM to discharge the stored latent heat completely during its transition range; and thus the cyclic PCM latent heat storage capacity is defective if the PCM maintains a fully loaded state.

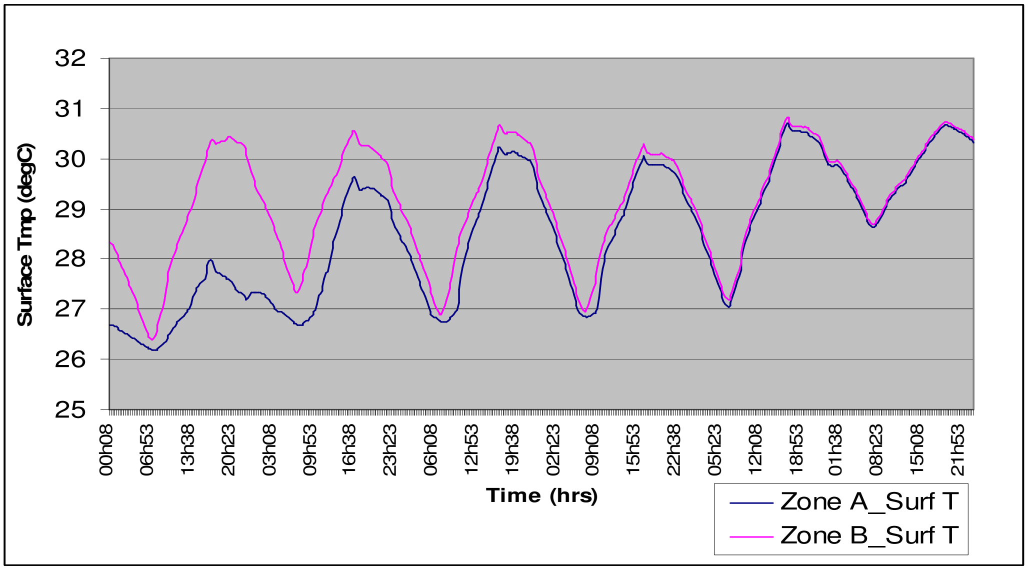

Figure 11 *Graph representing the surface temperatures of Wall-4.*

In Fig.12, the node temperature profile, where the PCM was applied in Wall-4, emphasises the fact that the PCM was not able to discharge. The phase transition temperature range of the PCM is not reached as a result of progressive warming of the outdoor and indoor climate. The PCM was thereafter fully loaded and unable to absorb any of the heat flux at the wall surface using its large latent capacity, and its thermal behaviour mimicked that of a plain solid material such as was used in Zone B; utilising its sensible heat capacity for the rest of the simulation.

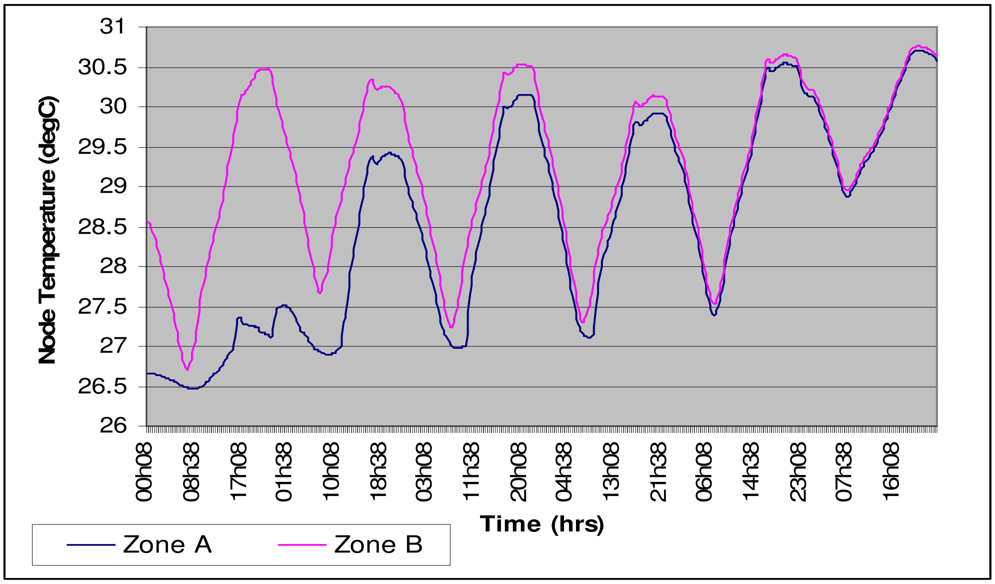

Figure 12 *Graph of node temperatures in PCM applied Wall-4 and regular Wall-4.*

This thermal performance was replicated in Wall-2 and Wall-3 of Zone A when PCM1 was applied to the same node in the gypsum plasterboard. Over a prolonged period of thermal cycling, this type of behaviour is a potential threat to the effectiveness of the PCM. Continued excessive heating of the PCM may lead to super-saturation, resulting in a higher proportion of liquid to crystal particles in the melted state. This may alter the specific heat capacity of the material during the solidification phase and in affect consign the PCM redundant.

PCM1 was also applied to the floor surface, where the surface temperature in each zone is relatively cooler in comparison to the other surfaces during this period. However due to the PCMs low thermal conductivity of 0.2W/m.K, a common disadvantage associated with organics, for both liquid and solid phases, and high specific heat capacity, complete melting did not take place and therefore the material performed as a sensible heat storage material after the phase change had occurred. The thermal resistance provided by the ceramic floor tiles is another contributing factor to this poor heat transfer process. The performance is identical to the floor surface of Zone B throughout the simulations. This shows that a higher thermal conductivity in the solid phase is a necessary property for the PCM to function effectively and efficiently.

4.2 Results: PCM 1 applied to surfaces in Zone A; Zones cooled actively;

Period	June		July		August		September	
Zone	A	B	A	B	A	B	A	B
Applied Surface	East		East		East		East	
Cooling Hours (kWhrs)	-146.17	-153.43	-313.05	-313.31	-300.1	-297.66	-126.84	-125.54
Hours	200.5	200.3	225.3	224.5	231.3	230.3	181.5	169.3
Average Cooling Load (kW)	-0.2	-0.21	-0.42	-0.42	-0.4	-0.4	-0.176	-0.174
Max Indoor Tmp	30.68	30.86	33.3	33.3	33.52	33.52	30.02	30.68
Min Indoor Tmp	17.69	17.69	23.5	22.92	22.78	21.88	18.16	17.44

A	B	A	B	A	B	A	B
Floor		Floor		Floor		Floor	
-152.48	-152.58	-310.14	-313.83	-297.53	-298.39	-125.59	-125.55
200	200	224.3	224	230.5	230.3	170.5	168.8
-0.21	-0.21	-0.41	-0.42	-0.39	-0.4	-0.17	-0.17
30.65	30.83	32.64	33.28	32.9	33.44	30.22	30.55
17.69	17.69	22.98	22.92	22.18	21.92	17.45	17.55

A	B	A	B	A	B	A	B
West		West		West		West	
-145.53	-153.43	-313.26	-313.31	-299.66	-297.66	-128.55	-125.54
200	200.3	225	224.5	231	230.3	182.3	169.3
-0.2	-0.21	-0.42	-0.42	-0.4	-0.4	-0.17	-0.17
30.83	30.85	33.33	33.33	33.53	33.53	30.1	30.7
17.69	17.69	23.42	22.92	22.58	21.88	18.23	17.44

A	B	A	B	A	B	A	B
North		North		North		North	
-145.2	-152.55	-313.02	-313.83	-301.97	-298.4	-127.05	-125.54
200.5	200	225.3	224	231.3	230.3	180.5	168.8
-0.2	-0.21	-0.42	-0.42	-0.4	-0.4	-0.17	-0.17
30.1	30.8	33.28	33.29	33.44	33.44	29.82	30.55
17.69	17.69	23.66	22.92	22.93	21.92	18.1	17.5

Table 5 Cooling load requirements; Average Cooling loads; Max. and Min. db Temperatures.

The energy used for air conditioning systems in the Mediterranean climate increases annually. During the occupied hours scheduled air conditioning was used in the zones to maintain the internal room temperature at 24^{o}C. The cooling loads required for each month over the simulated period are shown in the tables above.

4.2.1 Impact of PCM on required cooling loads

Focussing only on the occupied hours in this section, it can be seen from the results tables that the differences in the required cooling between the two zones are very small. During the month of June the thermal effect of the phase change material helps to decrease the overall cooling load required to maintain the set point of the air conditioning system.

The thermal energy is being absorbed by the PCM during and after the cooling hours as it is able to operate within its specific transition range and helps to keep the air temperature lower after cooling has ceased.

As the climate gets warmer though at the end of June, the PCM surface temperature remains approximately isothermal on a diurnal basis. The air conditioning is preventing the warm air naturally ventilated into the building from interfering with the performance of the PCM as the surface and node temperatures in the wall lining do not exceed 27^{o}C and remain more or less constant at 26^{o}C. During the same period but in the initial passive environment simulated, heat transfer was taking place from the room to the surface of the wall due to the room air temperature being higher than the surface temperature; but this heat transfer became independent of the thermal effect provided by the PCM and solely dependent on the ambient dry bulb temperature variations and its sensible heat capacity as has been described.

4.2.2 Impact of air conditioning on PCM

Fig.13 is showing an example of the thermal behaviour of Wall-3 in zones A and B. The temperature difference between the internal room temperature and the wall surface for the end of June is maintained approximately at 2 degrees centigrade during the occupied hours; the average surface temperature being 25.94^{o}C. This smaller temperature gap is sustained during the course of the occupied hours and prevents the ideal surface temperature conditions for the PCM to function correctly from being reached. The limited fluctuations developed over this period, representing the temperature of the PCM, is a result of saturation, where an equilibrium state between the dissolved crystals and the remaining solid part of the material has formed. The

PCM is unable to reach its completely liquid phase when the room temperature increases from the set 24°C; and it is unable to discharge fully within the resultant temperature range in the zone. The narrow temperature gaps do not induce the thermal energy required by the PCM for a full response due to its high specific heat capacity. Thus the PCM was once again only varying in temperature as a result of sensible heat storage.

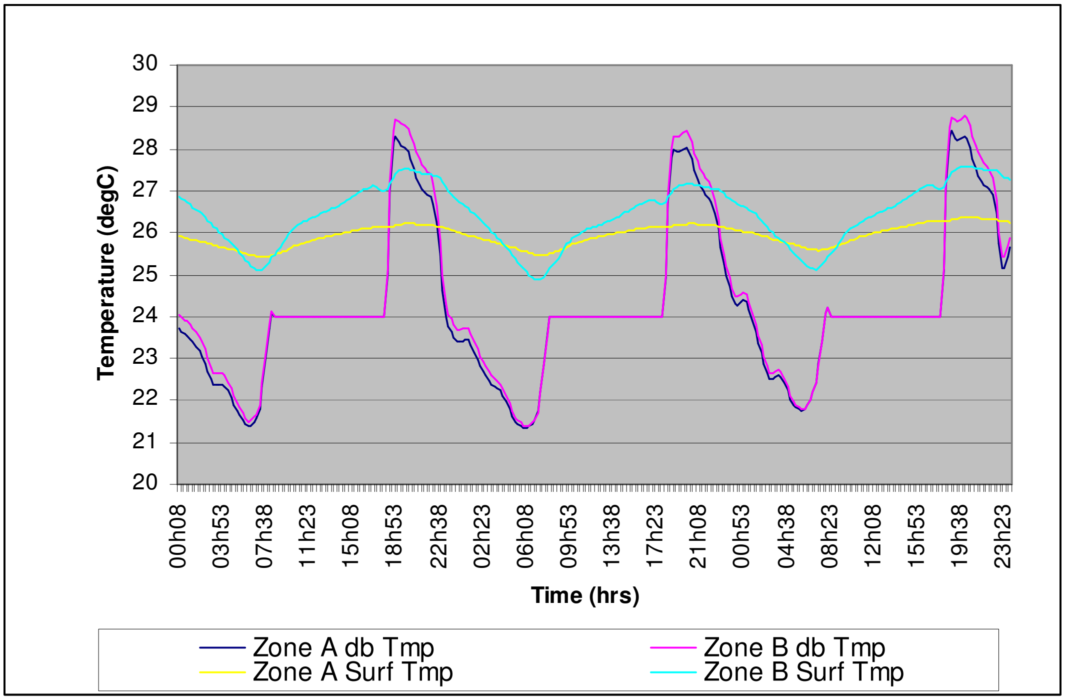

Figure 13 *Graph showing relationship between Surface and Internal db temperature.*

As the room temperature falls below the melting point of the PCM in the evenings, the surface temperature begins to drop as heat transfer by free convection from the wall surface takes place. The cooler night time air being circulated in the zones brings the internal temperature down, enhancing the heat transfer process and displacing the latent heat energy being discharged into the room from the PCM. From the graph it can be seen that the internal dry bulb temperature within Zone A was lower during the hours of natural ventilation. Low thermal conductivity in the liquid phase results in a reduced rate of conductive heat transfer between the PCM layer and the internal surface of the wall; which shows the enhanced sensible heat storage capacity of the PCM in comparison to the normal wall in Zone B. The high latent heat of fusion property of PCM1 also, over this phase change temperature range, prevents the completion of the phase change process and so is an aspect of PCM design which needs to be considered carefully for this type of application.

4.2.3 Impact of diurnal temperature fluctuations on PCM response

Figures 14 and 15 illustrate once again that during the hottest parts of July and August, the PCM became fully loaded as the surface temperature did not drop to the transition temperature range of the PCM. The surface in Zone A acts identically to the same plain surface in Zone B and a convective heat exchange takes place from the wall into the room purely as a result of the greater temperature differential produced whilst the air conditioning is operating. The constant mechanical and buoyant forces driving the air flow within the zones coupled with the large diurnal room temperature fluctuations taking place during and after the cooling hours prevent the phase change from occurring. The material is unable to adjust its latent heat of fusion whilst this convection is taking place as it is in a superheated state, thus remaining in a steady state.

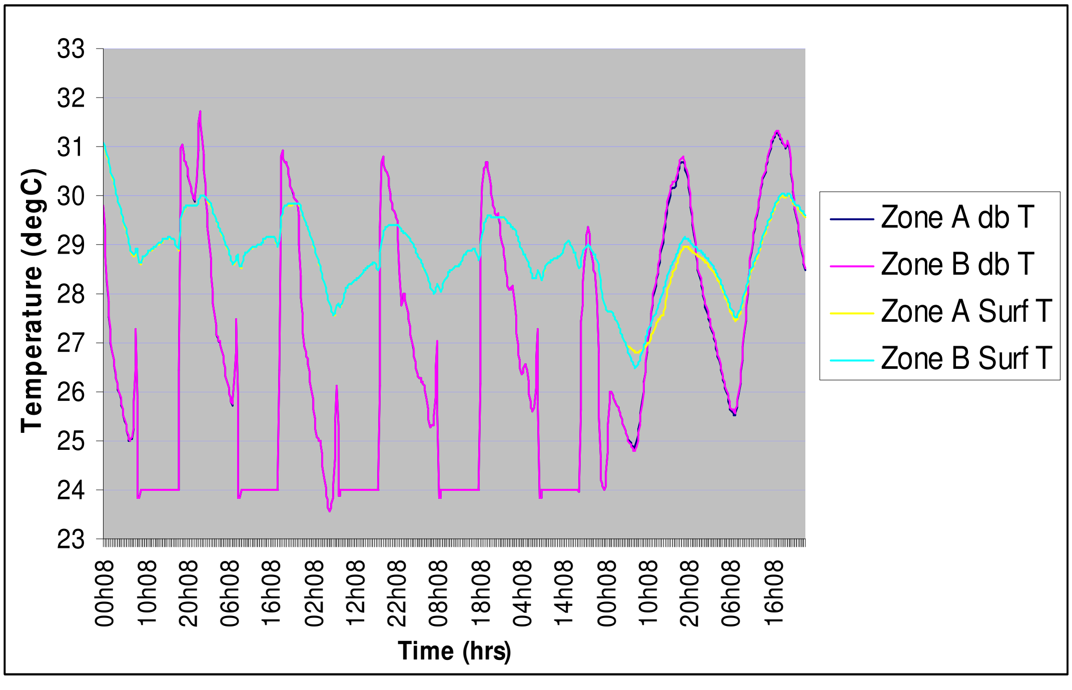

Figure 14 *Surface and Internal db Temperatures for Wall-3 with and without PCM1 Period: July.*

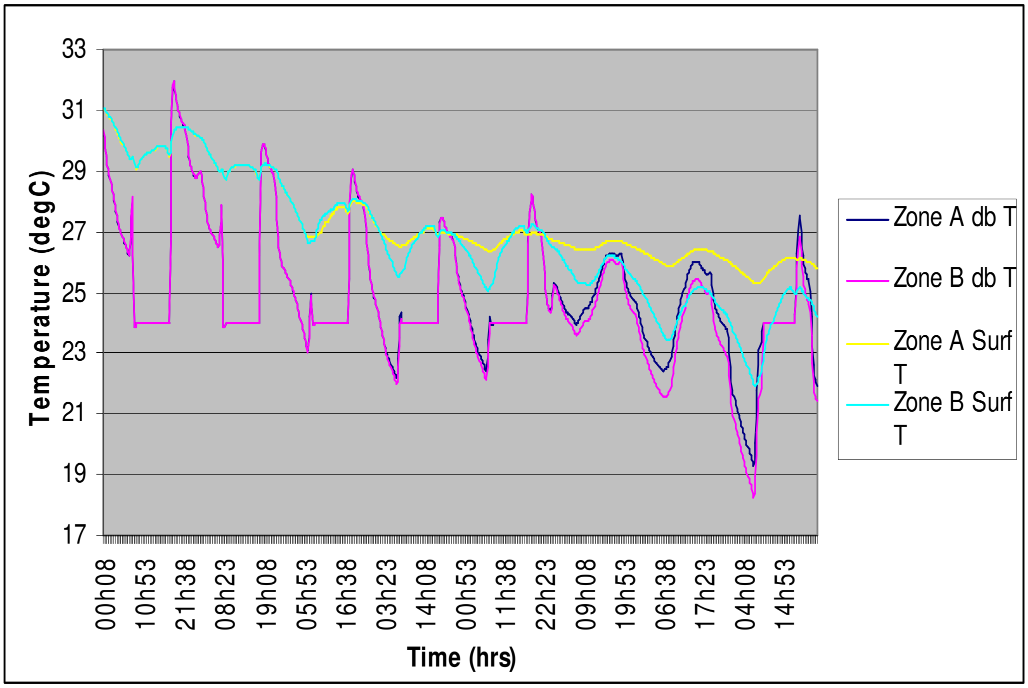

Figure 15 *Surface and Internal db Temperatures for Wall-3 with and without PCM1. Period: August.*

The response of the PCM was dependent on the outdoor temperatures falling sufficiently in the evenings so that the internal convective flux from the surface would increase as the internal room temperature decreased.

4.2.4 Impact of PCM location on heat transfer process

As the outdoor climate cools in September, the cooling loads are reduced to similar levels achieved in June. The surface and applied PCM node temperatures are on average at 24.1^{o}C and increase to a maximum of 28^{o}C for the vertical surfaces simulated; and an average of 23^{o}C and a maximum of 27.5^{o}C for the floor, which are suitable for the phase change properties of this particular material.

With lower maximum daytime surface temperatures, positioning this PCM into the floor resulted in lower cooling loads during July and August in comparison to the vertical wall PCM integration. With a higher thermal conductivity in the solid phase of the material, there is potential to further reduce the required cooling load as the phase change process would occur when the PCM surface temperature is closer to the temperature of the air inside the room. However in September the behaviour of the

PCM impregnated floor in Zone A was identical to the plain floor surface in Zone B as the heat convection taking place was less than the heat being conducted through ground. As a result of the low thermal conductivity in the solid state the rate of heat transfer necessary to achieve a change in state during the phase change range is not great enough with such high specific heat capacity and latent heat of fusion properties; and so the PCM behaviour resembles that of a plain surface.

4.3 Results: PCM 2 applied to surfaces in Zone A; Zones cooled passively;

PCM applied Surface *Wall-2*

Period:	**June**		**July**		**August**		**September**	
Zone:	A	B	A	B	A	B	A	B
Max Tmp	33.1	34.86	38.15	38.77	38.51	38.82	33.57	35.39
Mean Tmp Diff	-0.61		-1		-0.69		-0.17	

Wall-3

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
33	34.86	38.14	38.77	38.5	38.82	33.49	35.39
-0.59		-1.1		-0.67		-0.14	

Wall-4

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
33	34.86	38.17	38.77	38.52	38.82	33.64	35.39
-0.66		-0.97		-0.7		-0.1	

Floor

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
34.2	34.86	38.2	38.77	38.55	38.82	34.59	35.39
-0.42		-0.83		-0.82		-0.47	

Table 6 Maximum db Temperatures in zones; Average db temperature difference.

4.3.1 Impact of Climate on Internal Temperature fluctuations

The thermal performance of PCM2 relative to PCM1 is very similar over the period that has been simulated. During the month of June the maximum temperatures reached in Zone A and the average temperature differences observed show minimal variation.

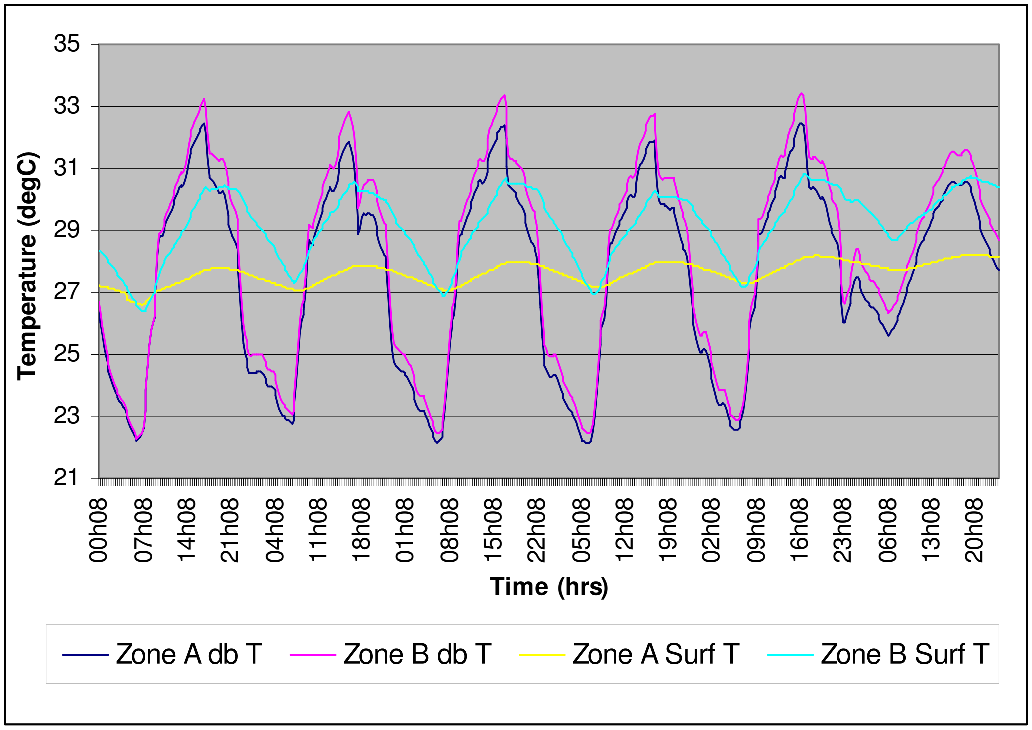

Figure 16 *Surface Temperatures of Wall-4 and Internal db Temperatures. Period 25th-30th June*

4.3.2 Internal Zone Temperature impact on Surface Temperatures

When comparing Wall-4 during the same period at the end of June, as was simulated for PCM1, it is recognised from Fig.16 that the surface temperature of the PCM applied surface in Zone A remains within the phase change temperature range. This thermal behaviour is maintained into the late part of July as the main factors influencing the response of the PCM are the temperature inside the room which fluctuates as a result of day and night time natural ventilation; and the casual gains produced during the occupied hours. The higher thermal conductivity of PCM2 in the solid phase (0.79W/m.K) and lower specific heat capacity improves the response of the material when the air temperature has reached its melting point thus increasing the volume of latent heat stored in the PCM and prolonging its effectiveness.

However as the outdoor ambient temperature increases during July the behaviour of the PCM became more erratic as can be seen from the surface temperature of Wall-4 in Fig.17 below. The PCMs thermal response was dependent on the variations in outdoor climatic conditions and behaved increasingly more like plain gypsum plasterboard.

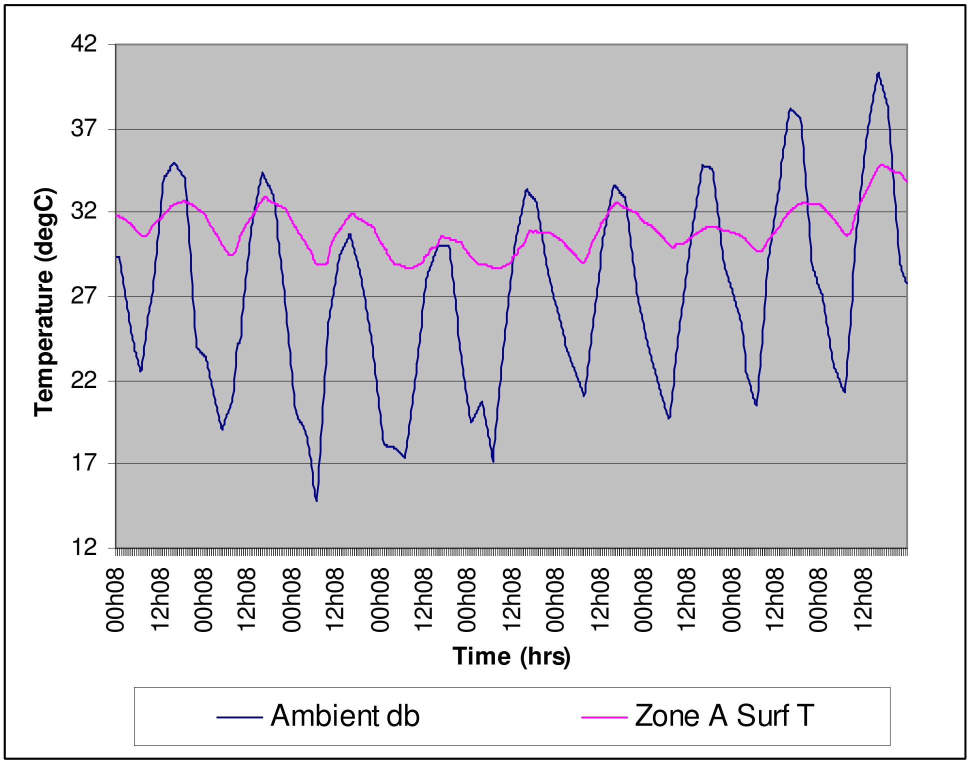

Figure 17 *Response of Wall-4 temperature to ambient db temperature. Period 12th- 20th August.*

The node temperature range where the PCM has been applied is fluctuating identically to the surface temperature. The material has been made ineffective as it can not release any of the latent heat stored; and this is a result of superheating the PCM, where the temperature range it operates in is surpassed due to the surface temperature being maintained at an average of 30.9°C throughout August; and a maximum observed at 34.9°C on the 20th August. The convective flux decreases as the temperature difference between the room temperature and the surface temperature decreases, reducing the possibility of heat discharge to periods when there are no factors such as casual gains interfering with the diurnal db temperature of Zone A. The PCM performance then resembles that of a sensible heat storing material.

The PCM remains in the liquid state until the ambient dry bulb temperatures have decreased sufficiently in the night time hours so that natural ventilation can reduce the internal dry bulb temperature. The lower ambient temperatures occur during the latter part of August and throughout September which enable the PCM to discharge. The completed discharge of the PCM takes place on the 23rd September where a sustained period of night time ambient dry bulb temperature below 15°C brought the surface temperature of the PCM applied wall below its melting point.

4.3.3 Impact of PCM location on Surface Temperature

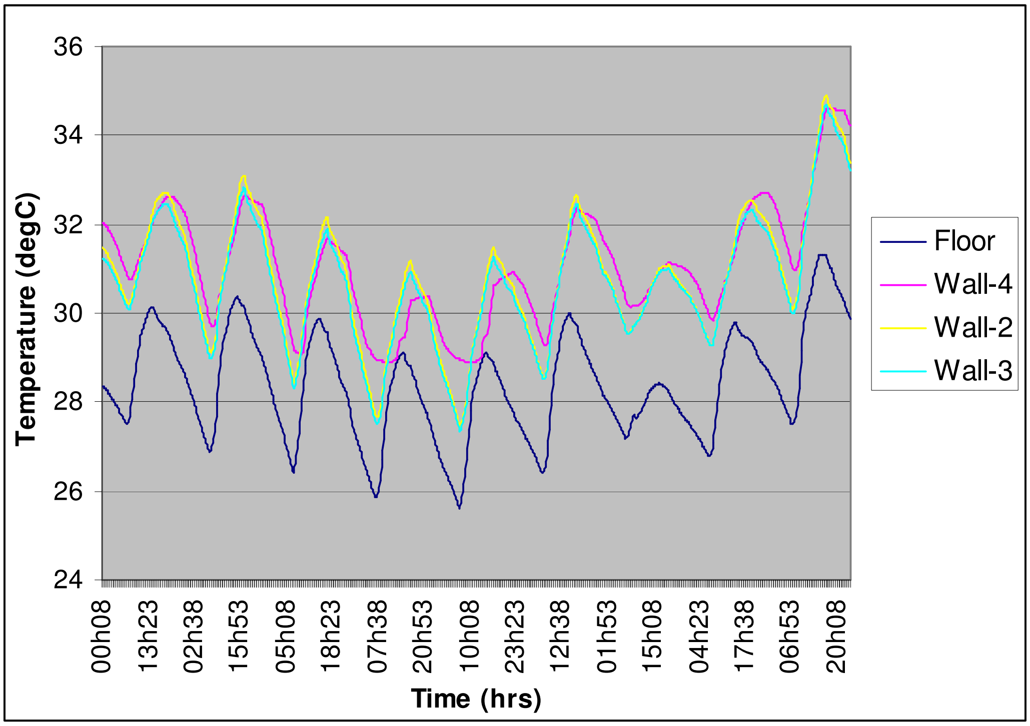

Figure 18 *Effect of PCM location on surface temperature. Period 12th-20th August*

From the graph in Fig.18 it can be seen that the application of PCM into the floor surface of Zone A enables an average surface temperature of 28°C to be maintained. This lower surface temperature was sustained over a longer period of time in comparison to the effect of the PCM applied in the other surfaces, and therefore the

PCM was still acting as a storage material. As the ambient dry bulb temperature increased, so did the internal zone temperature and therefore the PCM became overloaded once again; but for a shorter duration as this thermal effect occurred only during the hottest period of August shown in the graph above. The higher thermal conductivity in the solid phase and lower specific heat capacity of PCM2 resulted in an improved thermal performance when compared to PCM1.

4.4 Results: PCM 2 applied to surfaces in Zone A; Zones cooled actively;

Period	June		July		August		September	
Zone	A	B	A	B	A	B	A	B
Surface	East		East		East		East	
Sensible Cooling Load (kWhrs)	-152.58	-152.58	-306.47	-313.8	-311.02	-298.4	-128.25	-125.56
Hours	200.3	200	225.5	224	234.5	230.3	172	168.8
Average Cooling Load (kW)	-0.21	-0.21	-0.41	-0.42	-0.41	-0.4	-0.17	-0.17
Max Indoor Tmp	30.2	30.8	32	33.3	32.7	33.4	30	30.5
Min Indoor Tmp	17.69	17.69	23.7	22.9	23.5	21.9	17.4	17.5

A	B	A	B	A	B	A	B
Floor		Floor		Floor		Floor	
-152.58	-152.58	-315.47	-313.85	-300.12	-298.39	-125.89	-125.55
200	200	224.3	224	230.3	230.3	168.8	168.8
-0.21	-0.21	-0.42	-0.42	-0.4	-0.4	-0.17	-0.17
30.8	30.8	33.1	33.2	33.2	33.4	30.5	30.5
17.69	17.69	22.9	22.9	21.9	21.9	17.5	17.5

A	B	A	B	A	B	A	B
West		West		West		West	
-151.75	-152.57	-305.1	-313.8	-311.52	-298.4	-129.3	-125.56
200.5	200	225.5	224	234	230.3	174.3	168.8
-0.21	-0.21	-0.41	-0.42	-0.41	-0.4	-0.18	-0.17
30.1	30.8	32	33.3	32.8	33.4	30.1	30.5
17.69	17.69	23.7	22.9	23.4	22	17.44	17.5

A	B	A	B	A	B	A	B
North		North		North		North	
-152.08	-152.57	-306.82	-313.79	-312.04	-298.4	-127.74	-125.55
200	200	225.5	224	235	230.3	169.3	168.8
-0.21	-0.21	-0.41	-0.42	-0.41	-0.4	-0.17	-0.17
30.2	30.8	31.9	33.3	32.5	33.4	30.1	30.5
17.69	17.69	23.54	22.92	23.6	21.9	17.5	17.5

Table 7 Cooling load requirements; Average Cooling loads; Max. and Min. db Temperatures.

The overall effect of PCM2 on reducing cooling loads was very similar to the performance of PCM1. The main difference occurs in June as the lower temperature phase change range of 25-27^{o}C for PCM1 enabled a percentage of heat absorption to take place before the air conditioning system began to operate in its scheduled period; whereas PCM2 did not begin to function until the 25th of June when outdoor ambient dry bulb temperatures were high enough to increase the internal dry bulb temperatures in the zones and initiate the response of the PCM.

4.4.1 Impact of PCM location on reducing cooling loads

The thermal behavioural pattern that developed over the simulated period indicated that a material with a higher phase change temperature resulted in higher cooling loads. The graphs below show the surface temperature of the four surfaces simulated in the model during the hottest periods of July and August.

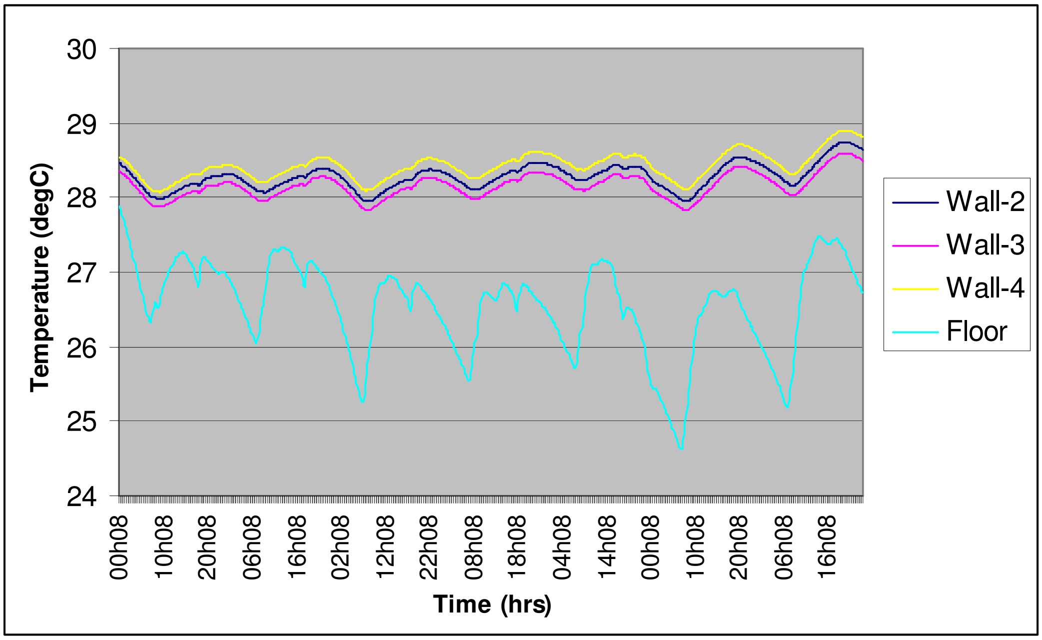

Figure 19 *Surface Temperatures when PCM2 was applied. Period: 16th-22nd July*

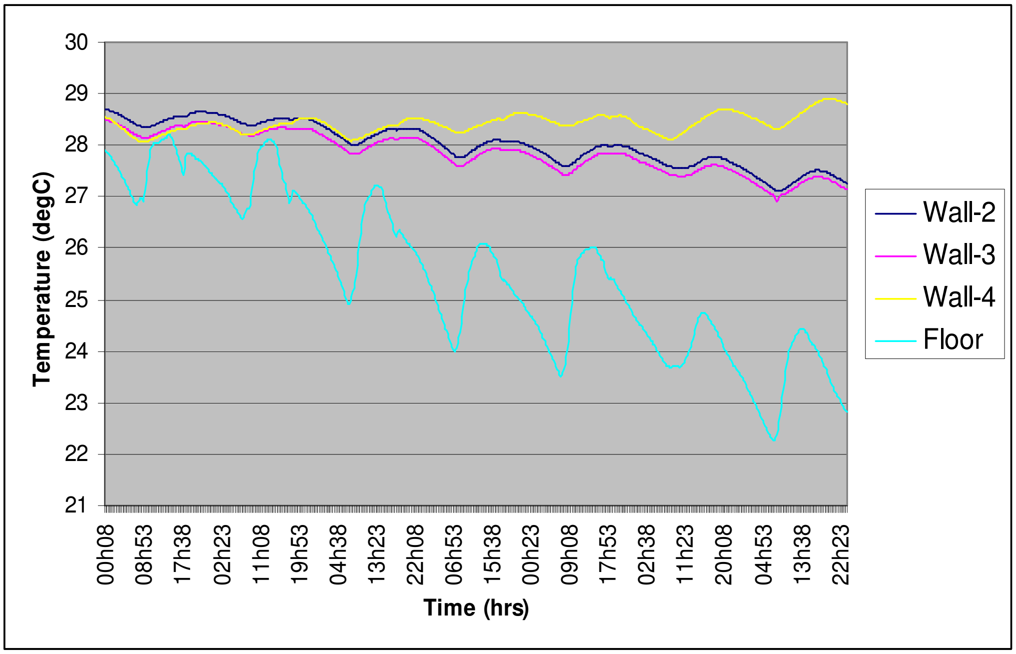

Figure 20 *Wall Surface Temperatures when PCM2 was applied. Period: 20th-26th August*

The temperature difference between the applied PCM surface and the internal dry bulb temperature was kept relatively constant in the vertical surfaces. With the air temperature in the room lower than the surface temperature, the convective flux flowed from the wall surface into the room. The small temperature variations shown in Fig.19 and 20 suggest that the thermal gradient between the surface PCM was applied to and the internal dry bulb temperature would have remained high throughout the selected periods; as a result of the saturated state achieved and the higher surface temperature reached due to the higher transition range of PCM2. This greater temperature resulted in more heat being discharged into the room; increasing the level of cooling load required.

This thermal effect remains consistent throughout the weekdays when the air-conditioning is operating, and the natural ventilation occurring in the evening does not impact on the surface temperature where the PCM has been applied. The latent heat stored in the PCM is unable to be released soon after the air-conditioning is turned off, similarly to the simulations that incorporated PCM1, as a result of saturation. The rise in indoor temperature is reduced by the buffering effect of night time ventilation and so the peak temperature reached is lower than in Zone B. The higher temperature of the air ventilated into the zones during the day does not increase the surface to air temperature difference sufficiently to allow heat discharge from the PCM.

During the weekend periods though the cooling system is not operated and therefore an opportunity for the PCM to fully charge arises. On extremely hot days the air and surface temperature increase dramatically when mechanical cooling is stopped. The surface temperature has increased sufficiently to enable further melting of the PCM which had not dissolved. The phase change that occurs increases the resultant air temperature difference between Zone A and Zone B with Zone A showing to be slightly cooler. This effect is cumulative during July and August until the average diurnal ambient dry bulb temperatures decrease.

4.4.2 Impact of mechanical cooling on convective flux

The rate of heat flux from the PCM applied surface in Zone A compared to that in Zone B is a problem that arises under actively cooled conditions. As described in the previous section, the natural cooling that occurs over the weekend is beneficial for Zone A as the PCM is able to charge further, absorbing a proportion of the heat from the air in the zone. However after this occurs, the PCM remains in a saturated state and the night time ventilation is not adequate to create a substantial air temperature drop so that the PCM can discharge; sustaining the higher surface temperature achieved during the melting process. The same wall in Zone B cools at a rate relative to the external temperature fluctuations and so its surface temperature will fall below that of Zone A. Hence the convective flux from the PCM applied surface in Zone A will be greater, further increasing the load demand.

4.5 Results: PCM 3 applied to surfaces in Zone A; Zones cooled passively;

PCM applied Surface

Wall-2

Period	**June**		**July**		**August**		**September**	
Zone	A	B	A	B	A	B	A	B
Max db Tmp	32.8	34.86	38.16	38.77	38.5	38.82	33.95	35.39
Average Tmp Diff	-0.76		-0.98		-0.72		0.14	

Wall-3

June		**July**		**August**		**September**	
A	**B**	**A**	**B**	**A**	**B**	**A**	**B**
34.21	34.86	38.2	38.77	38.55	38.82	34.59	35.39
-0.42		-0.83		-0.82		-0.47	

Wall-4

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
34.21	34.86	38.2	38.77	38.55	38.82	34.6	35.4
-0.42		-0.83		-0.82		-0.47	

Floor

June		**July**		**August**		**September**	
A	B	A	B	A	B	A	B
34.21	34.86	38.2	38.77	38.55	38.82	34.6	35.4
-0.42		-0.83		-0.82		-0.47	

Table 8 Maximum db Temperatures in zones; Average db temperature difference.

4.5.1 Impact of Internal Temperatures on PCM performance

With a higher thermal conductivity in the solid phase, both PCM2 and PCM3 were able to melt during a shorter time period. As the internal temperature was dependent on the external conditions, the thermal behaviour of PCM3 was dependent on the diurnal temperature fluctuations in the room. The average internal room temperatures achieved in Zone A did not result in the complete charging of the PCM as it remained in a saturated state between its melting and solidification temperatures until the midpoint of July; where higher ambient dry bulb temperatures helped the PCM attain an entirely loaded state. The PCM was unable to release the latent heat as the room temperature exceeded the solidification temperature. The PCM responded to the temperature fluctuations within the room due to its sensible heat capacity; similarly to the behaviour of the plain Wall-4 in Zone B. This is shown in the graph below.

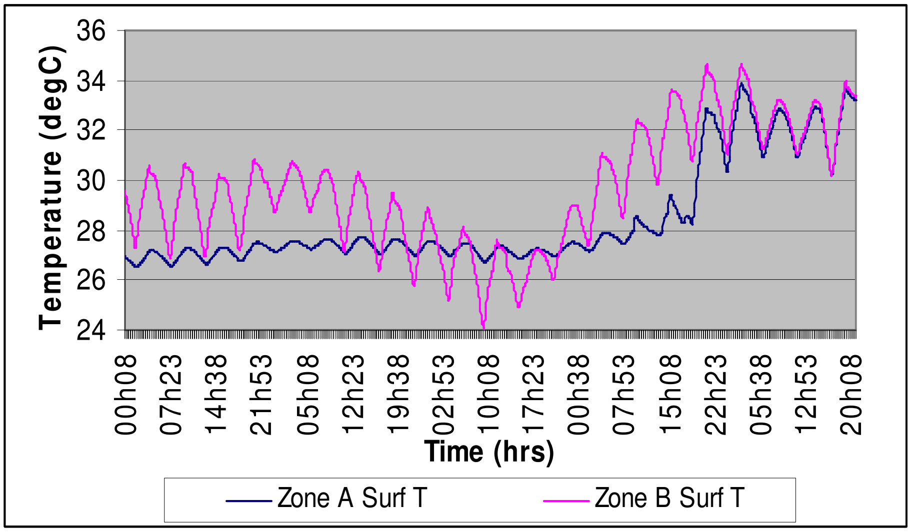

Figure 21 *Surface temperature at Wall-4.*
Period 26th June-26th July

4.5.2 Impact of PCM location on thermal performance

The higher thermal conductivity enabled melting to take place in all of the surfaces tested; and a lower specific heat capacity was beneficial as the PCM was more responsive to smaller convective heat flux between the air temperature and the wallboard surface temperature; resulting in an improved performance when the phase change material was installed in the floor during June.

The four surface temperatures observed in Zone A during July and August where PCM3 was applied showed that the problem of saturation was still occurring in all surfaces. The average surface temperatures for the tested surfaces were above the transition temperature range (July=29.3°C; August=29.5°C)

4.6 Results: PCM 3 applied to surfaces in Zone A; Zones cooled actively;

Period	June		July		August		September	
Zone	A	B	A	B	A	B	A	B
Surface	East		East		East		East	
Sensible Cooling Load (kWhrs)	-147.9	-152.56	-298.65	-313.78	-307.99	-298.4	-133.69	-125.57
Hours	201.8	200	225.5	224	233.8	230.3	185.3	168.8
Average Cooling Load W	-0.2	-0.21	-0.4	-0.42	-0.41	-0.4	-0.18	-0.17
Max Ind Tmp	29.8	30.8	31.8	33.3	33.3	33.4	29.9	30.5
Min Ind Tmp	17.69	17.69	23.6	22.9	23.4	21.9	19.6	17.5

A	B	A	B	A	B	A	B
Floor		Floor		Floor		Floor	
-152.58	-152.58	-312.91	-313.84	-297.36	-298.39	-126.51	-125.56
200	200	224.3	224	230.5	230.3	168.8	168.8
-0.21	-0.21	-0.42	-0.42	-0.39	-0.4	-0.17	-0.17
30.7	30.8	32.7	33.3	33	33.4	30.4	30.5
17.69	17.69	22.9	22.9	22	22	17.5	17.5

A	B	A	B	A	B	A	B
West		West		West		West	
-145.3	-152.55	-301.57	-313.79	-305.75	-298.4	-134.77	-125.57
201.3	200	225.3	224	232.8	230.3	190.3	168.8
-0.2	-0.21	-0.4	-0.42	-0.41	-0.4	-0.18	-0.17
29.8	30.8	31.9	33.3	33.4	33.4	29.9	30.5
17.69	17.69	23.6	22.9	23.3	21.9	20.3	17.5

A	B	A	B	A	B	A	B
North		North		North		North	
-148.92	-152.57	-294.68	-313.76	-310.65	-298.4	-135.45	-125.57
201.5	200	225.5	224	235	230.3	184.8	168.8
-0.2	-0.21	-0.39	-0.42	-0.41	-0.4	-0.18	-0.17
29.8	30.8	31.6	33.3	33	33.4	30	30.5
17.69	17.69	23.7	22.9	23.6	21.9	19.4	17.5

Table 9 Cooling load requirements; Average Cooling loads; Max. and Min. db Temperatures.

4.6.1 Impact of mechanical cooling on PCM performance

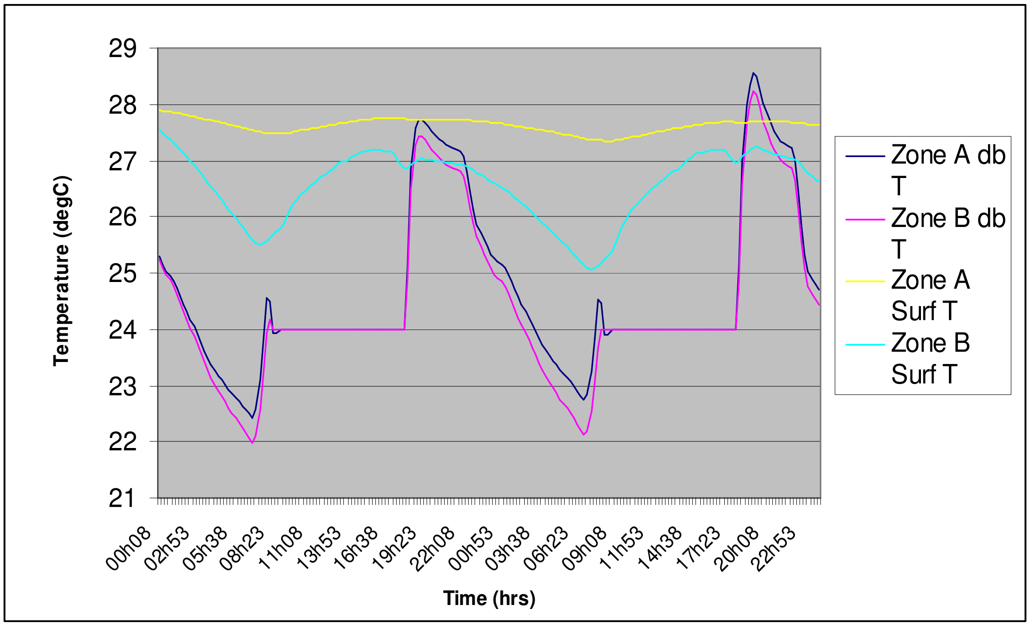

Figure 22 *Surface Temperature of Wall-3 in both zones; Internal db Temperature. Period 23rd-24th August*

Fig.22 highlights that the problem of higher surface temperatures during the occupied hours persisted despite a new PCM being incorporated. The saturation of the PCM is not avoided as a result of the latent heat capacity is reduced. Night time ventilation does not enable the PCM to reach its solidification temperature; and daytime air conditioning prevents completion of the charge process as heat is only absorbed due to the sensible heat capacity of the wallboard.

4.7 Thermal performance of a proposed PCM for internal wallboard application

This attempt to improve the thermal performance of a PCM in this climate involved using new thermal properties for a proposed ideal PCM. The characteristics of the new material were as follows:

T_m (°C)	T_s (°C)	k_m (W/mK)	k_s (W/mK)	C_s (J/kgK)
20	*24*	*1.8*	*0.5*	*1000*

Table 10 Thermal properties for idealised PCM.

The latent heat of fusion for this material was maintained at a constant of 20000kJ/kg during the solid-liquid and liquid-solid phase changes.

The floor was selected as the surface for applying the PCM. From previous simulations, it was found that the average floor surface temperature was lower than those reached by the vertical surfaces monitored before being combined with the PCM. Results from the new simulations carried out in passive cooling conditions showed that there was a marginal reduction in the maximum internal room temperatures achieved.

Period	**June**		**July**		**August**		**September**	
Zone	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Max db Tmp	32.4	33.4	35.6	37.6	37.2	38.2	33.4	33.7
Average Tmp Diff	-0.5		-1.3		-0.7		0.6	

Table 11 Max. db Temperatures in zones; Average db temperature difference between zones.

The thermal resistance of the floor tiles has already been identified as a factor influencing the response of a PCM integrated into the floor surface. The surface temperature profiles of the PCM wallboard during selected periods of the whole simulated period are shown below in Fig.23.

Over the selected periods, the surface temperatures are varying as a result of latent and sensible heat storage. The nodal temperatures are showing that during the four month period the temperature of the PCM does not complete a single phase change. Instead the latent heat of fusion is increasing until 23rd August where the PCM reaches a maximum temperature of 23.5°C. This latent heat store from the phase change that has occurred is then discharged steadily over the remainder of the simulated period; explaining how the difference in maximum room temperatures achieved in September is brought about. The heat being discharged from the PCM is being conducted through the cement screed and floor tile layers above it adding to the sensible heat already being stored in these materials. The temperature difference between the floor tile surface and the air in the zone increases during the night time periods resulting in a higher convective heat transfer into the room. This additional heat source arising in September will be beneficial for reducing the required heating loads.

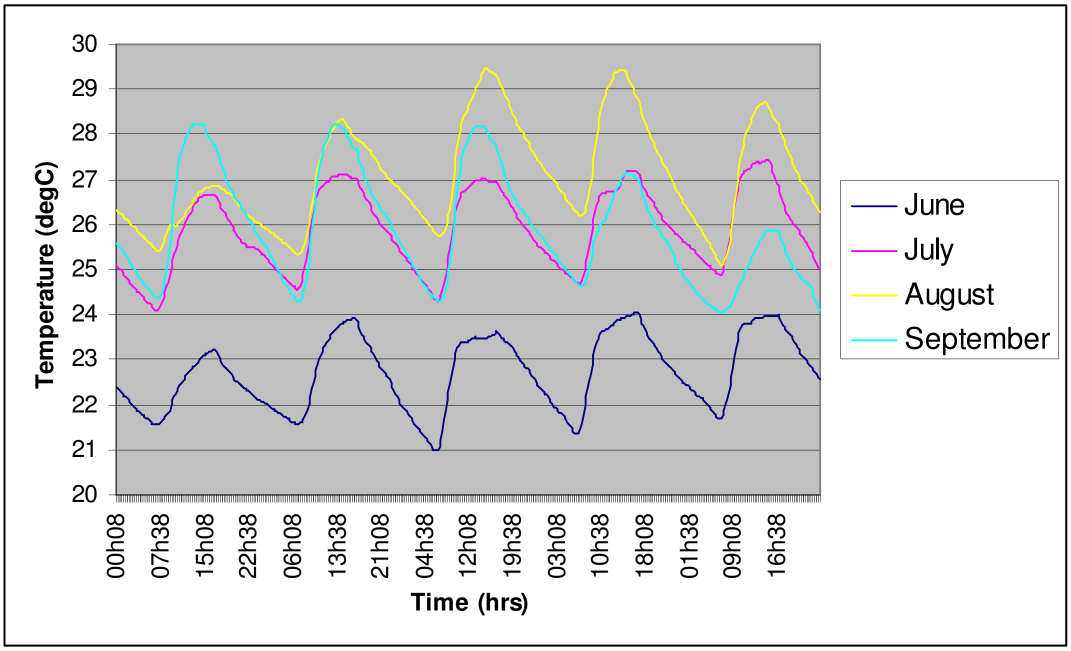

Figure 23 *Floor Surface Temperature for selected periods.*

<u>4.7.1 Response of proposed PCM wallboard to mechanical cooling</u>

The cooling load requirements in Zone A were significantly reduced as a result of this PCMs thermal performance. There was a significant decrease in cooling achieved between June and August in comparison to the previous PCMs tested. The table below presents these differences.

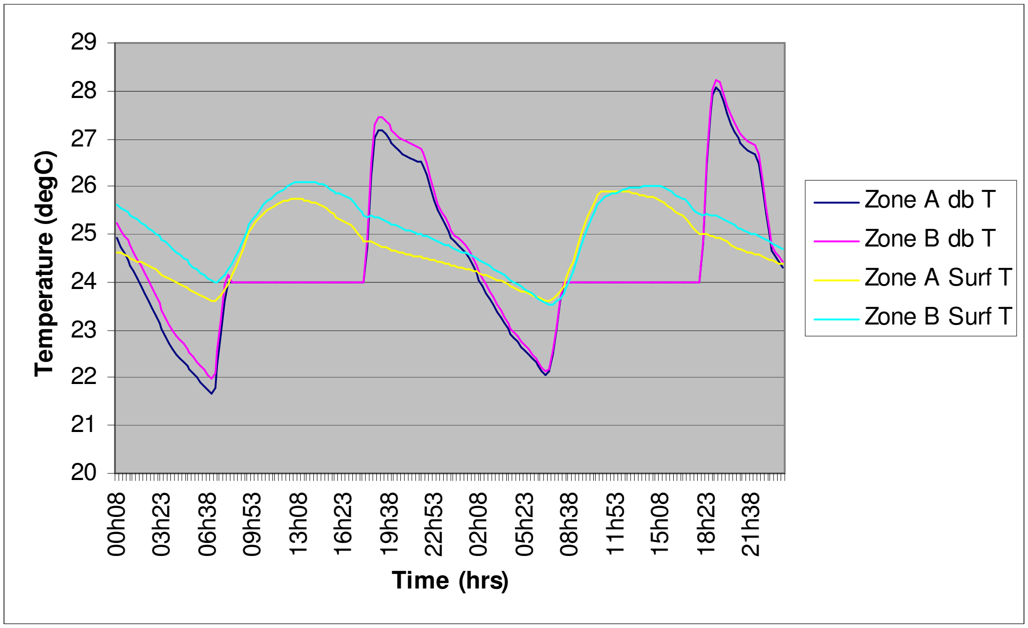

Figure 24 *Surface Temperature of Base-6 in both zones; Internal db Temperature. Period 23rd-24th August*

Fig.24 shows that although the temperature of the PCM applied surface in Zone A fluctuates above the materials solidification temperature, the sensible heat stored in the PCM is released at a similar rate to that of the plain surface in Zone B. In comparison to PCMs 2 and 3, the proposed PCM is not in a saturated state on a diurnal basis. Lower latent heat capacity of the idealised PCM and higher thermal conductivity, enabled the loaded state to be achieved and maintained; and as the surface temperature of the PCM wallboard remains below that achieved in Zone B, a combination of the latent heat store and increased effect of natural ventilation on reducing surface temperature, a lower resultant convective flux will occur during the scheduled cooling hours in Zone A thus reducing the cooling load required.

The impact of the proposed PCM on decreasing the cooling load demand can be seen.

	June		July		August		September	
	A	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Sensible Cooling Load (kWhrs)	*-111.87*	*-122.93*	*-242.38*	*-289.11*	*-248.76*	*-270.8*	*-108.86*	*-103*

Table 12 Cooling requirements.

The thermal gradient of the melting taking place over the course of the entire simulated period remained small. The average surface and node temperatures remain below the cooling set point at 23.6°C and 21.2°C respectively over the four months. This temperature difference between these two points maintains the conduction of heat from the surface to the PCM layer. The variation in room temperature as a result of the thermal performance of the PCM whilst using mechanical cooling did not have a significant effect on the surface temperature of the floor. The temperature variation that did occur was a result of the materials sensible heat capacity. The sensible heat flux in Zone A from the PCM applied surface was consistently lower compared to Zone B due to the increased thermal mass.

5 Conclusion

A study was conducted to investigate the thermal response of selected organic, inorganic and inorganic eutectic PCMs in an actively cooled building environment. The aim of the project was to discover the thermal characteristics of a PCM necessary to achieve optimum thermal performance of the PCM under the specified conditions.

The results obtained from the simulation analysis conducted have shown that the resultant thermal behaviour of a PCM impregnated wallboard provides both benefits and disadvantages. Substantial reductions in the cooling load required to sustain a set point are achievable. The study was carried out using climate data for a Spanish location during the period from June to September; and results show that reductions in room temperatures and cooling load utilisation are attained through the use of latent heat storage materials.

Identifying the most effective surface to integrate the PCM into was done for both a passively and actively cooled building. The resultant room temperatures achieved under the passive conditions indicated that the thermal effect of all three PCMs was limited. Internal room temperatures were dictated primarily by the changes in ambient dry bulb temperatures; and therefore the rate of convective heat transfer from the PCM wallboard into the room only varied as a result of its sensible heat capacity. The PCMs were then left in a loaded state over the period simulated as the surface and internal node temperatures of the wallboard composite maintained temperatures in excess of the solidification temperature despite the diurnal room temperature fluctuations. The potential for the PCM to overheat and super-saturate under these repeated thermal cycles is known to increase the effectiveness of the material consigning it to a permanently loaded state.

The actively cooled internal climate resulted in the saturation of the incorporated PCMs. The nodal temperature within the PCM layer remained at an average temperature in between the melting and solidification temperature range due to the stability of the internal room temperatures during the scheduled cooling hours; and ineffective natural ventilation in the night time. This resulted in higher sensible heat flux from the wallboard into the room during the scheduled cooling hours. A reference building was modelled to quantify the thermal effect of the PCM; and the behaviour described above resulted in higher cooling loads in the zone incorporating PCM compared to the reference zone.

A proposed PCM with a phase change temperature range of 4°C (T_m = 20°C) was tested in the floor of the model and results indicated that greater cooling load reductions of approximately 10% during the whole period were achievable. The larger phase transition range prevented the PCM from melting in its entirety. Mean surface and PCM applied node temperatures remained within the transition temperature range of the material throughout the simulated period. Increased thermal resistance in the materials above the PCM-concrete layer and low levels of solar absorption were factors reducing the latent heat stored by the PCM. The resultant latent heat stored however was produced over a longer period of time and was then released during the latter part of September; when there became a need for heating the space.

Previous studies have shown that achieving human thermal comfort conditions within a passive solar building through the use of PCMs is possible in mild climates. More extreme thermal conditions experienced in the Mediterranean region prevent a passive solar building from functioning effectively in order to maintain human comfort. Installation of air conditioning units is becoming a more frequent occurrence increasing the level of electricity demand; and additionally the amount of greenhouse gas emissions. The simulations have shown that the thermal properties of the selected PCM need to adhere and respond efficiently to the intensive climate conditions it will operate in.

Introducing latent heat storage technology into active and passive solar buildings in this study has shown that more improvements are possible. Optimising the performance of a PCM in this type of environment requires a higher thermal conductivity in the solid phase and a lower latent heat capacity as has been shown in this investigation. Further simulation analysis is necessary to define ideal thermal properties for various PCMs integrated into all surfaces of an occupied space during the summer season; which could help reduce the cooling demand in the short term and in parallel reduce the heating load required in the long term.

References

Cabeza L F et al, (2007) Use of micro-encapsulated PCM in concrete walls for energy savings, *Energy and Buildings*, Volume 39;

Eastop T D, McConkey A, (1993) *Applied Thermodynamics for Engineering Technologists,* England: Prentice Hall;

Farid M M et al, (2004) A review on phase change energy storage: materials and applications, *Energy Conservation and Management*, Volume 45;

Hawes D W et al, (1992) The stability of phase change materials in concrete, *Solar Energy Materials and Solar Cells*, Volume 27;

Heim D et al, (2004) Numerical modelling nd thermal simulation of PCM-gypsum composites with ESP-r, *Energy and Buildings*, Volume 36;

Heim D, (2005) Two solution methods of heat transfer with phase change within while building dynamic simulation, *Building Simulation*;

Hoogendoorn C J et al, (1992) Performance and Modelling of Latent Heat Stores, Solar Energy, Volume 48;

Incropera F P et al, (2007) *Introduction to Heat Transfer,* USA: John Wiley&Sons;

Khudhair A M et al, (2004) A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Conservation and Management, Volume 45;

Neeper D A, (2000) Thermal Dynamics of wallboard with latent heat storage, *Solar Energy*, Volume 68, Issue 5;

Pincemin S et al, (2008) Highly conductive composites made of phase change materials and graphite for thermal storage, *Solar Energy Materials and Solar Cells*, Volume 92;

Regin A F et al, (2007) Heat transfer characteristics of thermal energy storage system using PCM capsules: A review, *Renewable and Sustainable Energy Reviews*;

Sari A et al, (2006) Eutectic mixtures of some fatty acids for latent heat storage: Thermal properties and thermal reliability with respect to thermal cycling, *Energy Conversion and Management*, Volume 47;

Sari A et al, (2008) Preparation and thermal properties of capric acid/palmitic acid eutectic mixture as a phase change energy storage material, *Materials Letters*, Volume 62;

Schossig P et al, (2005) Micro-encapsulated phase-change materials integrated into construction materials, *Solar Energy Materials and Solar Cells*, Volume 89;

Sharma A et al, (2005), Latent Heat Storage Materials and Systems: A Review, *Green Energy*, Volume 2;

Sharma A et al, (2007), Review on thermal energy storage with phase change materials and applications, *Renewable and Sustainable Energy Reviews*;

Suppes G J et al, (2003), Latent heat characteristics of fatty acid derivatives pursuant phase change material applications, *Chemical Engineering Science*, Volume 58;

Tyagi V V et al, (2005) PCM thermal storage in buildings: A state of art, *Renewable and Sustainable Energy Reviews,* Volume 11;

Zalba B et al, (2003) Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, Volume 23;

Zhang Y et al, (2007), Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook, *Building and Environment*, Issue 42;

www.epsltd.co.uk

www.fincaparcsresales.com

www.micronal.de

www.rubitherm.de