Investigation of Passive Storage of Thermal Energy at Different Temperatures

A Thesis Submitted for the Degree of Doctor of Philosophy

By

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Declaration

I, Hasnat Jamil, declare that this thesis titled “Investigation of Passive Storage of Thermal Energy at Different Temperatures” is my work and has not been submitted previously, in whole or in part, in respect of any academic award. No material, to my best of knowledge, has been published in any form by any other person except where due reference is made.

Hasnat Jamil

June 15, 2016
Abstract

Research and development of different energy saving techniques and efficient use of renewable energy are important in addressing the global greenhouse gas emission problem. The thermal energy storage (TES) is an attractive system for effective utilisation of renewable energy. In this thesis, the application of phase change material (PCM) as a latent heat thermal energy storage at room temperature was investigated to study its effectiveness in energy savings, temperature attenuation and thermal comfort. In addition, the thermal properties of geopolymer were determined to find its feasibility as a new TES material in high-temperature application.

In this study, the effectiveness of PCM in reducing the energy consumption of residential houses were investigated. Simulations were carried out with different PCM melting ranges in eight Australian cities. It was found that the effectiveness of PCM strongly depends on local weather, thermostat range, PCM layer thickness and surface area. Depending on local weather, the integration of PCM resulted in a maximum of 17-23% annual energy savings in the studied house. For a given amount of PCM, energy saving potential was found to improve with the increase of applied surface area and decrease of PCM layer thickness.

An experimental study and a numerical investigation were carried out to investigate the feasibility of PCM as a retrofitting option in an existing house in Melbourne, Australia. In the experimental study, PCM was installed in the ceiling of one of the rooms and its indoor air temperature was recorded. A simulation model was developed and validated using the recorded experimental temperature data. The results showed up to 1.1°C reduction of indoor air temperature during daytime and 34% reduction in thermal discomfort hours for PCM application in the ceiling. It was observed that PCM is more effective in reducing thermal discomfort hours if windows are kept open for night purging and the internal doors are remained closed to stop internal mixing.

The effectiveness of PCM also was studied experimentally and numerically in the hollow core based ventilated system where PCM was incorporated in the supply air duct (PCM-
air duct) of the system. In the experimental work, PCM was installed in a pilot scale air duct where temperature change of air flow was recorded. In the numerical model, the PCM-air duct with different configurations were carried out. The results indicated that the increase of PCM amount by spreading over a longer distance of the air duct is better than increasing the PCM layer thickness. In a real summer weather, PCM-air duct was found to reduce the daytime maximum temperature more than 1°C for 47% of simulated days.

For high-temperature TES application, the geopolymer was studied as a new thermal storage material. An experimental work was carried out to determine the thermal conductivity and the specific heat capacity of the geopolymer using the hot wire method. The properties of geopolymer were found to be highly dependent on the presence of moisture, physical and chemical changes. The thermal conductivity of geopolymer and geopolymer concrete were found to have a similar trend, though values for concrete were higher than that of the geopolymer. With subsequent heating and testing, the thermal conductivity of geopolymer concrete becomes more stable as the physical and chemical changes inside the geopolymer concrete mitigate. This was followed by a numerical study, where the Levenberg-Marquardt method was used in solving the inverse problem to determine the thermal properties from a transient temperature distribution. Finally, a heat transfer simulation was carried out using the calculated properties and compared with the experimental temperature profile.

The thesis presents high temperature and ambient temperature passive storage of energy using thermal energy storage (TES) systems using (1) concrete in combination with PCM; (2) PCM only; and (3) Geopolymer concrete at high temperatures. Concrete and PCM are found to be good materials for passive storage of energy at ambient conditions. While normal concretes are unstable in high temperatures, geopolymer concrete have been found to be a good candidate for TES at high temperatures based on the results presented in this thesis.
# Acknowledgement

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My beloved father would have been very proud and happy to see me finishing my Ph.D. work. His love for knowledge and respect for details have been a source of inspiration for me. He was and still is my first teacher. I am immensely grateful to have my mother in my life. Her prayers and unconditional love have made tough times look easy. I dedicate this thesis to my parents who has made me as I am. This is for you two. I thank both of you from the depth of my heart.
To Ammu and Abbu
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$C_p$</td>
<td>Specific Heat capacity</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Heat capacity or Volumetric heat capacity</td>
</tr>
<tr>
<td>$C_{ps}$</td>
<td>Specific heat capacity of solid</td>
</tr>
<tr>
<td>$C_{pl}$</td>
<td>Specific heat capacity of liquid</td>
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<tr>
<td>$C_{pe}$</td>
<td>Equivalent specific heat capacity</td>
</tr>
<tr>
<td>$C_{ap}$</td>
<td>Apparent specific heat capacity</td>
</tr>
<tr>
<td>$C_{pcm}^{ps}$</td>
<td>Heat capacity of PCM in solid phase</td>
</tr>
<tr>
<td>$D_{opt}$</td>
<td>Optimum PCM panel thickness</td>
</tr>
<tr>
<td>$Ei(x)$</td>
<td>Exponential integral</td>
</tr>
<tr>
<td>$g_L$</td>
<td>Temperature dependent additional latent heat generation rate</td>
</tr>
<tr>
<td>$g_s$</td>
<td>Specific heat generation rate</td>
</tr>
<tr>
<td>$H$</td>
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</tr>
<tr>
<td>$\Delta H$</td>
<td>Latent heat of fusion</td>
</tr>
<tr>
<td>$h$</td>
<td>Average heat transfer coefficient</td>
</tr>
<tr>
<td>$I_{design}$</td>
<td>Air change per hour</td>
</tr>
<tr>
<td>$i$</td>
<td>Counter</td>
</tr>
<tr>
<td>$J_{C_v}$</td>
<td>Sensitivity vector</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$k_{pcm}^{liq}$</td>
<td>Thermal Conductivity of the liquid PCM</td>
</tr>
<tr>
<td>$k_{pcm}^{sol}$</td>
<td>Thermal Conductivity of PCM in solid phase</td>
</tr>
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<td>$k_b$</td>
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<td>$L$</td>
<td>latent heat of fusion</td>
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<tr>
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<tr>
<td>$l_f$</td>
<td>Melted fraction of PCM</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Measured temperature at time $t_i$</td>
</tr>
</tbody>
</table>
\( n \quad \text{Iteration step} \\
\( n_{\text{max}} \quad \text{Maximum number of iteration} \\
\( P_r \quad \text{Rate of the energy transfer} \\
\( \mathbf{P} \quad \text{Vector of unknown parameters} \\
\( Q \quad \text{Heat flux} \\
\( R \quad \text{Radius} \\
\( S \quad \text{Sum of the square error} \\
\( T \quad \text{Temperature} \\
\( T_i \quad \text{Temperature computed at time } t_i \\
\( T_n \quad \text{Night time room temperature} \\
\( T_d \quad \text{Daytime room temperature} \\
\( T_{\text{zone}} \quad \text{Zone temperature} \\
\( T_{\text{odb}} \quad \text{Outdoor dry bulb temperature} \\
\( T_m \quad \text{Melting temperature} \\
\( T_{m,\text{opt}} \quad \text{Optimum phase change temperature} \\
\( T_{\overline{r}} \quad \text{Average room temperature} \\
\( T_R \quad \text{Reference temperature} \\
\( t \quad \text{Time} \\
\( t_{\text{stor}} \quad \text{Storage cycle} \\
\( t_d \quad \text{Charging time} \\
\( t_n \quad \text{Discharging time} \\
\( W_s \quad \text{Wind speed} \\
\( w_d \quad \text{Width of phase change region} \\
\( w_i \quad \text{Weight fraction} \\
\( w_{\text{pcm}} \quad \text{Weight fraction of the PCM} \)
Greek Letters

\( \alpha \)  
Thermal diffusivity

\( \rho \)  
Density

\( \rho_{pcm}^{liq} \)  
Density of the liquid PCM

\( \rho_{pcm}^{sol} \)  
Density of PCM in solid phase

\( \Delta \theta \)  
Temperature difference between measurement and reference thermocouple

\( \mu^n \)  
Damping factor

\( \Omega^n \)  
Diagonal matrix

\( \varepsilon \)  
Tolerance
CHAPTER ONE

1 INTRODUCTION

1.1 BACKGROUND

Fast industrial growth around the world and high living standards have resulted in a huge increase in energy demand. Over the period 1979–80 to 2009–10, there was a 90% increase in Australia’s total energy use, from 3,131 petajoules to 5,925 petajoules [1]. Approximately, 95% of Australia’s total energy consumption comes from fossil fuels (coal, oil and gas) [2] which results in harmful greenhouse gas emissions (Figure 1.1). In 2009-10, the energy consumption of residential building was around 25% of total energy consumptions and contributed around 13% of total Australia national greenhouse gas emission [1, 3].

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Figure 1.1 Primary energy consumption in Australia by Fuel [2]
To address this issue, efficient ways of energy savings and increasing and effective use of renewable energy plays an important role. One of the obstacles in using the renewable energy to its full extent is that its availability is not uniform (e.g. solar radiation). So, a storage system is essential to utilise the renewable energy. Thermal Energy Storage (TES) system evens out the mismatch between the supply and demand by storing the energy during the off-peak periods and supply it when it is needed. Thus, it can be used to shift the load as well as increase the energy efficiency through reducing the operational energy requirements. TES improves the reliability and performance of the energy system.

There are mainly two types of TES systems, sensible heat storage system and latent heat storage system [4]. In the sensible heat storage system, the thermal energy can be stored (or released) by raising (or lowering) the temperature of the storage material. The capacity of the system depends on the density and the specific heat capacity of the material. On the other hand, the latent heat storage system can store heat energy nearly isothermally by changing the phase of the storage material e.g. from solid-to-liquid or liquid-to-gas. Nowadays, mainly solid-to-liquid transition is used in the latent storage system and the material used in this system is called Phase Change Material (PCM). The capacity of this latent storage system depends on the heat of fusion of the material. The high heat of fusion of PCM makes it possible to store a large amount of heat in a relatively small volume of material.

Both sensible and latent storage systems are used in various applications at different temperature ranges. The applications can be broadly divided into two categories in terms of temperature, (a) room-temperature application and (b) high-temperature application (50°C to 800°C).

In the case of room temperature application, TES system can offer an attractive means of increasing the energy efficiency of a building through reducing the operational energy requirements such as space heating and cooling, water heating etc. of the building. The concept of using building fabrics as a sensible heat TES has been known for thousands of years and is reflected in the designs of many old buildings. The principle building elements used for sensible heat storage are masonry walls, floors and ceilings. In the
latter case, the physical state of the storage material is changed [5]. Of late, the use of PCM has received much attention in the building thermal energy management. PCM can be integrated into different parts of the building such as ceilings, wallboards, floors, ventilation ducts, etc. [6-8]. There are many numerical and small scale experimental studies [9-23] which explore the potential application of PCM as a passive storage of thermal energy in ambient temperature. But it is important to find out the influential factors that dictate the effectiveness of PCM in reducing the energy consumption. Furthermore, real house experiments with PCM application which is rare in the literature needs to be explored to better understand the efficiency of PCM in real situation.

In the case of high-temperature application, the TES system is mostly used in the solar thermal power plants where solar energy is stored as thermal energy at daytime and later it is utilised at night. The typical examples are molten salt (Liquid sensible storage), PCM (NaNO₃, etc. as latent storage), etc. [4, 24]. Recently, some study suggested that Portland Cement concrete can be used as efficient sensible energy storage in solar thermal power plant [25-28]. But the problem with the concrete is spalling, a disintegration process which mainly happens above 400°C. Geopolymer can be a better option as a sensible thermal energy storage as it has better thermal stability at high temperatures [29-32]. To understand the thermal behaviour and thermal storage capacity, the thermal properties are important. But in literature, the thermal properties like thermal conductivity and heat capacity of geopolymer at high temperatures are hard to find.

1.2 Aim and Research Objectives

The aim of this research is to investigate the potential of PCM and geopolymer as a passive storage of thermal energy in ambient temperature and high-temperature applications respectively. The specific research objectives are the following:

- To investigate the different influencing criteria of PCM application (local weather, PCM layer thickness, location of applications, etc.) in reducing the heating and cooling energy consumption.
• To study the effectiveness of PCM in a real house through experimental and numerical investigation and to study the ways of further improvement.
• To investigate the PCM performance in combination with a hollow core concrete slab system in reducing the diurnal temperature fluctuation.
• To study the thermal conductivity and specific heat capacity of geopolymer at high temperatures to understand its potential as a thermal storage at high temperature.

1.3 Thesis Overview

The thesis is organised into eight different chapters. Chapter 2 firstly provides a general overview of the PCM as a thermal storage used in the room temperature applications. It is then followed by a literature review on the different types of PCM incorporation methods, types of applications and numerical studies of PCM applications carried out by previous researchers. It also includes the previous study of hollow core concrete slab system as a sensible thermal energy storage in the office building and incorporation of PCM to improve the system. Finally, a literature survey of different thermal energy storages used in the high-temperature applications, especially in the solar thermal power plant, were presented and the prospects of geopolymer material were discussed in the later section of the chapter.

Chapter 3 describes a numerical investigation of PCM effectiveness in Australian climates. It presents the performance of different PCMs in diurnal temperature fluctuation reduction (free running condition) and in reducing the annual energy consumption (HVAC operation) for weather of eight different major cities of Australia. It also summarises the influence of the PCM layer thickness, spreading area and the location of PCM application on the energy savings.

Chapter 4 presents an experimental and numerical study of the performance of PCM in a 5 energy star real house in Melbourne, Australia. It describes the ways of improvement of PCM efficiency through the change of some user behaviours. Finally, it outlines the thermal comfort achieved through the different configuration of PCM applications.
Chapter 5 describes the incorporation of PCM in the supply air duct of the hollow core concrete slab system. It discusses the overall performance of the hollow core slab system due to the PCM application in reducing the diurnal temperature fluctuation. The chapter outlines the experimental and numerical methods used to study the influence of PCM application in hollow core concrete slab.

Chapter 6 describes the experimental study of thermal conductivity and heat capacity of geopolymer at high temperatures using standard steady state method. It also explores the same properties of geopolymer concrete at high temperatures with repeated heating cycle. Chapter 7 outlines a numerical approach to identify these thermal properties of geopolymer under time-dependent dynamic heating condition.

Finally, the conclusions of this research are presented in Chapter 8 followed by the future recommendations from the author.
CHAPTER TWO

2 LITERATURE REVIEW

2.1 THERMAL ENERGY STORAGE (TES) SYSTEM IN ROOM TEMPERATURE APPLICATIONS

2.1.1 Introduction
Thermal energy storage (TES) system offers an attractive means of increasing the energy efficiency of a building through reducing the operational energy requirements such as space heating and cooling, water heating etc. of the building. The storage of thermal energy in a building can be accomplished through either storing the heat as sensible heat or latent heat (phase change) in the building materials [5]. In the case of sensible heat storage, the thermal energy is stored by increasing or decreasing the temperature of the storage material. The concept of using the sensible heat of the building materials for thermal storage has been known for thousands of years and is reflected in the designs of many old buildings. The principle building elements used for sensible heat storage are masonry walls, rock beds, concrete floors, and ceilings, etc. In the case of latent heat storage, the material changes its phase and store the heat as a latent heat of fusion [5]. Of late, the use of latent heat storage materials has received much attention. This is because it can provide more effective storage of heat with a comparatively very small amount of materials and can store heat at almost constant temperature. Latent heat storage materials are known as Phase Change Material (PCM).

2.1.2 Latent Heat Thermal Energy Storage (LHTES)

2.1.2.1 Phase Change Material (PCM)
Phase change materials (PCM) changes their phase as the temperature increases or decreases beyond the phase change temperature. During this phase change, PCMs
absorb (which is called ‘charging’) or release (which is called ‘discharging’) the energy equivalent with their latent heat [5]. Figure 2.1 shows a typical temperature vs stored heat curve for both the sensible and latent heat storage system. In case of sensible heat storage system, the temperature of the building material increases continuously with stored thermal energy. For latent heat storage system, energy is stored as sensible heat until the temperature reaches the phase change temperature. At this point, phase transition occurs from solid to liquid or liquid to gas and the energy is stored as latent heat at nearly constant temperature. When the phase transition is completed, energy is stored as sensible heat again. The latent heat storage system is more effective due to its higher heat storage capacity per unit volume compared to the sensible heat storage system [33]. When the ambient temperature drops again, the PCM returns to its previous state by giving up the absorbed heat. This cycle stabilises the interior temperature, cuts off cooling and heating loads.

![Figure 2.1 Typical temperature vs stored heat curve for thermal storage system](image)

### 2.1.2.2 Types of Phase Change

The types of phase change that occur at a constant temperature with the absorption or release of latent heat includes [5]:

1. Solid-solid transformation
2. Solid-liquid transformation
3. Liquid-gas transformation
4. Solid-gas transformation
5. Liquid-liquid transformation

Of all the transformations, vaporization has the highest latent heat per unit weight. But, this is not practical because of large volume change. It will require large pressure vessels which greatly complicates the design of the thermal storage system (TES). The liquid transformation involves very small amount of energy change and solid-solid transformations would involve special packaging to accommodate volume changes. Hence, the most suitable phase change for TES in buildings is the solid-liquid transformation. The volume change in melting are rather small and the design problems are drastically simplified compared to the systems with other types phase change [5].

2.1.2.3 Selection Criteria of PCM
The phase change materials should have certain thermodynamic, kinetic and chemical properties for their application as heat storage in building constructions. These are summarized in Table 2.1 [34, 35]:

---

**Table 2.1**

<table>
<thead>
<tr>
<th>Property</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermodynamic</strong></td>
<td>High heat capacity, low latent heat</td>
</tr>
<tr>
<td><strong>Kinetic</strong></td>
<td>Fast phase change, low viscosity</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td>Stable, non-toxic</td>
</tr>
</tbody>
</table>

---
### Table 2.1 Selection criteria of phase change materials for thermal storage

<table>
<thead>
<tr>
<th>Types of criteria</th>
<th>Brief description</th>
</tr>
</thead>
</table>
| **Thermodynamic Criteria**| - Phase change temperature range close to the desired comfort temperature range.  
- High latent heat of fusion per unit mass, so that smaller quantity of material can absorb a higher amount of energy.  
- High density, so that a smaller container volume can hold the material.  
- High specific heat to provide additional sensible heat storage.  
- High thermal conductivity to ensure good heat transfer rate during charging and discharging of PCM.  
- The material should have a congruent melting point so that the liquid and solid phases are identical in composition. Otherwise, there will be differences in densities which would lead to segregation and change in chemical composition.  
- During the phase change, the change of volume should be small to facilitate simpler containment and heat exchanger geometry. |
| **Kinetic Criteria**       | - No supercooling and an adequate crystallization rate are required during freezing. The material should solidify at its thermodynamic freezing point. This requires a large rate of nucleation and growth. Otherwise, the liquid will have supercooling effect and the stored energy will not be released. |
| **Chemical Criteria**      | - Chemical stability despite cycling to ensure long term application.  
- Non-corrosiveness to construction material.  
- Non-toxic and non-flammable. |
| **Economic Criteria**      | - Should be cheap and available in large quantities |

#### 2.1.2.4 Types of PCM

Phase change materials can be divided into three types based on their chemical composition [33, 34, 36] as shown in Figure 2.2:
Each group has its typical range of melting temperature and enthalpy which is shown in Figure 2.3 [33].
2.1.2.4.1 Organic PCM

Organic PCMs can be divided into two subgroups: i) paraffin and ii) non-paraffin.

Paraffin

Paraffin are mainly straight-chain hydrocarbons (C\(_n\)H\(_{2n+2}\)) with a limited amount of branching. The thermal capacity of the paraffin is within the range of 120 kJ/kg to 210 kJ/kg and they are relatively cheaper in price. They are non-corrosive, non-toxic, melt congruently during phase change and are available in a wide range of melting temperatures from approximately 20°C to 70°C. Furthermore, they are non-corrosive, have good chemical stability and do not suffer from supercooling. However, paraffin has lower thermal conductivity and it is a inflammable material which narrow down its applications. Also its change of volume during the phase change is larger [33]. The thermal conductivity of the paraffin can be improved by using metallic fillers and matrix structures, while large volume change can be facilitated by using plastic containers of different geometric shapes [33].

Non-paraffin

The non-paraffin organic PCMs consist of wide range of fatty acids, esters, alcohols, and glycols. Among these, fatty acids (CH\(_3\)(CH)\(_{2n}\)COOH) are widely used. Commonly used fatty acids as PCM can be divided into six groups: caprylic, capric, lauric, myristic, and palmitic acid. They have the ability of repeatable melting and freezing behaviour with little or no supercooling during freezing [34]. The latent heat of fusion of these PCMs are high and also volume change during the phase change is limited. One of the main disadvantages is that these PCMs are costlier than that of paraffin [34].

2.1.2.4.2 Inorganic PCM

Inorganic PCMs are generally non-flammable, less expensive and have good thermal conductively. The heat of fusion of these PCMs is quite high (Figure 2.3). On the negative side, most of them show corrosive behaviour to metals and experience supercooling and phase decomposition. Hydrated salts are among the commonly used inorganic PCMs. They have a greater storage density of about 240 kJ/kg, a higher thermal conductivity of about 0.5W/(mK) and they are economic compared to paraffin waxes. Most notable one
is Glauber’s salt which has a melting temperature range of 32°C to 35°C with a latent heat of 254 kJ/kg [33]. Among the disadvantages, the salt hydrates PCMs have the problem of incongruent melting which leads to phase segregation. Without the proper measures, this phase changing process can become irreversible, i.e. the constituents will not combine during freezing process. Another issue is the poor nucleating properties due to which these PCMs experience supercooling prior to the freezing process [34].

2.1.2.4.3 Eutectics

Eutectics are a mixture of multiple PCMs. They can be classified into three groups according to the materials of which they consist: (i) organic–organic, (ii) inorganic–inorganic and (iii) inorganic–organic eutectics. Generally, they have narrower melting/freezing points. Also, they have slightly higher volumetric storage density compared to the organic compounds.

A comparison of different kinds of PCM is presented in Table 2.2:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic PCMs</strong></td>
<td>1. Availability in a large temperature range</td>
<td>1. Low thermal conductivity (around 0.2 W/m K)</td>
</tr>
<tr>
<td></td>
<td>2. No supercooling</td>
<td>2. Relative large volume change</td>
</tr>
<tr>
<td></td>
<td>3. Chemically stable and recyclable</td>
<td>3. High Flammability</td>
</tr>
<tr>
<td></td>
<td>4. Good compatibility with other materials</td>
<td>4. High cost</td>
</tr>
<tr>
<td></td>
<td>5. Ability to melt congruently</td>
<td>5. Low volumetric latent heat storage capacity</td>
</tr>
<tr>
<td></td>
<td>6. High heat of fusion</td>
<td></td>
</tr>
<tr>
<td><strong>Inorganic PCMs</strong></td>
<td>1. High heat of fusion</td>
<td>1. Supercooling</td>
</tr>
<tr>
<td></td>
<td>2. High thermal conductivity (around 0.5 W/m K)</td>
<td>2. Corrosion</td>
</tr>
<tr>
<td></td>
<td>3. Low volume change</td>
<td>3. Segregation</td>
</tr>
<tr>
<td></td>
<td>4. Cheap</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Not flammable</td>
<td></td>
</tr>
<tr>
<td>Classification</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>----------------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td>6. High volumetric latent heat storage capacity</td>
<td></td>
</tr>
<tr>
<td><strong>Eutectics</strong></td>
<td>1. Narrow melting temperature</td>
<td>Thermo-physical properties data are not available</td>
</tr>
<tr>
<td></td>
<td>2. High volumetric thermal storage density</td>
<td></td>
</tr>
</tbody>
</table>

A list of PCMs that are investigated in the literature for application with Building materials has been presented in Table 2.3:

**Table 2.3 List of PCM used in Building materials.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Types</th>
<th>Chemical name</th>
<th>Melting point (°C)</th>
<th>Latent heat (kJ/kg)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic</strong></td>
<td>Paraffin</td>
<td>CH₃(CH₂)₁₆CH₃</td>
<td>18 – 23</td>
<td>205.1</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tech. grade octadecane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heptadecane</td>
<td>22</td>
<td>214</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hexadecane</td>
<td>18</td>
<td>236</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Octadecane</td>
<td>28</td>
<td>244</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30% K18 (alkyl hydrocarbons)</td>
<td>23.9 – 32.2</td>
<td></td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paraffin C₁₆-C₁₈</td>
<td>20 – 22</td>
<td>152</td>
<td>[39-41]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paraffin C₁₃-C₂₄</td>
<td>22 – 24</td>
<td>189</td>
<td>[39-41]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paraffin C₁₈</td>
<td>28</td>
<td>244</td>
<td>[39-41]</td>
</tr>
<tr>
<td><strong>Non-paraffin</strong></td>
<td></td>
<td>CH₃(CH₂)₁₁OH</td>
<td>17.5 – 23.3</td>
<td>188.8</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dodecaol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₃(CH₂)₁₀COO(CH₂)₃CH₃</td>
<td>22.5 – 26.2</td>
<td>140</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Butyl stearate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₃(CH₂)₁₀COOC₃H₇</td>
<td>16 – 19</td>
<td>186</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propyl palmitate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Caprilic Acid</td>
<td>16.5</td>
<td>149</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vinyl Stearate</td>
<td>27 – 29</td>
<td>122</td>
<td>[39-41]</td>
</tr>
</tbody>
</table>

13 | Page
<table>
<thead>
<tr>
<th>Group</th>
<th>Types</th>
<th>Chemical name</th>
<th>Melting point (°C)</th>
<th>Latent heat (kJ/kg)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PolyglycolE600</td>
<td>Inorganic</td>
<td>KF·4H₂O</td>
<td>18.5 – 19</td>
<td>231</td>
<td>[37]</td>
</tr>
<tr>
<td>Inorganic</td>
<td>Hydrate salts</td>
<td>Potassium fluoride tetrahydrate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CaCl₂·6H₂O</td>
<td>24 – 29</td>
<td>192</td>
<td>[42]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calcium chloride hexahydrate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mn(NO₃)₂·6H₂O</td>
<td>25.8</td>
<td>125.9</td>
<td>[39-41]</td>
</tr>
<tr>
<td>Eutectic</td>
<td>Organic-Organic</td>
<td>45/55 Capric–lauric acid</td>
<td>17 – 21</td>
<td>143</td>
<td>[37]</td>
</tr>
<tr>
<td>Eutectic</td>
<td>Organic</td>
<td>Emerest 2325 (butyl stearate + butyl palmitate 49/48)</td>
<td>17 – 21</td>
<td>138</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emerest 2326 (butyl stearate + butyl Palmitate 50/48)</td>
<td>18 – 22</td>
<td>140</td>
<td>[44]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capric–lauric 82/18</td>
<td>19.1 – 20.4</td>
<td>147</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capric–lauric 61.5/38.5</td>
<td>19.1</td>
<td>132</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capric–myristic 73.5/26.5</td>
<td>21.4</td>
<td>152</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capric–palmitate 75.2/24.8</td>
<td>22.1</td>
<td>153</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capric–stearate 86.6/13.4</td>
<td>26.8</td>
<td>160</td>
<td>[45]</td>
</tr>
<tr>
<td>Organic-Inorganic</td>
<td>Inorganic-Inorganic</td>
<td>CaCl₂(48%)+NaCl(4.3%)+KCl(0.4%)+H₂O(47.3%)</td>
<td>26.8</td>
<td>188</td>
<td>[34, 39-41]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca(NO₃)₂·2.4H₂O (45%)+Zn(NO₃)₂·6H₂O (55%)</td>
<td>25</td>
<td>130</td>
<td>[5]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CaCl₂·6H₂O+Nucleat+MgCl₂·6H₂O(2:1)</td>
<td>25</td>
<td>127</td>
<td>[39-41]</td>
</tr>
</tbody>
</table>
2.1.2.5 Methods of PCM introduction in Building

Hawes et al. [46] reported three methods of introducing PCMs in the conventional building materials: direct incorporation, immersion, and encapsulation.

2.1.2.5.1 Direct incorporation during manufacturing

In this method, PCM filled fillets are added to the wallboards during manufacturing. It is potentially the least expensive and most practical method. No additional equipment is required for this method of incorporation. But the major drawbacks of this method are leakage and incompatibility of the PCM with original building materials. Its successful application depends on some critical factors. PCM used in this method should be in the solid phase at mixing and setting temperature of concrete so that PCM does not hinder the hydration process and does not alter the strength of the paste-aggregate bond. Also, there should not be any significant reaction between PCM and either of the components of the mix or the products [46, 47].

2.1.2.5.2 Immersion Technique

This technique involves dipping the building blocks in liquid PCM. In this process, the PCM is heated and melted under controlled temperature in a container where aggregates (or wallboard, concrete, etc.) are immersed in PCM for some time. After the adsorption process, the aggregates are then taken out and left to drain off the excess PCM and drying [48]. The process is quite flexible and can be used for a variety of PCM application temperatures. In addition, this method can be applied to introduce PCM in ordinary concrete products, either as a part of the continuous production process or as a batch process and can be done at any time of production [47]. Moreover, since the facilities required for immersion are relatively simple and not related to basic products, they can be set up at any convenient place in, adjacent to or remote from the plant. The amount of heat that can be stored in the block with PCM, incorporated in this technique, will depend on process condition such as the temperature of PCM, the temperature of the block, time of immersion and number of immersion [47]. However, on the negative side, few studies have reported leakage problem in this method which is unfavourable for long time application [36].
2.1.2.5.3 Encapsulation

This process comprises of putting the PCM in a capsule of different materials, forms and sizes before incorporating it into construction materials. Thus, they can be conveniently introduced into the mix [47]. There are two principle means of encapsulation:

*Macroencapsulation*

This procedure involves the insertion of PCM in packages such as tubes, pouches, spheres, and panels etc. as shown in Figure 2.4. These packages can work as heat exchangers as well as can be combined in a building product. Using macro-encapsulated PCMs, there will be no leakage and the effect on building structure is less. However, the disadvantage of macro-encapsulation method is the poor heat transfer through the PCM due to low thermal conductivity. When it is time to discharge the heat to the surroundings through the phase change, PCM solidifies only around the edges of the container and thus reduces the efficiency of the system [35, 47].

*Figure 2.4 Macro-encapsulated PCM [49, 50]*

*Microencapsulation*

In this process, small spherical or rod-shaped PCM particles are confined in a thin, high molecular weight polymeric film [35]. Then, the micro-size coated particles can be introduced into any matrix compatible with the encapsulating film. It follows that the film coating must have a neutral effect on both the PCM and the matrix. Unlike macro-encapsulation method, the particle dimensions are very small which results in high heat
transfer rate due to high surface to volume ratio of the microcapsules. Through the microencapsulation, PCM inclusion in building materials becomes simpler and economic. The shell of the microcapsules is hard enough to handle the volume change during phase transition. Although the microencapsulation method is expensive, it is much safer method due to the fact that PCM is not in direct contact with the building materials. Microencapsulation of PCM in concrete is quite effective. The drawback of microencapsulation in concrete is that this can also adversely alter the mechanical strength of the concrete [35]. Several methods of microencapsulation are available in the literature. The most common methods are:

- Interfacial polymerization [51-54]
- Emulsion polymerization [55]
- In situ polymerization [56]
- Spray drying and coacervation [57]
- Core–shell templating [58]

**Table 2.4 Thermal properties of some commercial PCMs [36, 40, 59, 60].**

<table>
<thead>
<tr>
<th>Commercial name</th>
<th>Type of PCM</th>
<th>Melting point (°C)</th>
<th>Heat of fusion (kJ/kg)</th>
<th>Source</th>
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<td>Heat of fusion (kJ/kg)</td>
<td>Source</td>
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### 2.1.2.5.4 Shape stabilized PCM

Due to the leakage issue and high costs associated with encapsulation, a novel PCM compound called shape stabilized PCM has become popular among the researchers [61-63]. In shape stabilised PCM, the paraffin PCM is dispersed in the high-density polyethylene (HDPE) or other supporting material. The important thing is this type of compound PCM can maintain its shape even if it experiences a temperature over the melting point of the paraffin PCM. The HDPE act as an auxiliary material to the paraffin PCM where it prevents leakage of the liquid paraffin at temperatures between the
melting temperature of paraffin and HDPE. Therefore, the encapsulation problem of the paraffin can be solved [63]. Moreover, Sari [63] reported that the thermal conductivity of Shape stabilized PCM compound can be increased by 24% with the addition of 3wt% exfoliated graphite. This can improve the heat transfer rate of PCM and make it more efficient. Zhang et al. [64] studied a shape stabilised PCM (Figure 2.5) and reported that it can effectively simplify the thermal storage system due to the fact that it does not require any special mechanism or containers for the encapsulation process. Thus, the shape stabilised PCM, as they suggested, has the potential to be easily implemented in the building applications such as floor, ceiling and wall. However, it was reported that in the shape stabilised PCM the paraffin tends to diffuse towards the surface and slowly escape out of the PCM compound. This creates various problems such as leakage, frosting and rapid weakening of thermal properties. Different surface treatments such as grafting and cross-linking can be implemented to avoid leakage issue [64].

Li et al. [65] incorporated microencapsulated paraffin (MEP) into a matrix of HDPE/wooden floor composite. In this composite PCM, Micro-mist graphite (MMG) was introduced to increase thermal conductivity. The scanning electron microscope (SEM) images showed that the form-stable PCMs have a consistent structure and most of MEP particles in them were intact. Leakage of molten paraffin was prevented by both the shell of MEP and the matrix. For this reason, the composite PCMs were called as form-stable PCMs. The results from DSC indicated that the latent heats, the melting and the freezing temperatures of the form-stable composite PCMs is appropriate for applications in LHTES. Thermal cycling test presented that this type of PCMs has good thermal stability even if it was exposed to 100 melt-freeze cycling. The thermal conductivity of the composite PCM was improved by 17.7% by introducing 8.8wt% of MMG and this addition of MMG did not adversely affect the mechanical properties of the PCM. The experimental results concluded that due to their suitable phase change temperatures, enhanced thermal conductivity, leak-proof characteristics and good mechanical properties, the form stable PCMs can be suitable for thermal energy storage applications. In a recent study, Li et al. [66] incorporated expanded graphite (EG)/paraffin PCM composite into cement mortar in an attempt to increase the heat storage capacity of cement mortar. First of all, the composite was prepared by absorbing
paraffin into EG with vacuum absorption method. The ratio of EG and PCM was selected in such a way that liquid PCM does not leak from the composite. Hence, encapsulation of PCM was not required and also the EG increased the thermal conductivity of the PCM composites. The PCM composites were then mixed with the cement in different proportions and the heat storage coefficients of the prepared specimens were tested through an equation proposed by them. It was reported that the heat storage coefficient of the cement mortar with composite PCM is 1.74 times higher than that of ordinary cement mortar.

Figure 2.5 (a) Shape-stabilized PCM plate (b) Image from scanning electric microscope (SEM) [64]

2.1.2.6 Classification of PCM Application

Figure 2.6 shows a classification of PCM application from Rodriguez-Ubinas et al. [67]. The classification was carried out based on two points which were – (1) the way PCM are introduced in buildings (2) the factors associated with their usage. The first level, the application is divided into the PCM application in the passive and active system. In the passive system, no mechanical equipment is used. The heat transfer takes place automatically depending on the change of air temperature beyond the melting point of the PCM. The passive system can be benefited from both solar gains (direct or indirect) and internal thermal gains. On the other hand, the active system requires the use of a mechanical device for charging and discharging of thermal energy. The second level of classification is connected to the introduction of PCM in the buildings. They can be used as components or integrated into the building materials or used as separate storage units.
Among these, the PCM is used as components when it is incorporated in the building sections as a layer or part. On the other hand, when the PCM is blended with the construction material, they are termed as “integrated”. PCM can be used as a component or can be integrated into the building materials in both, passive and active systems. PCM application as a storage unit is only applicable for active applications. In general, it is kept thermally detached from the building through insulation. In active systems, water, air or both can be used as a thermal energy exchange medium.

![Figure 2.6 PCM applications classification diagram](image)

2.1.2.6.1 Passive application

(a) *PCM in Wallboard*

Wallboard is one of the most commonly used building materials. It is also inexpensive. For these reasons, it is an excellent choice for applying PCMs. The addition of PCM with wallboards serve as distributed thermal storages which enable passive solar design and cooling in off-peak times within a typical frame of structure and small thermal mass [33, 68].

Kedl [69, 70] impregnated conventional gypsum wallboard with octadecane paraffin (melting point 23°C). The wallboard was immersed in the molten paraffin for the impregnation process. The studies reported that a maximum concentration of 35% of wax by weight can be achieved in the final combined product. Both laboratory scale and full-scale wall board were tested and after impregnation, the properties of wallboard were found unchanged. High-temperature tests and thermal cycling tests of the
wallboards did not indicate any tendency of migration of the paraffin in the wallboard, and TES capacity was intact. But a small amount of paraffin did evaporate and condense on the chamber door. The appearance of surface frost on the material, similar to hoarfrost as seen on a cold winter morning, was also observed.

Feldman et al. [43] made an energy storage gypsum wallboard in laboratory scale by directly applying 21-22% commercial grade butyl stearate (BS) during the typical gypsum board production. The introduction of BS was aided using a small quantity of dispersing agents. The physio-mechanical properties of the constructed wallboard remained quite similar in comparison with the standard gypsum board. In terms of energy storing capacity of the PCM incorporated wallboard; it was found that the capacity improved ten times greater than that of a typical gypsum wallboard.

Athienitis et al. [71] carried out an experimental and numerical investigation of the performance of a PCM incorporated gypsum wallboard in a full-scale outdoor test room in Montreal. The PCM-gypsum board used contained about 25% by weight proportion of butyl stearate which had a phase change temperature range of 16°C – 20.8°C. It was shown that the maximum room temperature decreased by 4°C during daytime through the utilization of PCM-gypsum wallboard instead of normal gypsum wallboard.

Kissock et al. [18] carried out an experimental study of two identical outdoor test-cells. In one cell, typical wallboard was used whereas in another cell, wallboard with commercially available paraffinic PCM K18 (30% by weight) was introduced. It was found that in the PCM cell, the maximum temperature was reduced by 10°C than that of the typical cell during sunny days in Dayton, Ohio. However, it was pointed out that K18 is not optimum PCM for building applications in that area as the range of melting temperatures (23.9°C – 32.2°C) does not coincide with normal operating temperatures in buildings (18°C – 23.9°C).

A similar study of twin identical test cell also carried out by Scalat et al. [72]. The results of their study showed that wallboard embedded with PCM was able to keep the room temperature within the thermal comfort zone for greater periods. It is important to note that the HVAC system was kept off during the period. It was concluded that PCM
wallboard can contribute to the peak load shifting and also improve the efficiency of the heating and cooling equipment operation. Stovall and Tomlinson [73] also showed that PCM wallboard has significant load management potential. It was reported that success of using PCM depends on the critical interactions between thermostat control strategy (when to turn on and off), PCM melting temperature and PCM placement. The thermostat should be controlled in such a way that the PCM remains completely charged i.e. melted at the start of the on-peak period (the period during which thermostat remains completely off to avoid using the on-peak high-cost energy). It was also reported that two different PCM with two different melting temperature can be used in a single structure where it can provide improved thermal comfort, the overall reduction in energy consumption and allow usage of PCM all the year round.

Neeper [74] investigated the thermal dynamics of a paraffin wax and fatty acid impregnated gypsum wall board. The PCMs were exposed to the diurnal change of room temperature but were not directly exposed to the sun. The melting temperatures of these PCMs were regulated using a blend of different ingredients. The parameters of PCM wallboard which were studied are (a) the temperature of melting of the PCM; (b) the range of temperatures over which melting happens; and (c) the latent capacity per unit area of the wallboard. The study showed that the diurnal energy storage was maximum when the melting temperature of the PCM was near to the average comfort room temperature. Diurnal energy storage reduced when the phase transformation happened over a range of temperature. Zhang et al.[75] reported that PCM application in the internal wall would be the maximum energy efficient approach in a solar house.

Shilei et al. [76] studied the impact of PCM wallboard on the thermal comfort of the room during winter in the northeast of China. A blend of lauric acid and capric acid was used as PCM which was integrated into PCM wallboard through immersion technique. It was found that the use of PCM wallboard decreases the temperature swing inside the room as well as the scale of heating equipment and relevant costs. Chen et al. [15] reported that energy savings can get to 17% or higher if phase transition temperature and enthalpy is set at 23°C and 60 kJ/kg respectively during winter season in north China.
Kuznik et al. [9] studied the thermal behaviour of PCM wallboard in a controlled test room, known as MINIBAT, where 12 spotlights were used to simulate the sunlight and solar radiation. A 5 mm thick PCM wallboard consisting of 60% microencapsulated PCM were used in the side wall. Figure 2.7 shows the schematic of the wall compositions with and without PCM used in their study.

The results reported that the incorporation of PCM wallboard decreases air temperature fluctuation inside the test room. The available thermal storage energy was doubled by using PCM wallboard and the energy storage was equivalent to an 8 cm concrete slab [9]. Kuznik and Virgone [77] investigated the performance of PCM in three different weather condition of the year: summer season day, mid-season day and winter season day. Night ventilation system was used in the experiment of summer season day and A 1500W heating system was placed into the room to heat it up if the temperature falls below 20°C in the winter season day experiment. For all the weather conditions, the PCM wallboards decreased the air temperature of the room in comparison to that of typical wallboards. The decrement factor (the ratio between the amplitude of the indoor air temperature in the cell with and without PCM) of the air temperature amplitude varied between 0.73 and 0.78. In their other study [78], it was reported that the temperature vs enthalpy graph does not follow the same path during melting and solidification. The hysteresis effect was clearly shown in the experiment where the melting was found to be starting at a temperature above the solidification process.
Borreguero et al. [79] investigated the effect of the incorporation of microencapsulated PCM in the gypsum wallboards to increase its thermal storage capacity. At first, the influence of the variable core/coating mass ratio on the polymerization process was studied. It was found from the results that the increase of paraffin wax to styrene monomer mass ratio decreases the efficiency of microencapsulation process. The maximum energy storage capacity and suitable microencapsulation efficiency were reported when the mass ratio of Rubitherm RT27 to styrene monomer was 1.5. It was also noticed that the energy storage capacity varies with the particle size. The highest capacity was reported when the particle size is 500 µm.

Figure 2.8 (a) Micronal® PCM (from BASF) incorporated Gypsum wall board; (b) thermalCORE phase-change drywall (from National Gypsum) [79]

Finally, studies were conducted with three gypsum wallboards to investigate their thermal characteristics. One wallboard did not contain any PCM and the other wallboards were loaded with microencapsulated PCMs containing Rubitherm RT27 with an amount of 4.7% and 7.5% by weight and at the best core/coating mass ratio. The outcomes of the investigation indicated that the amount of microcapsules can influence the external wall temperature. The greater the quantity of PCMs incorporated to the wallboard, the higher or lower the temperature of the external wall for cooling or heating process respectively. Also, the introduction of PCMs to wall increased the time needed to reach steady-state and hence insulation capacity of the walls was improved with the increasing of PCMs content.

Oliver [80] reported that a PCM incorporated gypsum board of 1.5 cm thickness can store thermal energy five times more than a typical gypsum board. This is also
equivalent to the energy stored by a brick wall with a thickness of 12 cm within the comfort temperature range (20°C to 30°C). In recent times, National Gypsum ThermalCORE Panel, a new type of wallboard panels with embedded Mirconal PCM, has been manufactured by National Gypsum. Figure 2.8 shows this kind of panels. The melting point and latent heat capacity are 23°C and 22 BTU/ft², respectively.

Rudd [81] measured the thermal storage capacity of PCM incorporated (coconut fatty acid) wallboard in both small and room scale experiments. It was shown that the thermal storage capacity in room scale experiments varied by only 8.7% compared to small scale DSC measurement. This showed that small scale testing can sufficiently predict the thermal behaviour of a wallboard with PCMs for a full-scale use. Therefore, large-scale testing, which is often costly and time-consuming, may not be needed for the initial stage of investigation. Shilei et al. [13] also reached to the similar conclusion in their experimental study where 5.66% variation in thermal storage capacity was reported between the room scale experiments and small-scale DSC measurements.

(b) **PCM in Concrete**

PCMs can also be introduced in building materials by incorporating them into concrete matrix or open cell cements. This composite is known as thermocrete. Hawes et al. [46, 47, 82] studied the thermal performance of PCMs (Butyl stearate, dodecanol, paraffin, tetradecanol) in different types of concrete blocks. PCMs were incorporated through immersion technique in their study. The effects of concrete alkalinity, temperature, immersion time and PCM dilution on PCM absorption during the incorporation process were investigated. Autoclaved concrete block was found to be most suitable for PCM application due to its low alkalinity. It was reported that the thermal storage of concrete increased up to about 30% due to the incorporation of PCMs. Hawes and Feldman [83] investigated PCM absorption mechanism in the building materials. They developed a way of finding absorption constants for PCM in concrete so that it is possible to determine how much PCM is needed to achieve certain thermal storage capacity.

Slayer [84] showed that the most promising PCM containment methods in hollow core building blocks are: (1) Incorporating the PCM into porous materials, 2) Putting the PCM into finely divided special silicas and 3) Infusing the PCM into polymeric carriers. They
have found that the PCM when implanted into the hollow space of concrete blocks in the form of PCM melt-mix, PCM/silica dry powder, or the PCM/HDPE, it can facilitate a greater amount of PCM which can help achieving higher thermal storage capacity.

Zhang et al. [85] developed a two-step method for adding PCM in building materials. In the first step, porous aggregates and PCM in liquid form is mixed to produce thermal energy storage aggregates (TESAs). Vacuum impregnation technique was used to carry out this step. In the second step, thermal energy storage concrete (TESC) was made by blending Portland cement, TESAs, and other raw materials of typical concrete. This technique uses porosity of the aggregates to facilitate adequate storing space for PCM. Also, there is less leakage and pollution of the PCM due to the existence of surrounding cement material. It was found that PCM can enter into the pores of a diameter of 1 to 2 µm and thereby, can take maximum 75% of the entire pore area. It was reported that TESC can be more effective in energy conservation of building compared to that of normal concrete.

Hadjieva et al. [86] used sodium thiosulphate pentahydrate (Na2S2O3 .5H2O) as a PCM material. PCM was incorporated into concrete by immersing the concrete into the liquid PCM. Maximum 60% of the pore space of the concrete was filled up by PCM. However, this value was found to decrease by 10% after repeatable thermal cycling of the samples. It was established that the greater absorption area of porous concrete can provide a good supporting matrix to the PCM and hence provide stability to the PCM structure during thermal cycling.

Cabeza et al. [14] used MOPCON concrete (a mixture of commercially available microencapsulated PCM called Micronal® PCM and concrete) in their experimental study. The mechanical strength and thermal behaviour was tested. It was reported that the MOPCON concrete can reach a compressive strength of over 25 MPa and a tensile strength of over 6 MPa (after 28 days). These high mechanical strengths looked promising for the structural application of MOPCON concrete. Therefore, two full-size concrete cubicles were built at Puigverd of Lleida in Spain where one of the cubicles contains MOPCON concrete in south, west and roof walls (Figure 2.9). The results showed an increase in thermal energy storage in the walls. PCM walls took 2 more hours
to reach the highest temperature in comparison to the walls without PCM. It implies that the thermal inertia was increased by the addition of PCM. It was also reported that the user behaviour (such as opening and closing windows) is important for the effectiveness of phase change materials. The effectiveness of PCM was found to vary with the opening and closing of windows. It was reported the night ventilation is very important to achieve full PCM cycle during summer. Castellon et al.[87] installed a trombe wall on the south wall of the reference [14] and investigated the possibility of reaching the PCM melting temperature i.e charging the PCM when the outside temperature is below the melting point of PCM. It was reported that trombe wall can be used to increase the wall surface temperature during winter in order to melt the PCM. The main advantage of melting the PCM in winter season is that the wall minimum temperatures can be increased in 1 or 2°C.

Figure 2.9 Experimental concrete cubicles[14]

Hunger et al. [88] carried out a number of experiments with varying quantity of microencapsulated PCM. It was found that increase in PCM amounts lessened thermal conductivity and increased heat capacity. Both of these characteristics yield significant improvement in thermal performance of concrete and thereby save energy. Energy savings up to 12% was calculated as a result of the inclusion of 5% PCM in the concrete mix. On the other hand, it was observed that increasing PCM dosages lead to significantly lower compressive strengths. However, the measured compressive
strength of the concrete containing 3% PCM was 35 MPa which is adequate for the structures applications. Destruction of PCM microcapsules, which results in leakage of wax materials, during mixing with concrete was attributed to the loss of compressible strength. Development of stronger shells was recommended for the micro-encapsulated PCM.

Shi et al. [89] carried out an experimental study to investigate the performance of a macro-insulated PCM attached to different positions of the concrete wall. This study was carried out in a room model (545 mm × 545 mm × 560 mm) placed in a weather of Shenzhen city, China. Paraffin PCM was macro-encapsulated in a steel box and it is attached to the concrete wall at three positions, i.e. externally bonded, laminated within and internally bonded. The results concluded that the model with laminated or sandwiched macro-encapsulated PCM was the best among three in temperature reduction and a reduction of maximum temperature by 4°C was reported from this model compared to the base model. However, the model with internally bonded PCM was found to be most effective in humidity control where a minimum of 16% reduction of relative humidity was recorded compared to the base model without PCM.

Memon et al. [90] developed a macro-encapsulated paraffin-lightweight aggregate (LWA) as a thermal energy storage. The paraffin PCM was introduced in porous LWA through the vacuum impregnation. Then epoxy was used to seal the LWA. To improve the thermal conductivity of the macro-encapsulated paraffin-LWA, a 15% wt of graphite powder, an optimum amount evaluated through the experiment, was incorporated into the epoxy. The study found that the maximum amount of paraffin soaked by LWA was 70% and the thermal conductivity of the final product was increased by 162% due to the incorporation of graphite powder. Finally, the macro-encapsulated paraffin-LWA was introduced in normal weight aggregate concrete (NWAC). The indoor experimental results showed that the maximum reduction of indoor temperature was 3°C due to the incorporation of macro-encapsulated PCM in NWAC. In another study, Memon et al. [91] this macro-encapsulated PCM technology to lightweight aggregate concrete (LWAC). The similar indoor experiment showed that LWAC was able to reduce the maximum temperature by 4.7°C with the help of macro-encapsulated paraffin-LWA.
Also the outdoor performance test suggested that the optimum performance of macro encapsulated Paraffin-LWA in adjusting the room temperature was found to be dependent of large swing between the day and night-time temperature.

Zhang et al. [92] developed a novel cement composite where flaky graphite-doped microencapsulated PCM (FGD-MPCM) was incorporated into it. The composite structure was tested through different techniques and the results showed that the spherical microcapsules were well dispersed and thermally stable in the cement composite. The storage capacity was improved with the increase of the FGD-MPCM incorporation in the composite matrix. Nonetheless, the mechanical strength of the composite was affected by the increase of FGD-MPCM incorporation as well as the porosity of the composite. The results concluded that the model test room with cement composite containing 20% FGD-MPCM was able to decrease the maximum temperature by 6.22°C.

Baetens et al. [33] showed that the concrete buildings with the enhanced thermal mass is better than the application of PCM wallboard due to the greater thermal capacity of thermocrete. Nevertheless, the main issue was reported to be the high cost of the PCM product.

*(c) PCM in Insulation Materials*

In this process, the microencapsulated PCM is incorporated into the conventional insulation materials of the buildings. It was developed by Oak Ridge National Laboratory in collaboration with Microtek Labs and Advanced Fiber technologies during 2007-2008. In this new technology, the PCM is blended with cellulose and fiberglass insulations as shown in Figure 2.10 [93]. These new insulation-PCM blends have low flammability which made them first-ever organic microencapsulated PCMs to be suitable for U.S insulation market.
(d) PCM Under Floor
Entrop et al. [94] embedded microencapsulated PCM directly into the concrete floor to warm up the living room during the evening and early night using solar irradiation. It was found that the using PCM in concrete floors caused a decrease in highest floor temperature up to 16±2% and increased the lowest temperatures up to 7±3%. They suggested that the most efficient ways of PCM incorporation would be to apply the PCM in the concrete mix so that it would work as a thin layer over the floor. This will ensure the PCM to be exposed to direct solar radiation.

(e) PCM in Building roof
Kosny et al. [95] investigated the thermal performance of solar roof/attic containing photovoltaic PCM (PV-PCM) and compared against the traditional shingle roof/attic. It was demonstrated that, during winter the PV-PCM attic had a 30% reduction in roof-generated heating loads compared to a conventional shingle attic. Conversely, during the cooling season, the generated cooling loads from the PV-PCM attic were about 55% lower than the shingle attic. In addition, about 90% reductions in peak daytime roof heat fluxes were observed with the PV-PCM roof.

Pasupathy and Velraj [96, 97] built two similar test rooms to investigate the effect of using PCM panel on the roof of the building. Both the roofs were made of concrete and one of them was incorporated with PCM. It was found that in Chennai city, PCM panel in the roof keeps a constant temperature at the ceiling from the month of December to
April. But during the month of May to November, PCM panel had a negative effect on the indoor temperature. The study recommended that a double layer of PCM should be utilised to reduce the temperature swing and to work well for all seasons.

(f) **PCM in Sandwich Panels**

Sandwich panels are mostly used in commercial buildings because of their good modular features (Figure 2.11). This panels can provide thermal insulation which cannot be achieved by other construction technique. Sandwich panels have various positives like cladding, water tightness, thermal insulation and higher mechanical strength. These panels are made up of two metal sheets and polyurethane foam is sandwiched between them as an insulating material [98].

Castellon et al. [98] conducted experiments to investigate whether application of microencapsulated PCM (Micronal BASF) in sandwich panels increases the thermal inertia of the panels and decrease the requirement for energy in the building. PCM was added to the panels in three ways. Thermal characteristics of all the three cases were studied. In the first case, microencapsulated PCMs were mixed with one of the liquid components of the polyurethane. In the second case, the PCM was combined at the starting point of the production process, before polyurethane was added (Figure 2.12a) and, in the third case, the PCM was added after the polyurethane (Figure 2.12b). In the first case, it was found that the effect of PCM was outweighed by an increase in the thermal conductivity. In the third case, increased thermal inertia was reported. The second case showed conflicting results due to the poor spreading of the PCM. It was observed that using microencapsulated PCM increased stress concentration in the foam and the panel structure. Therefore, the sandwich panels with PCM failed at much lower
stress compared to that of a standard one. Further study was recommended to improve the process.

Ahmad et al. [99] studied the performance of a test cell made of light wallboards with PCMs. It is then compared with the performance of a test cell without any PCMs. A vacuum insulation panel (VIP) was placed with the PCM-containing panel in order to enhance the wallboard efficiency. In the case of the cell without PCM, a VIP was placed between the plywood and fibre panels. In the case of the cell with PCM, walls were made up of a VIP and an additional PCM panel sandwiched between the plywood and the fibre panel, as shown in Figure 2.13. During the summer season, the highest temperature in the cell with PCM was reduced by 20°C over a 24 hours’ cycle. During the winter season, the PCM was able to keep the inside temperature above zero, where the other cell without PCM reaches -9°C when the outside temperature was -6°C. It was also shown that even after 480 thermal cycles the PCM was able to act as a thermal absorber.
Carborani et al. [100] tested four prototypes of PCM incorporated sandwich panels and used them as walls inside a model room to simulate various outdoor and indoor environmental conditions. It was found that the inclusion of an air layer in the middle of the PCM and the final exterior layer improves the thermal performance of the PCM.

(g) PCM in Plaster

Schossig et al. [101] carried out an experimental investigation to study the feasibility of incorporating microencapsulated PCMs into the plaster. Two full-size test rooms with a lightweight construction were built. The interior walls of one of the test rooms were coated with PCM plaster and the other one was coated with normal plaster. Figure 2.14 shows a schematic drawing of this concept with PCM microcapsules integrated into the plaster. Two different PCM plasters were used:

- A 6mm thick plaster with 40% wt. PCM.
- A 15mm thick gypsum plaster with 20% wt. PCM.

It was shown that the temperatures in the test room equipped with PCM decreases up to 4°C compared to the other room without PCM. In the room without PCM, the temperature was greater than 28°C for more than 50 h, whereas the PCM test room was warmer than 28°C only for about 5 h. However, the main limitation of this system was the heat sink at night. In order to function correctly, the passive systems needed a higher
air-change rate at night to discharge the PCM at night. They suggested cooling system (cooling tower and capillary tubes in the plaster) to overcome this limitation.

Voelker et al. [102] used modified gypsum plaster on the wall which consisted of microencapsulated paraffin PCM with a melting of 25°C – 28°C. It was reported that PCM plaster can reduce the maximum room temperature 4°C. Similar to Schossig et al. [101], they also observed that the functionality of PCM decreased after a few consecutive hot days because of the insufficient discharge of PCM during that period. Hence, efficient night ventilation is important for the solidification of PCM.

Vaz Sa et al. [103] incorporated microencapsulated paraffin PCM into cement based plastering mortar. Two small sized closed test cells (one with regular mortar and another with PCM-based mortar) were built using the regular mortar in one and the PCM based mortar in another. It was observed that PCM reduces the internal temperature amplitude at both climate conditions but the effectiveness of PCM was found to be strongly dependent on the environmental thermal cycles. Hence, an optimum operating condition (PCM percentage and melting range) is far from unique and therefore, a compromised solution should be achieved to have the best performance throughout the year.
(h) *PCM in Shutter*

Mehling [104] presented the idea of incorporating PCM in the window shutters. He suggested that the highest shading temperature was deferred by three hours and room temperature was decreased by 2°C with the application of the PCM shutter as shown in Figure 2.15.

**Figure 2.15 PCM shutters [104]**

2.1.2.6.2 Active application

(a) *Hollow Core Concrete Slab*

Many researchers used PCM to enhance the thermal storage benefit of the hollow core slab system. Lee et al. [105] performed large-scale experiments to compare the performance of thermal storage between ordinary hollow core concrete blocks and PCM incorporated hollow core concrete blocks. The concrete block was heated and immersed in the molten PCM bath until required PCM absorption was achieved (3.9%–8.6%). Two types of concrete blocks (Regular block and autoclaved block) and PCMs (Butyl stearate and paraffin) were used. The blocks were laid contiguously to allow continuous air flow through the tunnels formed by their hollow cores as shown in Figure 2.16. For limiting the heat losses, the blocks were installed in a thermally insulated wooden case. Heating and cooling were provided by means of two separate air conditioning systems. The comparative characteristics of these PCM-concrete combinations were examined. It was
demonstrated that the PCM incorporated concrete block has the ability to store the sensible heat of concrete as well as the sensible and latent heat of PCM. This allows the supply of heating and cooling from utilities to be shifted to an off-peak period.

Figure 2.16 Schematic plan of testing facility of Lee et al. [105]

Whiffen et al. [19] presented a laboratory scale experiment on the hollow core slab system with the PCM enhancement. The optimum design of the PCM system which was chosen from the modelling was constructed from aluminium sheet and honeycomb. A 7.5 kg bio-based PCM with an average melting temperature of 24.5°C was used in this study. The installed PCM provided a 29% active surface area with 12.5% energy storage capacity to the overall system. The PCM-enhanced hollow core slab system yielded an average temperature reduction of 1°C during 8 h fixed occupancy period compared to the standard system. During the diurnal operation, 0.1 kWh of energy was saved per day due to the addition of PCM in the system with a maximum of 0.2 kWh reduction during the peak period.
In a similar study, Pomianowski et al. [106] investigated building fabrics with thermal storage in hollow core slab combined with a microencapsulated PCM layer. The PCM layer was placed consist of grooved mortar tiles and PCM which was placed at the bottom of the slab (Figure 2.17). The grooved surface provides increased surface area to enhance the heat transfer. The hollow core slab also included a piping for water circulation system for thermal mass activation. The results of the experiment indicated that the incorporation of PCM layer in the hollow core slab actually reduced its cooling capacity which was attributed to the low thermal conductivity of the PCM or the experimental error.
Navarro et al. [22, 107] developed an innovative hollow core slab system with PCM inside its core, in order to use the system as an efficient thermal storage system. The PCM was macro-insulated in aluminium tubes which were distributed along the air circulation path of the slab (Figure 2.18). The prefabricated prototype was tested in a house like two-story cubicle [22] where the system was used as an internal slab to store thermal energy in order to minimize or eliminate the use of HVAC systems. The cool night time air was used to charge or solidify the PCM as well as the room (free cooling) to prepare itself for the next day cooling operation. An investigation from the control temperature experiment [22] suggested energy savings of 30% - 55% and 15% - 20% in the HVAC system under mild conditions and severe conditions respectively compared to the reference cubicle.

(b) Ventilation

Some researchers also highlighted the benefit of the use of PCM integrated into the ventilation system. To increase energy efficiency of a building, Yanbing et al. [108] suggested an LHTES system consists of PCM Packed Bed Storage with night ventilation (NVP) (Figure 2.19). At night, the LHTES is charged by blowing the outdoor cold air. At daytime, the LHTES system releases the cold to the adjacent room through the air circulation. An experimental setup was constructed using 20 shelves with three layers (2.4 m × 3 m × 0.12 m). They were placed on the ceiling of the test room. About 2000 capsules of fatty acid PCM were used in the study which is equal to 150 kg of PCM. The results of the study showed that the NVP system can reduce the room temperature and increase the thermal comfort.
Takeda et al. [109] developed an airing system where direct heat transfer occurs between air and PCM granules. The PCM packed bed was fitted at vertical position in a supply air duct. The air was passed through the bed under certain conditions where air exchanges heat with the PCM granule and thus heated or cooled (Figure 2.20).

Figure 2.19 Schematic of the NVP system [108].

Figure 2.20 Elevation view of the experimental apparatus [109]
The PCM bed, weighing 4.59 kg, contained 65%wt. ceramic materials and 35%wt. paraffinic hydrocarbons. It had a latent heat of 38 kJ/kg. The inlet air temperature was varied between 21.5°C and 28°C and the outlet air temperature was measured. It was found that the outlet air temperature was steady and remained within the range of the phase change temperature. After that, computer simulations were carried out to investigate the performance of the system in reducing the ventilation load during summer time in eight Japanese cities. The results showed that a highest of 62.8% reduction in ventilation load could be achieved in Kyoto city. It was also established that the range of daily temperature fluctuation is more important than the average temperature for the ventilation load reduction.

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Figure 2.21 PCM/air system developed by Borderon et al. [110]

Lopez et al. [111] proposed a numerical model of a PCM – heat exchanger where PCM in the forms of layer placed along the air pathways in the air duct. This facilitated a force convection, hence increased heat transfer between the air and the PCM. The model was showed a good agreement with the experimental results. Based on this work, Borderon et al. [110] developed a PCM/air system coupled with a ventilation system (Figure 2.21). This PCM/air system was modelled in Matlab® and numerically tested with an insulated French house modelled in TRNSYS® software for four different weather. The simulation was carried out for different PCM configuration and necessary condition was identified
for effective PCM application. The results reported an improvement of 8% - 15% in reduction of overheated hours due to the incorporation of PCM/air system.

Arkar and Medved [112] carried out an investigation on latent heat thermal energy storage (LHTES) integrated into a mechanical ventilation system. The LHTES system was consist of macro-encapsulated PCM (paraffin RT20) in sphere form. A numerical model of LHTES was developed to determine different influential parameters, optimum PCM temperature, and a temperature response function. The model was integrated in the TRNSYS® simulation software through the temperature-response function, where a single-family low energy building was modelled with the proposed system. The temperature response from the model suggested that ventilation system with LHTES could be an effective cooling system and satisfactory thermal comfort could be achievable by using LHTES with 6.4 kg of PCM for the modelled house.

In another study, Turnpenny et al. [113, 114] developed a fan assisted LHTES system which used heat pipe embedded in PCM. During the day time, the PCM melts while absorbs the heat through the heat pipes which are placed near the ceiling. Night time cool air is used to solidify the PCM through a fan installed on top of heat pipe arrangement (Figure 2.22). The authors demonstrated that the system coupled with night ventilation would provide sufficient storage to eliminate overheating and thus significant energy savings in UK summer weather.
Stritih and Butala [115] carried out an experimental study of PCM cold storage for the purpose of building cooling. The PCM storage was consist of a metal box with aluminium fin, filled with PCM which was designed to be integrated into the air duct (Figure 2.23). The paraffin with 22°C melting temperature was used for the storage. During the daytime, the air from the room was circulated through the PCM storage when the cooling is needed. On the other hand, the night-time ventilation was used to solidify the PCM. The experiment was carried out for a number of different conditions, e.g. different velocities of air, air temperature, heat flux, etc. From the results, it was reported that the PCM could cool an air flow with 26°C temperature and 1m/s velocity to 24°C for more than 2.5 h.

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Figure 2.23 PCM free cooling system proposed by Stritih and Butala [115]

(c) Floor
Lin et al. [116] investigated a different type of electric floor heating system, which consists of shape stabilized PCM. The electric heating system is placed under the floor surface. It is made up of 120mm thick polystyrene insulation, electric heaters, 15mm thick PCM, 50mm thick air layer, 40mm thick floor cover, cylindrical supports, air inlets and outlets with a fan (Figure 2.24). The experimental results showed that interior temperature can be raised efficiently using the supplied air during the work hours. The PCM plate temperature was kept at the phase transition temperature for the whole day. The total electrical energy usage was moved from the peak period to the off-peak period which would be cost effective as there are usually different tariffs at day and night. In their other study [117], a numerical model was developed to investigate the thermal performance of this new heating system. The outcomes of the model indicated that this
type of under-floor heating system works better in ordinary buildings. In addition, it is also possible to apply this system in the buildings with different heat load given that the phase transition temperature and the thickness of air layer is appropriately selected. During the winter season, the inside temperature can be set within thermal comfort range by regulating the underfloor heating area.

Li et al. [118] performed both an experimental study and a numerical modelling to investigate the potential of form stable PCM as a thermal storage system within the under-floor electric heating system. A distinct decline in electric heating film’s start-stop number was detected due to the application of PCM which would potentially extend the service life of the heater.
Farid and Chen [119] suggested a paraffin PCM-integrated under-floor heating system. A schematic diagram of the under floor heating system with thermal storage is shown in Figure 2.25. A PCM layer of 30 mm thickness was put between the heating surface and the floor. From the computer simulation, it was indicated that the heat output of the floor could be increased from 30 to 75W/m² due to the incorporation of PCM storage.

In other study, Farid and Kong [120] constructed two concrete slabs with a hot water pipe embedded in both of them to provide the required heating as shown in Figure 2.26. Modules having a diameter of 75 mm and containing CaCl₂·6H₂O PCM were placed in one of the concrete slabs prior to its moulding. In comparison to the normal concrete slab, the concrete-PCM slab demonstrated a smaller fluctuation in surface temperatures and kept a satisfactory surface temperature all day long although the heating was carried out for only 8 hours.

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Figure 2.26 Experimental set up floor heating system [120]
Unlike the plain concrete slab, the concrete–PCM slab showed a much lower surface temperature fluctuation and maintained an acceptable surface temperature during the whole day even though the heating process was done for only 8 h.

2.1.2.7 Heat Transfer Enhancement of PCM

The issue of lower thermal conductivity is a major concern of many PCMs. In the case of paraffin wax and hydrated salts, the value of thermal conductivity is about 0.2 W/m.K and 0.5 W/m.K respectively [35, 36]. Lower conductivity prolongs the charging and discharging time of PCM. This has a negative effect on the efficiency of PCM. To improve the thermal conductivity of PCM, several methods have been recommended which are given below:

- Addition of highly conductive nanoparticles to PCM [121],
- Insertion of carbon fibres or metallic fillers [122, 123]
- Incorporation of PCM into graphite matrix [124]
- Application of metal fins and honeycombs [125-127]
- Metal foams embedded in PCM [128, 129]
- Microencapsulation of PCM [68]

Khodadadi and Hosseinizadeh [121] showed that the utilization of copper nanoparticles (10-50 nm) with PCM greatly improve the thermal conductivity. The nanoparticle-enhanced phase change materials (NEPCM) exhibited a higher rate of heat release compared to the conventional PCM. Fukai et al. [123] used carbon fibre brushes for enhancing the thermal conductivity of the PCM. It was observed that charging and discharging rate of the PCM increased by about 20% and 30%, respectively through the use of carbon fibres. Py et al. [124] incorporated paraffin wax in compressed expanded natural graphite (CENG) matrix using capillary forces in order to enhance the thermal conductivity of the paraffin PCM. This graphite matrix is porous in nature and up to 95% paraffin was loaded depending upon the density of the matrix. The thermal conductivities of the composite CENG/PCM were found to be in the range of 4 to 70 W/m.K depending on the density of matrix which is much higher than the conductivity of pure paraffin as reported earlier.
Bugaje et al. [127] embedded aluminium sheet metal and expanded aluminium matrices into the body of paraffin wax. It was reported that melting and freezing times reduced by factors of up to 2.2 and 4.2 respectively. Hasse et al. [126] recommended using honeycomb structure as this arrangement ensures larger contact area with the PCM. The honeycombs panels were built from aluminium where Paraffin was added as a PCM. Figure 2.27 shows the honeycombs panels filled with PCM before sticking the upper aluminium skin.

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Figure 2.27 A panel with honeycomb structure filled with paraffin [126].

Tian and Zhao [128] experimentally and numerically investigated the heat transfer rate of PCM embedded with metal foam. Two different cases were compared in this study, which was Case A (PCMs embedded with metal foams) and Case B (pure PCMs). It was shown that better heat transfer performance can be achieved by using the metal foams of smaller porosity and bigger pore density. Zhao et al.,[129] showed that the inclusion of metal foam increased the heat transfer rate of the PCM by three to ten times during the melting process depending on the materials and construction of the foam. It also decreased the time for solidifying by more than half. Figure 2.28 shows the copper foam embedded in paraffin (RT58).
It is already known that PCM absorbs and releases heat through melting and solidification at a certain temperature range. A moving solid-liquid boundary condition exists between two phases during transformation. A simple case of a moving boundary condition is the one-dimensional melting ice problem studied by Stefan [130]. The solidification of ice problems involves considering the conservation of energy in the $\Omega$ domain and dividing it into two separate subdomains in the liquid ($\Omega_l$) and solid state ($\Omega_s$) [131]. The overall domain $\Omega$ is the sum of these two subdomains and the energy conservation defined for the liquid state ($\Omega_l$) is,

$$ \rho_l C_{pl} \frac{\partial T}{\partial t} = \nabla \cdot (k_l \nabla T) \quad (2.1) $$

and for solid state ($\Omega_s$)

$$ \rho_s C_{ps} \frac{\partial T}{\partial t} = \nabla \cdot (k_s \nabla T) \quad (2.2) $$

Where, $T$ is the temperature, $k$ is the thermal conductivity, $\rho$ is the density, $C_p$ is the specific heat capacity, subscripts $l$ and $s$ represent liquid and solid respectively.

The absorption and release of heat energy is primarily governed by the latent heat energy of the material. Several methods have been used to represent the latent heat energy during phase transformation. These methods are generally divided into one domain (fixed mesh) and two domain (moving mesh) methods. One domain technique
comprises a solution of a continuous system with an implicit representation of the phase change process while two domain technique involves the separate representation of the solid and liquid regions as well as considering the phase change interface explicitly as a moving boundary [131]. Overall, the two domain method offers a higher accuracy of the representation of the phase changing thermal processes. However, in these methods, isothermal phase change is assumed i.e the melting and solidification temperature is constant whereas the technical grade paraffin and other phase change materials have a temperature range where solidification and melting occur. In such cases, the tracking of the solid-liquid interface using moving mesh method is difficult or even impossible [132]. Hence, one domain methods are generally preferred in the building simulation because of their simplicity and that they account for the phase change implicitly. Three most common one-domain methods for the solution of phase change process in buildings have been described below.

2.1.2.8.1 Effective Heat Capacity Method

In the effective heat capacity method, the additional heat capacity of to the phase transformation is presented with the function of time. The profile exhibits a limited and peak with a precise peak between the melting and solidification temperatures [133-138]. Figure 2.29 shows a typical temperature vs stored energy curve of phase change material where phase change occurs between temperature $T_1$ and $T_2$. Figure 2.30 shows a typical effective heat capacity vs temperature curve where stored energy between temperature $T_1$ and $T_2$ is taken into account through the rise in specific heat of the material. The precise values can be acquired from laboratory analysis. The Fourier heat conduction equation for effective heat capacity method can be expressed as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \quad (2.3)$$

Where, $C_p = C_{eff}(T)$, and $C_{eff}(T)$ is the temperature dependent effective heat capacity
Figure 2.29 Schematic of Temperature vs Stored energy curve

Figure 2.30 Schematic of effective heat capacity vs temperature curve

Figure 2.31 Schematic of enthalpy vs Temperature curve
2.1.2.8.2 Enthalpy Method

Enthalpy method uses the enthalpy-temperature curve to account for the stored energy during phase change [103, 139-141]. Figure 2.31 shows a schematic of enthalpy-temperature curve where stored energy between temperature $T_1$ and $T_2$ is taken into account through the rise in enthalpy of the material. The Fourier heat conduction equation for enthalpy method can be expressed as:

$$\rho \frac{\partial H(T)}{\partial t} = \nabla \cdot (k \nabla T)$$

(2.4)

Where, $H$ is enthalpy and is a function of $T$ and is easily obtained from laboratory measurement of the material.

2.1.2.8.3 Additional Heat Source Method

In the “Additional Heat Source Method”, some heat sources are considered which are related to the latent heat of the material [71, 133, 142]. These sources represent the change of enthalpy of the PCM during the phase transformation. The differential equation of transient heat conduction with the additional latent heat source can be expressed as follows

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + g_s + g_L$$

(2.5)

Where, $T$ is the temperature, $\rho$ is the density, $C_p$ is the specific heat capacity, $k$ is the thermal conductivity, $g_L$ is the temperature dependent additional latent heat generation rate and $g_s$ is the specific heat generation rate.

2.1.2.9 Numerical Study on PCM Applications

2.1.2.9.1 Passive Application

Borreguero et al. [134] developed a mathematical model based on one-dimensional Fourier heat conduction equation to investigate the influence of PCM in gypsum wallboards:

$$\frac{\partial (\rho H)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right)$$

(2.6)
Where, $H$ is the enthalpy, $x$ is the heat flux direction, $T$ is the temperature, $\rho$ is the wall density, $t$ is the time and $k$ is the thermal conductivity.

The temperature dependent of enthalpy function was given by:

$$h = C_{pa}^p (T - T_R)$$ \hspace{1cm} (2.7)

Where, $C_{pa}^p$ is the apparent specific heat capacity and $T_R$ is the reference temperature. The effect of phase change material was incorporated through specific heat capacity method. The temperature dependent $C_{pa}^p$ was obtained from Modulated Differential Scanning Calorimetry (MDSC) for different PCM percentage which is shown in Figure 2.32.

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Figure 2.32 Apparent specific heat capacity as a function of temperature for gypsum [134]

The thermal conductivity and the density of the material at any given temperature were calculated by using the initial values of these properties of the original material. At any given temperature, they are function of the fraction of melted PCM ($l_f$). The fraction of melted PCM was obtained from the following equations:
\[ T \leq T_1 \quad l_f = 0 \] (2.8)

\[ T_1 < T \leq T_2 \quad l_f = \frac{\int_{T_1}^{T} C_{p_{pcm}}^{ap} dT}{\int_{T_1}^{T_2} C_{p_{pcm}}^{ap} dT} \] (2.9)

\[ T > T_2 \quad l_f = 1 \] (2.10)

Where, \( l_f \) is the melted fraction of PCM, \( T_1 \) and \( T_2 \) are the initial and final temperature of PCM melting point, respectively. With the assumption that the total volume is constant, the thermal conductivity and the density of the wallboard at any temperature can be calculated using the following equations:

\[ k = \sum_{i=1}^{c} k_i w_i + w_{pcm}(l_f.k_{pcm}^{liq} + (1 - l_f).k_{pcm}^{sol}) \] (2.11)

\[ \rho = \sum_{i=1}^{c} \rho_i w_i + w_{pcm}(l_f.\rho_{pcm}^{liq} + (1 - l_f).\rho_{pcm}^{sol}) \] (2.12)

Where, \( k_i, \rho_i \) and \( w_i \) are the thermal conductivity, density and weight fraction of the building materials except PCM, \( w_{pcm} \) is the weight fraction of the PCM, \( k_{pcm}^{liq} \) and \( \rho_{pcm}^{liq} \) are the conductivity and the density of the liquid PCM, and \( k_{pcm}^{sol} \) and \( \rho_{pcm}^{sol} \) are their respective solid–phase density and conductivity. \( c \) is the number of wall building materials except the PCM and \( i \) is a counter. Finite difference method was used to solve equation (2.6). Good agreement between the theoretical and experimental data was reported. It was reported that the greater the amount of PCM in the wallboard, the greater the energy storage capacity. Also wall thickness should be reduced proportionally to get same level of comfort. However, the effect of PCM on the strength of wallboard was not reported which would certainly limit the PCM percentage in the gypsum wallboard.

Darkwa et al. [136] also utilised heat capacity method to carry out a simulation of PCM in their study. Instead of using DSC, the effective heat capacity was calculated using Gaussian distribution:

\[ C_{eff} = C_{pcm}^{ps} + Le^{-0.5(T-T_m)^2} \] (2.13)
Where, $C_{pcm}^{ps}$ is the heat capacity of PCM in the solid phase, $L$ is the latent heat of fusion and $w_d$ is the width of phase change region. PCM was applied inside the test room in two different ways: 1) laminated PCM and 2) randomly mixed PCM as shown in Figure 2.33. It was concluded that the laminated PCM with thinner phase change zone is more useful in decreasing night time temperature in a passively designed room than that of randomly mixed PCM.

\[ H = C_p T \quad T \leq T_1 \]  
\[ H = C_p T + L \quad T > T_2 \]  
\[ H = C_p T + \frac{T - T_1}{T_2 - T_1} L \quad T_1 < T \leq T_2 \]

Where, $L$ is the latent heat of fusion, $C_p$ is the specific heat capacity, $H$ is the enthalpy and $T$ is the temperature. Enthalpy-temperature relationship was obtained from equations (2.14) to (2.16). The heat conduction equation was solved through Finite Element Analysis (FEM). The numerical results were in close agreement.
with experimental data [103]. Parametric analysis was carried out by varying the PCM composition and PCM melting range. It was observed that an increase in PCM composition over 25% have negligible effect on the internal temperature fluctuation at constant climate conditions. On the other hand, a small change in PCM melting temperature range from 23-25°C to 24-26°C was found to increase the effectiveness of PCM. However, this result may not be representative for all type of situations, because different type of environment may need PCM with different melting range as well as different composition. Each PCM combination should be custom-made to handle a variety of environmental condition to give an optimum performance throughout the year.

Joulin et al. [142] used heat source method to carry out the simulation of the effect of phase change materials. The governing partial differential equation used for the phase change process was:

$$\frac{\partial H}{\partial t} = k \frac{\partial^2 H}{\partial x^2} - \rho L \frac{\partial l_f}{\partial t} \tag{2.17}$$

Where,

$$H = \int_{T_m}^{T} \rho C_p dT \tag{2.18}$$

Where, $T_m$ is the melting temperature. The liquid fraction $l_f$ was given by

$$l_f = 0 \quad T < T_m \tag{2.19}$$

$$l_f = 0 - 1 \quad T = T_m \tag{2.20}$$

$$l_f = 1 \quad T > T_m \tag{2.21}$$

Equation (2.17) (11) was solved using a fully implicit finite difference method. The resulting temperature variation and heat flux obtained from the above calculation were compared with the outcomes from the experiments and with the results obtained from ANSYS Fluent (Enthalpy method) code for the similar operating condition as shown in Figure 2.34. In the case of sensible storage (liquid or solid), the curves from experiments and simulations were very close (relative error of 2.2%) to each other and consequently the results were satisfactory. However, a small difference occurred between experiments
and numerical predictions in the region where both phases coexist. This result was justified by the behaviour of the PCM 27 which was different after every solidification process, because of a random crystalline re-organization.

Silva et al. [139] presented an experimental study and a numerical simulation to investigate the effect of macro-encapsulated PCM incorporation into a typical Portuguese clay brick masonry enclosure wall (Figure 2.35). It was reported that incorporation of PCM reduces the peak temperature by 2.5°C. The ANSYS® FLUENT code was used to perform numerical simulation. The simulated temperature data varied between 0°C – 3°C when compared with experimental data. The possible reasons for the deviation were identified.

Zhou et al. [140] applied enthalpy model to simulate the shape stabilised PCM (SSPCM) as an inner layer of a direct gain room of a multilayer building in Beijing, China. SSPCM plate was found to enhance the thermal mass of a lightweight construction and an increase of night temperature up to 3°C was obtained. For the studied location and weather condition, it was suggested that the melting temperature of PCM should be around 20°C and the heat of fusion should not be less than 90kJ/kg. Inner surface convection heat transfer coefficient was found to have significant effect on indoor air temperature. It was observed that SSPCM thermal conductivity influence the indoor air temperature only during charging process.
Carbonari et al. [100] numerically tested four prototypes of PCM incorporated sandwich panels used in prefabricated walls. Enthalpy method was used for the simulating PCM behaviour and the heat transfer equations were solved through finite element analysis. Combined effect of conduction, convection and radiation was considered through the use of the equivalent conductivity. It was found that the inclusion of an air layer in the middle of the PCM and the final exterior layer improves the thermal performance of the PCM. The results were found to be in good agreement with the experimental data with a maximum error of 1.07% and 3.03% for the without and with additional air layer, respectively. The high percentage of error with the additional air case was attributed to the equivalent thermal conductivity algorithm used in this case.

From simple heat transfer analysis, Peippo et al. [143] provided guidelines for selecting the optimum phase change temperature and thickness of the PCM panel to maximize the thermal energy storage:

\[ T_{m,\text{opt}} = \bar{T}_r + \frac{Q}{ht_{stor}} \]  \hspace{1cm} (2.22)
\[ D_{\text{opt}} = \frac{t_n h}{\rho \Delta H} (T_{m,\text{opt}} - T_n) \]  

\[ \bar{T}_r = \frac{t_d T_d + t_n T_n}{t_d + t_n} \]  

Where, \( T_{m,\text{opt}} \) is the optimum phase change temperature, \( \bar{T}_r \) is the average room temperature, \( Q \) is the heat absorbed per unit area of the room surface, \( h \) is the average heat transfer coefficient, \( t_{stor} \) is the storage cycle \( (t_d + t_n) \), \( D_{\text{opt}} \) is the optimum PCM panel thickness, \( t_d \) is charging time, \( t_n \) is discharging time, \( \Delta H \) is latent heat of fusion, \( T_n \) is night time room temperature and \( T_d \) is daytime room temperature. From the above equations, it was shown that the optimum phase change temperature lies in the range of 1-3°C above the average room temperature. Numerical simulations were carried out using weather data of Wisconsin and Helsinki. It was concluded from the numerical simulation that PCM board reduces 6% and 15% of annual energy consumption at Helsinki and Wisconsin, respectively. It was also reported that the value of optimum PCM thickness varies from 10-15mm. Kuznik et al. [144] investigated the effect of insulation thickness, outdoor air temperature, indoor air temperature and phase difference (difference between the time of maximum temperature at outside and inside of room) on the thickness of PCM panels. Numerical simulations were carried out using in house software CODYMUR. The results showed that stored energy is optimal for a PCM panel thickness of around 10mm which was in the range of previously reported values [144]. From theoretical investigation, Laouadi and Lacroix [145] reported that charging time of PCM is mainly controlled by the power supplied and the PCM thickness. Large supplied powers decreased the charge time while large PCM thicknesses did the inverse. The other parameters had less impact on the charge time. While the discharge time was nearly insensitive to the power supplied, it was strongly influenced by the PCM thickness, the radiation and convection coefficients and the NTU number. Large values of PCM thickness, convection coefficients and NTU, or low values of radiation coefficients increased substantially the discharge time. The average charge time of the unit varied between 2 to 2.4 h and the average discharge time varied between 4 to 6 h. Rostamizadeh et al. [146] showed that melting time change linearly with amount of PCM and 5 mm thickness were found suitable for better PCM performance.
Recently, Susman et al. [147] investigated a new way of incorporating PCM in the existing construction. In their study, PCM was incorporated through the creation of ‘Sails’ units (aluminium module and black module in Figure 2.36) designed for location below the ceiling in an occupied space as shown in Figure 2.36.

Enthalpy-porosity method of FLUENT was used to simulate the behaviour of PCM. The simulation results were found to be closely followed with the measurement melt end temperature of PCM after which discrepancies of up to 1°C were observed. This was due to the fact that a small step function was used as an assumption for the variation of heat flow with the phase transformation. However, the effectiveness of this ‘sail’ arrangement cannot be determined as no comparison was made with the ‘no sail’ case.

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Figure 2.36 Scematics of experimental set up [147]
2.1.2.9.2 Active Application

Alvarez et al. [148] presented an innovative way of incorporating PCM into the hollow core slab as shown in Figure 2.37. PCM was encapsulated in small vertical cylinders and inserted into the hollow chamber of the slab. Air was flown over the PCM through a fan. It was reported that this method increases the heat transfer area and the convective heat transfer coefficient by a factor of 3.6 and 14 respectively which results in more efficient charging and discharging of PCM. There were three operational modes in a 24 h cycle:

Day mode: This mode recirculates hot air from inside the house with the aim of cooling it. This period may also be referred discharge period, since it is at this time, when the “cold” stored in the phase change material is discharged. The target at this stage is to use the cold stored to reduce cooling consumption.

Inactive periods: During these time intervals, the airflow stops and closes all doors. The goal is to maintain stored the accumulated cool at night or wait until outside conditions are right to extract efficiently the heat that has been stored during the day.

Night mode: Air circulation is from outside to outside. This period can be called charging period, since it is the time when the cold is stored in the PCM.

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Figure 2.37 PCM cylinders in hollow core slab [148]
Zhang and Niu [149] carried out a numerical study using building simulation program ACCURACY and MATLAB® to investigate a hybrid system consists of microencapsulated PCM slurry storage tank and a nocturnal sky radiator (Figure 2.38). During the night time, the cooling acquired by the radiator was stored in the PCM slurry tank. During the daytime, the cooling stored in the slurry tank was discharged for cooling the building. Water was used as the heat transfer medium for both the radiator loop and building cooling loop to prevent mechanical damage of PCM slurry by the pump. Two heat exchangers were used in the slurry tank for heat transfer, and a stirrer with different speed settings was utilised for better mixing and facilitating a forced convective heat transfer. Also a typical chiller was used to facilitate the auxiliary cooling water generation under extreme conditions. The cooled panel was fitted on the ceiling to absorb the sensible heat from the room. A typical air-handling unit was installed for ventilation purpose to provide minimum cooled and dehumidified fresh air. The results suggested that the hybrid system can save energy up to 77% and 62% for low-rise buildings in Lanzhou and Urumqi cities of China.

2.1.2.9.3 Building Simulation Software

A number of building simulation software are available in the market. Among them, the following four are widely used:

Pederson et al. [17] simulated PCM incorporated wall using conduction implicit finite difference algorithm in EnergyPlus. Enthalpy model was used to simulate the PCM behaviour. The temperature dependent thermal conductivity and multilayer wall construction capability of EnergyPlus was presented. It was shown that the incorporation of PCM lowers the peak cooling load by 1000W at that particular simulation environment. Tardieu et al. [16] predicted the thermal performance of PCMs in a test room using EnergyPlus software. They used actual weather data instead of historical weather data file as input to their simulation. The results showed that PCM wallboards increases the thermal mass of the buildings and can reduce the diurnal temperature fluctuation by up to 4°C on typical summer day in Auckland.

Ahmed et al. [99] introduced a new wall component Type 101 into TRNSYS 15 to simulate the phase change material combined with a vacuum insulation panel. The phase change was considered through volume heat source leading to an equivalent specific heat capacity $C_{pe}(T)$ which was calculated from following equations:

$$C_{pe} = \frac{L}{T_2 - T_1} + \frac{C_{ps} + C_{pl}}{2}$$

(2.25)

During melting the variation of specific heat capacity with temperature is,

$$C_p(T) = \begin{cases} C_{ps} & T < T_1 \\ C_{pe} & T_1 \leq T < T_2 \\ C_{pl} & T \geq T_2 \end{cases}$$

(2.26)

And during solidification the variation of specific heat capacity with temperature is

$$C_p(T) = \begin{cases} C_{ps} & T < (T_1 - 1) \\ C_{pe} & (T_1 - 1) \leq T < (T_2 - 1) \\ C_{pl} & T \geq (T_2 - 1) \end{cases}$$

(2.27)

Where, $C_{ps}$ and $C_{pl}$ are the specific heat capacity of solid and liquid phases. The fluctuations of indoor temperature were found to be smaller in the numerical simulation.
than that of the experiment. Several possible reasons for the discrepancies were outlined. It was concluded from the parametric study that use of PCM is not efficient for a wall thickness over 20mm.

Kuznik et al. [150] used building simulation software TRNSYS to simulate the external building wall containing PCM. Finite difference method was adopted to solve the conduction heat transfer equation. A new TRNSYS type, named Type 260, was built to simulate the thermal behaviour of the exterior wall with PCM. The phase change process was introduced in the heat equation using effective heat capacity method which was measured using Differential Scanning Calorimetry (DSC). The results were validated against the available experimental data [78]. The calculated internal wall surface temperature was found to be in good match with experimental data with a maximum difference of 1.1°C and a mean difference of 0.2°C. Ibanez et al. [151] also developed a new Type 222 to simulate the phase change materials. A different method, based on equivalent heat transfer coefficient, was used to simulate the effect of phase change. The model showed some good results but more experimental validation was recommended.

Heim et al. [152] modelled the behaviour of PCM in a three zone building using building simulation software ESP-r. PCMs were implemented into ESP-r using special materials facility. Control volume approach was used to solve the partial differential equation numerically. Effect of phase change was incorporated to the energy equation through effective heat capacity method. Weather data of Warsaw, Poland was used in the simulation. It was concluded from the simulation that the PCM-gypsum wallboard decreases the heating energy demands significantly during spring (November). However, the model was not validated against the experimental data.

Rose et al. [153] presented a numerical study where the latent heat storage performance of the building materials with PCM was studied to estimate the effect on heating and cooling demands. The simulations were carried out using the commercial software package BSim which uses finite volume method to solve the energy equation. The behaviour of PCM was modelled using enthalpy-temperature function as shown in Figure 2.39. The effect of hysteresis in the enthalpy-temperature function was also taken into account through a simplified method. The results were validated against the
experimental data and reasonably good agreement was observed. The reasons for any discrepancies were explained. The results showed that there is a maximum limit of PCM amount that can be utilized in the building above which energy savings are negligible. The results also showed that in order to take the benefit of PCM, there must be a certain fluctuation in temperature. It is of no use to incorporate PCM in a building with a very steady temperature profile because the PCM will not be activated without a sufficient fluctuation in temperature.

Figure 2.39 Enthalpy-Temperature function of PCM [153]

2.1.3 Sensible Heat Thermal Energy Storage

2.1.3.1 Hollow Core Slab TES System

The sensible heat TES system are mainly used in office buildings where the building fabrics (masonry walls, concrete slabs, etc.) are utilised to store the sensible heat. Hollow core slab system, known as “TermoDeck®”, is an award winning sensible heat TES system in which exposed hollow core slab is used to provide low energy cooling and heating by passing the air through its cores (Figure 2.40). The supply air travels back and forth through the cores of the slab at low velocity. This allows a prolong contact between the air and the inside surface of the slab which eventually increase the heat transfer. By the time when air leaves the core and enters the conditioned room, it is already optimised for the thermal comfort of the occupants. Hollow core slab system is used with fan assisted ventilated system and simple duct works which can be incorporated in most
building types including offices, universities, libraries, theatres, etc. It only requires a main supply duct which runs perpendicularly to the hollow core slabs. The air is taken directly from the outside or from the heating, ventilation, air conditioning (HVAC) unit and then it is distributed through the main distribution duct to the slabs where it circulates and finally enters the conditioned rooms.

Hollow core concrete slab system works differently in summer and winter. During the summer season, the warmer daytime outside air cools down as it passes through the relatively cooler slab cores (Figure 2.41). The slab also absorbs the radiant heat from the equipment, people, etc. At night the cool ambient air circles through the hollow core slab, lowers its temperature and make ready for the next day operation. During the winter season, the hollow core can be warmed up with the air handling unit during off-peak period (night) and then it can be used to warm the cool winter air during the peak period. Hollow core concrete slab can also be utilised by using the solar collector during the winter time.

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Figure 2.40 TermoDeck System [154]
Many researches has been carried out to study the thermal behaviour of the hollow core slab system through modellings, simulations and experiments [23]. Winwood et al. [156] developed a computational fluid dynamics (CFD) model of hollow core slab with simplified three dimensional (3D) geometry (Figure 2.42). The model was constructed with 90,000 cells and k-epsilon model was used to approximate the turbulence. The model was validated with experimental results with 2.0% outlet temperature ($T_{\text{out}}$) and 2.7% average slab temperature ($T_{\text{slab}}$) accuracy. The study also reported the thermal behaviour of the slab due to the change of different parameters such as surface insulation, thermal conductivity, air flow rate, length of air flow, size of the slab, etc.
In another study, Winwood et al. [159] developed a multi-node model of hollow core slab which was compared with the experiment with reasonable accuracy. The multi-node model is then incorporated in a building simulation software ESP-r to simulate an office building. This was the first attempt to model a full building model with hollow
core slab of any length with any flow rate. Winwood et al. [157] also reported a study of hollow core application in a real office building (Weidmuller building, UK) which showed that the building could maintain a very steady temperature from day-to-day operation and one season to next. The analysis also suggests that with efficient fan operation, improved night time heating and better control, the building could reach energy target of 50 to 70 kWh/m² depending on the heat gain, heat loss characteristics and local weather.

Willis and Wilkins [158] carried out an experimental study on the TermoDeck system for UK climate. The test room was an office space with 4.8 m x 4 m x 3.75 m in size and designed for 2-3 persons. The structure consists of four hollow core slabs at the ceiling and four at the floor. Only two slab of the ceiling was used to condition the air without any mechanical ventilation system. The test was run for eight days of fan operation. The research suggested that the TermoDeck system offers not only an enhanced alternative to mechanical ventilation system but also match the performance of comfort cooling or conventional air conditioning system.

Shaw et al. [160] reported that the use of building fabric by coupling the thermal mass and the supply air makes the hollow core slab an efficient, environmentally benign alternative to mechanical ventilation system. Moreover, it can significantly reduce the energy consumption due to its low energy fan operation and, it can provide better thermal comfort to the occupants by absorbing radiant heat from the space.

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Figure 2.45 2D Hollow core slab model used by Zmeureanu and Fazio [161]
Zmeureanu and Fazio [161] developed a numerical model to simulate the hollow core model in two dimension (2D). The cores of the slab were modelled as parallel plates sharing the passage of air flow (Figure 2.45). Crank-Nicolson implicit discretization formula was used solve the partial differential equation numerically. The heat transfer coefficient along the air flowing pathways was assumed constant. The model was used to simulate a single office room in Montréal, Canada where Fanger’s Model was used for the thermal comfort calculation. The simulation result showed that the hollow core slab can save average cooling load from 28.4 W/m$^2$ to 44.2 W/m$^2$ compared to the mechanical system and it can provide thermal comfort without the mechanical system in the studied weather.

Ren and Wright [162] proposed a transient thermal model of hollow core slab along with associated room. The model was developed based on a thermal network which was capable of taking care of the heat transfer between the air and the slab cores, the thermal storage of the hollow core slabs as well as the disturbance in the associated room. By assuming the heat transfer coefficient of the bend area 50 times higher than that of straight cores, the model was able to validate experimental data with the RMS error of 0.5°C for average slab temperature and 1.0°C for zone air temperature.

\begin{center}
\includegraphics[width=\textwidth]{image}
\end{center}

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Figure 2.46 Results of three core and five core operation reported by Barton et al. [163]
Barton et al. [163] presented a theoretical study of the hollow core slab system with numerical modelling to investigate its thermal performance. A two-dimensional explicit finite difference model was used to simulate the hollow core slab system which yielded consistent results compared to the previous experimental study. The results also suggested that the bend section of the hollow core slab has minimal effect on the overall heat transfer process which was opposed to what other studies reported [156, 158, 159, 162]. Finally, the study found that five pass operation of hollow core slab could create greater thermal attenuation than the standard three pass operation of the hollow core slab TES system (Figure 2.46).

Russell and Surendran [164] developed a software based on the two dimensional finite difference model to simulate the cross section of the hollow core slab. The model was capable of incorporating the localized heat source or heat sink. Both steady state and transient simulation were carried out for hollow core slab with the different configurations (e.g. number and location of the cores, etc.) and their effect on the cooling capacity was investigated. Also a relationship between the air temperature and the cooling potential for different slab configuration was identified. The study reported that highest cooling capacity was achieved by placing the three active cores were placed near the room boundary which was 45% better than other three core configuration mentioned.

Corgnati and Kindinis [165] carried out a modelling of a hollow core slab with the night ventilation and compared the result with traditional mixing ventilation system. The simulation was conducted with the Simulink dynamic model for an office room placed in Milan, Italy. The results showed that the operative temperature offered by hollow core slab is at least 1°C lower than that of the traditional ventilation system (Figure 2.47). It also concluded that the mass activation coupled night ventilation can reduce summer cooling load and thermal comfort.
Chae and Strand [166] presented a computational model of the hollow core ventilated slab and implemented it to a whole building simulation program (EnergyPlus). The model included two things: supplementary air handling unit (AHU) and the radiant slab. The AHU was composed of supply fan, outdoor air mixer and the heating and cooling coil by which it can provide the conditioning when required. The radiant slab could exchange heat with the adjacent room/zone in radiant and convection heat transfer mode using various air delivery method. The developed model exhibited consistent results with the previous study for the variation of indoor temperatures and potential of cooling energy.
2.2 TES System in High Temperature Applications

The solar thermal power plant is becoming more popular in alternative energy production. It collects and concentrates the solar radiation as heat energy. This energy is used to produce steam which runs the turbine to generate electric power through generator. Effective thermal storage is one of the key components of solar thermal power plant. It increases the utilization of the power block and improves the efficiency of the plant operation [167]. It makes the system reliable by smoothing out the fluctuations caused by the solar insolation to avoid the grid instability problems. The TES system also increases the power generation capacity by saving the energy during the off-peak periods and using that energy during high-demand periods.

The high temperature TES system for solar thermal power plant can be classified into two categories, active system and passive system [168]. In the active system, the storage material (liquid form) itself passes through the heat exchanger (solar collector, steam generator). This system uses one or two tanks for storage material. The active system can be subdivided into two more categories, direct system and indirect system. In direct system the Heat Transfer Fluid (HTF) itself act as a storage material where in the indirect system, a separate fluid is used for storing heat. In the passive system, the storage material does not circulate, but the HTF passes through the storage material to charge or discharge it. Passive storage systems are made with solid storage media like concrete, PCM, etc.

2.2.1 Latent Heat Thermal Energy Storage

Latent heat storage system uses the energy absorbed or released during the isothermal phase change of the storage material (PCM). This type of storage is used in the passive system where HTF is passed through the PCM material to store the solar heat in it. So the melting temperature of the PCM should be in the range of charging and discharging temperature of the HTF. This type of storage concept was developed in the European project DISTOR [169].
In this project, a eutectic mixture of the KNO$_3$-NaNO$_3$ has been used as a PCM with melting temperature of 230°C. To increase the heat transfer in the PCM, three approaches has been tested in the lab-scale experiment [170, 171]. In one approach the PCM was macro-encapsulated in tubes before putting it in the pressure vessel (Figure 2.48). Though the lab experiment show that this approach is feasible, but because of complexity in filling and sealing procedure, high standard pressure tight capsuling, etc. made the macro-encapsulation economically unpromising. The other approach was to make a composite material from PCM (KNO$_3$-NaNO$_3$) and expanded perlite Figure 2.49. But it was unsuccessful because about 40% of the salt was separated from the graphite during the experimental process. The third concept was called sandwich concept where fin like structures are in the storage material. The fin was made of expended graphite-
foil which has higher performance in charging the storage material and also significantly cheaper than other material. This approach was successful in laboratory scale. So a bigger module, “DISTOR test module” was made and tested at the Plataforma Solar de Almería by CIEMAT. During the test, the maximum power was around 90kW where average output over one hour was 35kW. The melting temperature of the Nitrate salt used was 222°C.

Figure 2.50 Process scheme of a Solar Energy Generating System with integrated PCM-TES

Hunold et al. [173-175] investigated a single PCM storage module which was shell and tube type heat exchanger and he used single salt, nitrate (NaNO₃) with melting point 305°C. This system was further improved by Michels et al. [172] who suggested a cascade of five different PCM storages to be used to optimize the storage system in the temperature range of a solar thermal power plant (Figure 2.50). Michels et al. [176] carried out an experimental investigation of a configuration of three modules connected in series. He used the following nitrates: KNO₃, KNO₃/KCL and NaNO₃. A new study from Michels et al. [177] showed that cascade latent heat storage system has higher
utilization of phase change and more uniform outlet temperature with respect to the un-
cascade latent storage system.

### 2.2.2 Sensible Heat Thermal Energy Storage

#### 2.2.2.1 Liquid Thermal Energy Storage

The liquid storage materials are mainly used in the active system as a sensible storage media. Different types of fluid had been tasted to be used as Liquid TES including oils (silicone oil, synthetic oil, etc.), water, etc. before molten salt came up as a best option [24, 178, 179]. Molten salts are non-toxic, non-flammable, cheaper and operating temperatures are compatible with the high pressure and high temperature steam turbine (solar field output temperature can be around 450 – 500°C). The two main salts used in the solar power plant are so-called solar salt (a binary salt consisting of 60% NaNO₃ and 40% KNO₃) and a salt sold commercially as HitecXL (a ternary salt consisting of 48% Ca(NO₃)₂, 7% NaNO₃, and 45% KNO₃)[180].

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Figure 2.51 Schematic of two tank molten salt solar tower power plant (Planta Solar Tres) [4, 181]
Figure 2.52 Schematic of parabolic trough power plant with two-tank storage system [182]

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Figure 2.53 Schematics of parabolic trough power plant with single tank storage system [182]

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Figure 2.51 shows a schematic of the solar tower power plant “Solar Tres” of Fuentes de Andalucia, Spain [4, 181] which uses molten salt (mixture of NaNO₃ and KNO₃) as HTF as well as TES. This is an active direct system where two tanks are used to store cold and hot HTF separately. The molten salt is pumped from the cold storage tank at around 290°C to heat up in the solar receiver. The outlet temperature of the HTF coming out
from the receiver is around 565°C. This hot molten salt is then stored in the hot salt tank to be used in steam generation.

The molten salt can also be used in the active indirect systems. In this type of system, a separate HTF is used to heat the molten salt through a heat exchanger. The salt storage can be two tank system or single tank system (Thermocline storage) (Figure 2.52 and Figure 2.53) [182]. In the single tank system, the hot and cold fluid is separated because of thermal stratification (thermocline effect) [168]. The hot fluid is supplied to the upper part of the storage where the cold fluid extracted from the bottom. Some filler materials are used to help the thermocline effect, e.g. quartzite rock and silica [183].

The main disadvantage of the molten salts is that their freezing point is relatively high (120°C – 220°C) [183, 184]. Therefore, routine freeze protection method is required for proper functioning of the plant, e.g. passing the HTF through the pipe line during the night time to keep them warm by using the residual heat from the HTF. And if the temperature of the HTF falls below the critical temperature, auxiliary heater is used to maintain the temperature to avoid critical thermal gradients. Among the other drawbacks, more losses from the solar heat due to the higher outlet temperature of the HTF and also the high cost of molten salt itself, etc. are notable.

### 2.2.2.2 Solid Thermal Energy Storage

In this type of energy storage solid materials are used as a sensible energy storage medium. Thus storage material does not circulate but the HTF is used for charging and discharging (passive system). Among the solid materials, concrete and castable ceramics are studied more because of their low price and good thermal properties. Both of them were tested [185] and between them concrete proved to be more favourable material due to lower cost, easy handling and higher material strength.

### 2.2.2.1 Concrete Thermal Energy Storage

The concrete thermal storage system consists of tube register and storage concrete (Figure 2.54). The tube register is embedded in the storage concrete. It is used to distribute the heat transfer fluid (HTF) and transmit the heat to the storage while sustaining the fluid pressure. The concrete is used to store the heat [25].
The storage of thermal energy is defined by the heat capacity of the concrete and the difference in the temperature between the charging and discharging states [25]. The concrete storage is used as a regenerative storage where it is periodically passed through by hot and cold Heat Transfer Fluid (HTF). During the charging state, the hot HTF flows through the concrete storage to heat up the storage module. During the discharging state, the cold HTF flows through the concrete in the opposite direction and takes the heat with it. The fully charged state of the storage is defined by the maximum inlet temperature of the solar collector. The fully discharge state is defined by the minimum allowable temperature of turbine.

2.2.2.2.1.1 Recent Development of Concrete thermal Storage

The parabolic trough power plant of ANDASOL type uses thermal oil as a heat transfer media which takes heat from the absorber pipe and then transfer it to water-steam cycle through heat exchangers (Figure 2.55). For this type of power plant, a concrete storage test module of 20 m$^3$ has been validated for 23 months of running with the temperature range of 200°C – 400°C and more than 370 thermal cycles [25, 27]. Also a simulation of 50 MW$_{el}$ ANDASOL type power plant with a concrete storage of 1100 MW$_{th}$ capacity was analysed using real historical weather data which illustrates that this type of power plant can operate 3500 full load hours annually where 30% of the electricity generation comes from concrete storage [187]. For this simulation, the design temperature was 400°C.
There are other type solar-thermal power plants with Direct Steam Generation (DSG) in which water is directly heated and evaporated in the absorber pipe. For parabolic trough power plant with DSG, a three stage storage system was proposed [26] where phase change material (PCM) storage will be utilized to water/steam evaporation and concrete storage will be used for sensible heating i.e. preheating of water and superheating of steam. A pilot program of storage system with total 1MWh capacity, combining the PCM module for latent heat generation and the concrete module for superheating, has been successfully commissioned in 2010 [27, 188]. This test is running under real steam pressure of 100 bar and the concrete storage was designed to be heated up to 400°C.

Many similar studies have been conducted on concrete thermal energy storage with design temperature of 400°C to assess the storage capacity, stability and long-term cycle-ability [4, 167, 185, 189]. Recent oven test shows that the high-temperature concrete stabilizes at 500°C after a period of time and number of thermal cycles [188]. But it has not been studied in real time situation. It is very difficult to use a concrete thermal storage with operating temperature higher than 500°C because concrete degenerates at elevated temperature due to chemical and physical changes [190]. The Ca(OH)_2 decomposition occurs in Ordinary Portland Cement (OPC) at about 400°C [191] which may be responsible for deterioration of strength of the concrete after 400°C. The strength
loss at high temperature may also occur due to the brittleness of material and difference in thermal strain [192] of aggregate and paste of the concrete. Moreover, spalling of concrete may occur at high temperature due to the moisture presence in the concrete. When the water evaporates, it creates a vapour pressure inside the concrete. Also high temperature creates thermal stress because of the thermal gradient and build-up of pore pressure. Spalling occurs when these pressures exceed the tensile strength of the concrete [29]. Therefore, even though the concrete storage was tested within 400°C, special “Start-up Operation” has been done to handle the vapour pressure before using it as a thermal storage [25, 188].

2.2.3 Geopolymer

2.2.3.1 Basic characterisation and chemistry

Polymer is a class of chemical material in which a large amount of molecules is bonded together with many repeating units (monomer). The repeating unit of the chemical structure is dictates of the material properties. The long chain of molecules is formed through the repeated connection or bond of some atoms (carbon, silicon, etc.). This is called the backbone of the polymer. The polymer can be in crystalline or amorphous arrangement. In the former one, the molecules are organised with a distinct pattern. The amorphous arrangement does not have any molecular pattern at all because of the presence of atoms of materials with different sizes (e.g. C, O, Si, etc.).

The name “Geopolymer”, first used by Davidovits [193], represents a family of aluminosilicate based inorganic polymer which can be synthesised from the pozzolanic compounds or aluminosilicate source material under highly alkaline environment [194]. The polymerisation reaction yields an amorphous polysialate (poly-silicon-oxo-aluminate) matrix with Si-O-Al-O bonds which consists of a three dimensional polymeric chain of SiO₄ and AlO₄ tetrahedra connected with oxygen atoms in ring and cage form. The structure can be expressed with the following empirical chemical formula:

\[
M_n[\text{-(SiO}_2\text{)}_z - \text{AlO}_2\text{]}_n \cdot wH_2O
\]  (2.28)
Where, $M = \text{Na}, \text{K}, \text{Ca}$ or $\text{Mg}$ atoms and $n =$ degree of polycondensation and $z =$ degree of aluminate substitution ($1$, $2$, $3$ or higher up to $32$).

The chemical composition of geopolymer is very similar to the naturally found ziolitic materials, although the geopolymer is amorphous where ziolite has crystalline microstructure [195, 196].

The schematic formulation of the geopolymerisation process can be described by the following two equations [197, 198]:

\[
\text{NaOH/KOH} \quad \xrightarrow{(\text{Si}-\text{Al materials})} \quad n(\text{OH})_2\text{-Si-O-Al}^{\ominus}\text{-O-Si-(OH)}_3 + 4n\text{H}_2\text{O} \\
\]

A very simplified version of the geopolymerisation reaction mechanism was presented by Duxson et al. [199] as shown in Figure 2.56. In the first step the aluminate and silicate species are produced through dissolution of the solid aluminosilicate source by the alkaline hydrolysis. Once the species are released they are incorporated in the aqueous phase (which may also contain silicate from the activator) and a complicated mixture of aluminate, silicate and aluminosilicate is formed. In the presence of highly alkaline environment the dissolution of aluminosilicate occurs at high rate which eventually forms the supersaturated aluminosilicate solution. In a concentrated solution, supersaturated aluminosilicate solution results in gel formation. The connectivity in the gel network continue to increase with the rearrangement and reorganisation of the system. As the gel sets, spare molecular water is subsequently released and a three dimensional network of aluminosilicate is formed which is commonly named as geopolymer [199].
2.2.3.2 Geopolymer Constituents

2.2.3.2.1 Aluminosilicate Source Materials

Any material enriched in silicon and aluminium has the potential to be the aluminosilicate source of geopolymerisation. Davidovits [193, 197] utilised dehydroxylated kaolinite as the source of aluminosilicate solids. Among the other sources, natural minerals like wollastonite, augite, stilnite, etc. [196] and by product materials like fly ash [200, 201], blast furnace slag [202] have been successfully used as an aluminosilicate source of geopolymerisation.

Metakaolin is preferred by some geopolymer researchers due to the high dissolution rate in the reactant solution, easy control of Si:Al ratio and its distinct white colour [203]. But
due to the high cost of metakaolin, the mass production of geopolymer may not be feasible.

Many researchers also utilised fly ash as a source material to produce geopolymer [195, 198, 204, 205]. Fly ash is an industry by product which is cheap. Thus it is favourable to produce cost-effective and yet high quality geopolymer. But important to note that higher concentration of alkali solution is needed to activate the fly ash [195] in comparison to slag. Mostly, low calcium (class F) fly ash is preferred over the high calcium one (Class C). Because high calcium can hinder the geopolymerisation process and can potentially alter the microstructure [203].

2.2.3.2.2 Alkaline solutions as Activators

Most common type of alkaline solutions which were widely used as an activator to the source material are sodium hydroxide (NaOH) or potassium hydroxide (KOH) combined with sodium silicate or potassium silicate [195-197, 206-208]. Some authors also reported to use the single alkaline activator solution [195, 209].

Palomo et al. [195] reported that alkaline activator plays an important role on the dissolution of the aluminosilicate source. They found that the presence of silicate in the alkaline solution can potentially increase the reaction rate compared to the one with only alkaline hydroxide. It was further confirmed by Xu and Deventer [196]. They studied sixteen natural source material of Si-Al minerals to investigate the geopolymerisation reaction concluded that sodium hydroxide solution can create higher rate of dissolution than the potassium hydroxide.

2.2.3.3 Geopolymer Concrete

A significant study of geopolymer concrete was carried out by Rangan and his colleagues in Curtin university, Perth [204, 210-215]. They used 100% fly ash as a source material along with the sodium hydroxide and sodium silicate solution as an alkaline activator. The coarse and fine aggregate used in these studies were similar to those ones used in standard Portland cement concrete. Among the findings, these studies concluded that geopolymer concrete exhibited very similar relationship between the stress and strain with the Young’s modulus in the same range of conventional Portland
cement concrete. Poisson’s ratio was reported between 0.12 and 0.16. Geopolymer concrete also exhibited low creep, little shrinkage as well as less affected by sulphate attack. Similar results also reported by Palomo et al. [216] who suggested that the structural application of geopolymer concrete can easily be adopted using the current technology of typical concrete.

2.2.3.4 Thermal Properties of Geopolymer

Geopolymer exhibits superior thermal stability compared to the conventional cement due to its inorganic polymeric structure [217]. Thus it has a great potential to be used in the high temperature applications. Researchers studied the different thermal properties to understand the thermal behaviour of geopolymer. Some of them will be explained to the following sections.

2.2.3.4.1 Thermal Expansion or Shrinkage at Different Temperatures

The thermal expansion or shrinkage of geopolymer is isotropic in nature due to its amorphous structure, although localised expansion or shrinkage can happen from local variation in composition and temperature. A region-wise thermal expansion of most geopolymers with various temperature range was reported by Duxson et al. [218] and Rickard et al. [219, 220] as shown in Figure 2.57.

Like other materials, geopolymer structure expands with the increase of temperature (Region I). Geopolymer has physically bonded water absorbed in the pore as well as chemically bonded water molecule in the structure. In a well reacted sample, study through Thermogravimetric analysis (TGA) and Nuclear Magnetic Resonance (NMR) suggested that the presence of physically bonded water is higher in geopolymer than the chemically bonded water [219].

With the increase of temperature, the dehydration of physically bonded water occurs at various stage depending on the energy required to free the water molecule. This release of the water causes shrinkage effect in the geopolymer (Region II). This dehydration shrinkage depends on the water content of the geopolymer. Rickard et al. [220] reported that the presence of 15.2% wt of pre-curing water in the geopolymer can lead to 2% dehydration shrinkage at the temperature range of 100°C to 300°C (Figure 2.57). The
onset temperature and the duration of dehydration shrinkage can vary with the geopolymer structure and the heating rate. The diffusion rate of water through the pores can potentially affect the dehydration rate of the geopolymer [218]. So the porosity and pore structure can influence the rate of dehydration. Duxson et al. [218] observed that the increase of the heating rate yields higher onset temperature and longer duration of dehydration shrinkage in metakaolin-based geopolymer.

The release of the hydroxyl group or chemically bonded water causes slight shrinkage of the geopolymer in the temperature range of 300°C – 600°C (Figure 2.57, region III). The reaction can be generalised as follows:

\[ B - OH + OH - B \rightarrow B - O - B + H_2O \]  \hspace{1cm} (2.30)

Where, \( B \) = Si or Al atom.

The release of the hydroxyl group creates shorter link of \( B - O - B \) as shown in Eqn. (2.30). However, the small shrinkage due to dehydroxylation in region III is later found to be overshadowed by the thermal expansion of the secondary phase (Figure 2.57).
The region IV shows a large shrinkage that occurs at temperatures above 550°C. This happens due to the densification of the geopolymer matrix through sintering of the paste and filling of voids by viscous flow in the material. Raheir et al. [221] suggested that the densification of the geopolymer indicates the glass transition temperature.

After densification, literatures do not report any consistent results for the region V. Barbosa and MacKenzie [217] reported that the specimen were thermally stable, where Duxson et al. [218] and Dombrowski et al. [222] found shrinkage behaviour. On the other hand, Rickard et al. [220] and Rahier et al. [221] reported thermal expansion of the samples. The discrepancies may be due the variation in chemical composition and impurities present in the samples.

In the region VI large shrinkage occurs [218, 223] which is attributed to the continued densification, destruction of the crystalline phases, collapse of the pore system or melting of the sample.

2.2.3.4.2 Thermogravimetric Analysis (TGA) and Differential Temperature Analysis (DTA)

The TGA/DTA curve of the metakaolin geopolymer is presented in the Figure 2.58 [224]. The metakaolin-based geopolymer subjects to weight loss with the increase of temperature due to the dehydration of the physically bonded water. This weight loss is approximately proportional to the initial water content of the sample [220]. The dehydration continues to occur until 300°C when most of the free water is removed. According to some studies [217, 218, 220, 225], the geopolymer losses approximately 80% of its weight before 200°C, although the duration of the dehydration may change with the change of the heating rate.

The sharp drop in the DTA curve implies that the whole dehydration process in endothermic. Duxson et al. [218] suggested that the temperature at endothermic minimum and the duration of the endothermic process depends on the Si:Al ratio, and these reduces with the increase of the Si:Al ratio. After the dehydration, the geopolymers become thermally stable, though a little bit exothermic.
The weight loss geopolymer after 300°C is mainly attributed to the release of chemically bonded water or dehydroxylation. This time weight loss is much less than the
dehydration stage. The densification process of geopolymer at temperatures above 550°C did not contribute any weight loss as seen in the TGA curve (Figure 2.58).

Figure 2.59 shows a TGA/DTA curve of fly ash based geopolymer observed by Rickard et al. [220]. The thermoanalysis of the fly ash geopolymer is a bit complex due to the presence if the impurities. Rickard et al. [220] reported that geopolymer exhibited an exothermic peak in DTA at around 400°C and also a simultaneous weight loss in TGA plot. The peak was attributed to the exothermic change of poorly ordered crystallised iron oxide impurities (from fly ash) to hematite. The weight loss in this region is attributed to the release of chemically bonded water. At higher temperatures, geopolymers found to have gained weight in TGA results which was found to be an exothermic process in DTA in the presence of air. But in the presence of nitrogen, no weight gain observed in geopolymer. The weight gain occurs in the presence of air due to the oxidation of the iron oxides which an exothermic process.

2.2.3.4.3 Thermal Conductivity of Geopolymer

Some researchers studied the thermal conductivity of geopolymer to investigate its potential as insulation material. Liefke [226] investigated a low density geopolymer as a thermal insulator which resulted a thermal conductivity of 0.037 W/m.K. In another study, Duxson et al. [227] reported that the thermal conductivity of the metakaolin based geopolymer was approximately 0.8 W/m.K. Subaer and van Riessen [224] found a little bit lower value than that of Duxson et al. [227] which was between 0.55 W/m.K – 0.65 W/m.K. These values of thermal conductivity of geopolymer are higher than that of the Ordinary Portland Cement (OPC) paste which is 0.53 W/m.K [228]. Subaer and van Riessen [224] also observed that the 40% wt increase of the quartz aggregate may results in increase of thermal conductivity by approximately 40%. Also quartz of higher thermal conductivity can potentially increase the overall thermal conductivity of the geopolymer-quartz compound.

2.2.3.4.4 Change of Mechanical Strength of Geopolymer at High Temperatures

The evolution of the mechanical strength properties at high temperature exposure is important to investigate for the structural application of geopolymer. In most cases
mechanical strength is measured through the ex-situ measurement because in situ measurement is difficult at high temperature [219].

The change of mechanical strength of geopolymer in thermal exposure occurs through the change of material structure and phase composition [219]. The structural changes include densification, sintering, melting, cracking as well as the change of pore size or interconnectivity. On the other hand, the change of phase composition include dehydration, crystal growth and destruction and decomposition of geopolymer paste to release free Al, Si and alkali. Also during the thermal exposure, thermal dilation of the secondary phases like aggregates or crystalline impurities can occur which would have an effect on the mechanical strength of the geopolymer [223]. All of these changes may have positive or negative effect on the strength of geopolymer.

The mechanical strength of geopolymer increases with the sintering of the unreacted materials, e.g. crystalline fly ash particles, which creates stronger bonds among the particles [229]. Densification also results in higher mechanical strength by reducing the voids in the matrix and allowing more uniform stress gradients. The change in pore structure can have mixed effect on the strength of geopolymer. Usually pore act as a defect and the strength decreases with the increase of the size and volume of the pores. Nonetheless, increased pore interconnectivity can facilitate greater mobility of the water molecule and save the pore wall from the damage of the vapour pressure [229]. Hence, the higher the interconnectivity, the lower the strength loss of geopolymer at high temperature compared to the one with isolated pores. Previous studies [218, 230-232] reported that the pore structure of the geopolymer can vary at high temperature which results a nonlinear variation in mechanical strength during heating.

Kong et al. [32, 225, 229] carried out several studies to investigate and compare the change of mechanical strength of fly ash based and metakaolin based geopolymer due to high temperature exposure. The results from these studies reported that the fly ash based geopolymer was able to maintain higher compressive strength than that of metakaolin one. It was found that the fly ash geopolymer has large number of pore interconnectivity which allows the moisture movement through the pores and thus help the moisture to escape during heating. On the other hand, the metakaolin based
geopolymer was reported to have isolated pore structure which resists the escaping of the water. As a result, the internal structure is damaged by the vapour pressure which eventually reduces the mechanical strength of geopolymer during heating. Kong et al. [31] also reported that the strength of geopolymer concrete decreased by 65% while heating up to 800°C which was attributed to the mismatch of the thermal expansion between the aggregate and the geopolymer paste.

The evolution of the strength of geopolymer also reported to be dependent on the alkaline activator used to prepare the geopolymer. Bakharev et al. [230] found that the strength of the geopolymer made with potassium based activator was increased after the exposure of 800°C temperature. But in case of geopolymer made with sodium based activator the strength was greatly reduced after heating 800°C.

Dombrowski et al. [222] found that the addition of small amount of calcium increased the initial compressive strength of the geopolymer. But strength gain was found to be reduced when it was exposed to heating up to 1000°C compared to the sample without calcium. Zuda et al. [232] reported that, with the introduction of the slag (39% wt CaO), the compressive strength of the geopolymer was increased exposed to thermal load up to 1200°C.
2.3 CONCLUSION

Based on the literature review presented, there are a number of areas that is necessary to expand to understand the application of PCM material as a passive storage in normal room temperature applications. Also geopolymer as a high temperature thermal storage has not been studied before and evolution of thermal conductivity and specific heat capacity was not addressed in this respect. The work presented in this thesis is novel and will fill the current knowledge gap of in the understanding of these materials as passive storages of thermal energy at different temperatures. Main research questions that arose from the literature review that the research attempted to answer are as listed below:

- What are the main influencing factors of PCM application in residential buildings and how do they facilitate reduction in energy consumption in local weather?
- What is the effectiveness of PCM in local Australian typical residential buildings and how can it be improved?
- How can PCM be introduced in hollow core concrete slab system and what is the effectiveness of that application?
- What is the evolution of thermal conductivity and heat capacity of geopolymer during steady state and transient heating?
CHAPTER THREE

3 ROOM TEMPERATURE TES: NUMERICAL INVESTIGATION OF PCM APPLICATION IN AUSTRALIAN RESIDENTIAL HOUSES

3.1 INTRODUCTION

In recent years, Latent Thermal Energy Storage (LTES) systems in buildings have received serious attention for reducing the dependency on fossil fuels and contributing to a more efficient environmentally benign energy use. Latent heat storage materials, also known as phase change materials (PCM’s), absorb or release the energy equivalent to their latent heat when the temperature of the material undergoes or overpasses the phase change temperature [5]. PCM represent a technology that has the potential to shift peak load and reduce Heating Ventilation and Air-conditioning (HVAC) energy consumption in buildings. A large number of research studies on PCM application in buildings have been carried out during the last 30 years which resulted in the considerable amount of literature about PCM properties, PCM impregnation methods, locations of application and effect of PCM on thermal energy storage, indoor temperature, energy consumption and peak load shifting of buildings.

PCM can be incorporated in wallboards, concretes, plaster, roof, underground and insulation of buildings [10, 33, 36, 37, 40, 67]. From laboratory experiment, it was reported that the TES of the gypsum wallboard can be increased by ten times through the incorporation of PCM [43]. Oliver [80] observed that a 1.5 cm thick board of gypsum with PCM can store thermal energy equivalent to a 12 cm thick brick wall. A similar
phenomenon was also observed by Kuznik et al. [9]. In the case of concrete wall with PCM, 30% increase in TES was reported by Hawes et al. [46, 47, 82]. Hunger et al. [88] reported energy savings up to 12% through the inclusion of 5% microencapsulated PCM in the self-compacting concrete mix. From the theoretical investigation, Neeper [74] indicated that the maximum diurnal energy storage occurred when the PCM melting temperature was close to the average comfort room temperature.

After having studied PCM walls in the laboratory, several authors studied their performances in test rooms exposed to outdoor weather conditions. Athienitis et al. [71] observed 4°C decrease in maximum room temperature in Montreal using gypsum board with 25% butyl stearate PCM. Kissock et al. [18] observed a 10°C reduction in peak daytime temperature of Dayton, Ohio where wallboard imbibed with 30% commercial paraffinic PCM K18 was used. Shilei et al. [76] managed to decrease the room temperature by 1.02°C in the northeast of China by incorporating a mixture of capric and lauric acid into the wallboard. Chen et al. [15] showed that energy savings can get to 17% or higher if phase transition temperature and enthalpy is set at 23°C and 60 kJ/kg respectively during the winter season in north of China. Ahmed et al. [99] observed 20°C decrease in the indoor temperature amplitude of the test cell through the application of a composite wallboard with vacuum insulation panel and PCM during summer in France. In addition to the wall, several studies were carried out by incorporating PCM in the roof, floor and plaster of the test room [94, 96, 97, 101, 103] and reductions in room temperature fluctuation were observed.

With the advent of the more accurate computational method, numerical modelling is becoming increasingly popular to test the performance of PCM in buildings. In the numerical studies, the phase change effect has been taken into account through either enthalpy method [139-141] or heat capacity method [133-137]. Kuznik et al. [150] used building simulation software TRNSYS to simulate PCM wall where phase change process was taken into account through effective heat capacity method. The calculated internal wall surface temperature was found to be in good agreement with experimental data [78]. Heim et al. [152] modelled the behaviour of PCM in a three zone building using building simulation software ESP-r. Effect of phase transition was added to the energy
equation through effective heat capacity method. Pederson et al. [17] used building simulation software EnergyPlus to simulate buildings with PCM wall in Minneapolis MN, USA. Effect of PCM was modelled through Enthalpy method in EnergyPlus. It was shown that the incorporation of PCM lowers the peak cooling load by 1000W at that particular simulation environment. Using same software, Tardieu et al. [16] showed that PCM wallboards reduce the daily indoor temperature fluctuation by up to 4°C on a typical summer day in Auckland. Recently, after extensive verification and validation study Tabares-Valesco et al. [233] showed that EnergyPlus can accurately predict the thermal performance of buildings with PCM if several guidelines are met. Hence, “EnergyPlus v7.2” has been adopted as the investigation tool in the present study.

From the above literature, it is evident that integration of PCM in building materials results in an increase in thermal energy storage of building which in turn reduces the indoor temperature fluctuation and energy consumptions of the buildings. It is also observed that efficiency of PCM depends on local climate, types of PCM, the amount of PCM and the location of application in buildings. The aim of the present study is to investigate the potential of PCM in reducing building energy consumptions and some parameters (i.e. PCM melting ranges, applied surface area, PCM layer thickness, local comfort range, etc.) related to the effective application of PCM at different Australian cities. Finally, the potential effect of climate change on the effectiveness of PCM has been explored.

3.2 METHODOLOGY

3.2.1 Building Construction

A single room house was considered for the simulation as shown in Figure 3.1. The house was divided into two zones: attic zone and living zone. The dimensions of the living zone were 4 m (length) x 4 m (width) x 3 m (height) with 16 m² floor area. The living zone contains one window on each of the west and north wall and one south-facing door. The size of each window was 2.5 m (width) x 1 m (height) and the position was 1 m above the floor surface. All the roof, wall, door and window materials were chosen according to the Australian standard [234]. The total window area was
maintained as 25% which is within the recommendation of Building Codes of Australia (BCA) [234]. The thickness of windows is 3mm with Solar Transmittance = 0.45, Visible Transmittance = 0.7 and Conductivity = 0.9 W/m-K. The size of the south facing door was 2 m (width) x 0.8 m (height) and is positioned at an offset of 0.5 m from the left edge. The roof was of hip type with 45° pitch on east and west sides and 23° pitch on the other two sides. The roof has 0.5 m long eaves on all four sides.

The thermo-physical properties of all the building materials are presented in Table 3.1. The detail constructions of building roof, ceiling, walls and floors are specified in Table 3.2. All the constructions were chosen according to the standards suggested by the Insulation Council of Australia and New Zealand (ICANZ) [235]. The roof was constructed following the R0100 system-pithed tiled roof with a flat ceiling, and the external walls were constructed according to W0100 system-clay masonry veneer [235]. The ground level concrete slab was used as a floor. Only the living area zone of the building was conditioned to maintain the desired comfort range.

Figure 3.1 The model of the Single room house
Table 3.1 Thermo-physical properties of the building materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Thickness (m)</th>
<th>Conductivity (W/mK)</th>
<th>Density (kg/m³)</th>
<th>Specific heat (J/kg-K)</th>
<th>Resistance (m²-K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick veneer</td>
<td>0.110</td>
<td>0.547</td>
<td>1950</td>
<td>840</td>
<td>0.2</td>
</tr>
<tr>
<td>Insulation wall</td>
<td>0.07</td>
<td>0.044</td>
<td>12</td>
<td>883</td>
<td>0.63</td>
</tr>
<tr>
<td>(Glass fibre batt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation roof</td>
<td>0.162</td>
<td>0.044</td>
<td>12</td>
<td>883</td>
<td>3.68</td>
</tr>
<tr>
<td>(Glass fibre batt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasterboard</td>
<td>0.01</td>
<td>0.17</td>
<td>800</td>
<td>1090</td>
<td>0.059</td>
</tr>
<tr>
<td>Timber</td>
<td>0.035</td>
<td>0.159</td>
<td>721</td>
<td>1260</td>
<td>0.22</td>
</tr>
<tr>
<td>Carpet</td>
<td>0.02</td>
<td>0.0465</td>
<td>104</td>
<td>1420</td>
<td>0.43</td>
</tr>
<tr>
<td>PCM</td>
<td>0.005</td>
<td>0.2</td>
<td>860</td>
<td>1970</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 3.2 Construction of the different parts of the building

<table>
<thead>
<tr>
<th>Name</th>
<th>Construction (outside to inside layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>Brick veneer, 40 mm Air gap, Insulation, wall plasterboard</td>
</tr>
<tr>
<td>Roof</td>
<td>Roof tiles</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Roof insulation ceilings, PCM, plasterboard</td>
</tr>
<tr>
<td>Floor</td>
<td>Concrete, carpet</td>
</tr>
<tr>
<td>Door</td>
<td>Timber</td>
</tr>
</tbody>
</table>

3.2.2 Building Simulation Details

The building energy simulation software EnergyPlus v7.2 was used to carry out the simulation for eight different cities of Australia located in six different climate zones (Figure 3.2): Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth and Sydney. The standard International Weather for Energy Calculation (IWEC) files of these cities were used for the simulation. All the simulations were carried out for one year (8760 hours) using conduction finite difference algorithm (ConFD). The ConFD algorithm provides the opportunity to simulate materials with variable properties such as PCM. Table 3.3 shows the main operating conditions of the simulations. Time step of the simulation was set to 3 min as recommended by Tabares-Valesco et al. [233]. The thermostat heating and cooling set points for different cities and HVAC schedules were
set according to the Australian Building Codes Board (ABCB) [236] assuming that the simulated zone is a living room of a house. The metabolic heat generation rates of the occupants were defined from Table 4, Chapter 9 of ASHRAE Handbook [237]. The different metabolic heat generation rates represent different activities like sitting, writing, cooking, reading, etc.

Figure 3.2 Australian climate zones with the major cities [238]

The ZoneHVAC:IdealLoadsAirSystem module of EnergyPlus was used to calculate the heating and cooling energy consumptions [239]. This is an ideal Variable Air Volume (VAV) terminal unit with variable supply temperature and humidity. The supply air flow rate varies between zero to maximum and supplies cooling or heating air to the zone in sufficient quantity to satisfy the zone heating and cooling load. The Ideal System was used here instead of any particular HVAC system because the aim of this study was to calculate the total energy requirement of a building under various operating conditions. All of the building external surfaces were exposed to the outdoors
environment except the floor which was in contact with the ground. The heat transfer between the building floor and the ground were modelled using the GroundHeatTransfer:Slab module of the EnergyPlus software [239]. Infiltration in the conditioned zone was taken into account through Effective leakage area model ZoneInfiltration:EffectiveleakageArea available in the software. The dual thermostat setting (Heating set point and cooling set point) was provided using the objects ZoneControl:Thermostat and ThermostatSetPoint:DualSetPoint.

For each city, simulations were carried out using BioPCM® material with six different melting ranges: 20PCM (18-22°C), 21PCM (19-23°C), 22PCM (20-24°C), 23PCM (21-25°C), 24PCM (22-26°C) and 25PCM (23-27°C). The latent heat of the BioPCM® was 219 kJ/kg. Phase change was taken into account through the enthalpy-temperature graph of BioPCM® [240] as shown in Figure 3.3. The enthalpy-temperature graphs for all other PCM were obtained by shifting the curve according to the PCM melting ranges. Although BioPCM® is available in the form of square pouches, it was assumed as a constant layer because the PCM module in EnergyPlus allows the use of the PCM material as a continuous layer rather than blocks. BioPCM® pouches can be taken as a constant layer of BioPCM® by following the procedure described by Muruganantham [240]. Each simulation was performed twice: a) with and b) without HVAC system.

![Figure 3.3 Enthalpy-temperature graph of PCM 20](image)
### Table 3.3 Operating conditions used in the simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time step</td>
<td>3 min</td>
<td></td>
</tr>
<tr>
<td>Heating Set point (°C)</td>
<td>20</td>
<td>HVAC operates from</td>
</tr>
<tr>
<td>Cooling Set point (°C)</td>
<td>25 Adelaide</td>
<td>7am-12am everyday</td>
</tr>
<tr>
<td></td>
<td>24 Melbourne</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23 Hobart</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24 Canberra</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.5 Sydney</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.5 Brisbane</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26.5 Darwin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 Perth</td>
<td></td>
</tr>
<tr>
<td>People (person/m²)</td>
<td>0.0625</td>
<td></td>
</tr>
<tr>
<td>Metabolic rate (W/person)</td>
<td>108 (Writing, seating, standing)</td>
<td>7am – 6pm</td>
</tr>
<tr>
<td></td>
<td>171 (cooking, cleaning)</td>
<td>6pm – 8pm</td>
</tr>
<tr>
<td></td>
<td>108 (Reading, relaxing)</td>
<td>8pm – 10am</td>
</tr>
<tr>
<td>Lighting (W/m²)</td>
<td>2.5</td>
<td>6pm – 10pm</td>
</tr>
<tr>
<td>Electric equipment (W/m²)</td>
<td>1.875</td>
<td>7am – 10 pm</td>
</tr>
</tbody>
</table>

### 3.3 Validation

In the present study, the algorithm used in EnergyPlus and the application of the PCM module was verified against the experimental data of Kuznick and Virgone [9]. The building geometry and operating conditions were selected according to the experimental study [9]. The weather file was created using the temperature vs time plot and the radiative heat flux vs time plot provided in the same paper. The same wall construction was used in simulation with layers of 50 mm wood plate, 10 mm plaster board, 50 mm polystyrene, 5 mm PCM and 13 mm plasterboard as in the experiment [9]. The heat capacity of the PCM was taken from the heat capacity vs temperature curve provided by Kuznick and Virgone [9]. The simulation was carried out for 24 hours and the indoor room temperature from the simulation was compared with the experimental
data. Figure 3.4 shows that the simulated zone temperatures were in very good agreement with the experimental data with an average percentage of deviation of around 3% for both PCM and no PCM cases. The percentage of deviation is comparable with the study of Kuznik and Virgone [78] where 2.6% deviation was observed between the experimental results and Numerical model. Hence, the EnergyPlus PCM module can be used to analyse the thermal performance of studied house and benefits of PCM integration.

Figure 3.4 Experimental and simulated zone temperature a) without PCM and b) with PCM
3.4 RESULTS AND DISCUSSIONS

3.4.1 Effect of PCM Integration on Zone Temperature Fluctuation

At first, the model was simulated for all the cities under investigation without the HVAC system, and hourly zone temperature data were extracted to see the effect of PCM on zone temperature fluctuations. Figure 3.5 compares the living zone mean temperature for the simulations with and without PCM during first four days of April in Melbourne weather. The figure shows that with the integration of PCM the daytime temperature was reduced while the night-time temperature was increased. As a result, the overall zone temperature was moved closer to the comfort range of Melbourne (20-24°C). Here, PCM with 21°C melting point (melting range 19-23°C) was used. When the zone temperature reached near the melting range, PCM began to melt by absorbing the heat energy from the zone as a latent heat by changing its phase from solid to liquid which in turn held the zone temperature and prevented rising of temperature. During the nighttime when the zone temperature dropped below 21°C, the PCM began to solidify by releasing the stored heat to the zone. As a result, zone temperature was increased. With the PCM application, the average daytime zone temperature was reduced by 1.7°C and average night-time zone temperature was increased by 1.3°C in the month of April in Melbourne weather. Furthermore, due to the PCM integration, the duration (hours) of zone temperature outside the comfort zone was also reduced (Figure 3.5). For the four days shown in Figure 3.5, the zone temperature was outside the comfort zone with a duration of 76 hours for the model without PCM. On the other hand, with the PCM, the duration was reduced to 56 hours.

In Figure 3.5, the average maximum zone temperature reduction due to the PCM application is denoted by ‘a’ and the average minimum zone temperature increase is denoted by ‘b’. Now the sum of ‘a’ and ‘b’ can be termed as Average Temperature Fluctuation Reduction (ATFR). Figure 3.6 compares the monthly ATFR values for different PCM in different cities of Australia. The results show that the PCM effectiveness regarding ATFR was different at different cities in the different times of the year. In the cool temperate climate zone like Hobart, Melbourne and Canberra, PCM worked better during the months from January to April and September to December.
where the average fluctuation was found to be 3°C to 4°C. This is because the diurnal
temperature fluctuations of these months of the year were favourable for PCM to melt
(charging) and solidify (discharging). Thus, PCM acted a thermal storage by storing and
releasing the latent heat which contributed to the reduction of zone mean temperature
fluctuation. In those same cities, the ATFR values during the months of May – August
(winter) was less than 1°C, which indicates that the diurnal temperature fluctuation was
not favourable for the charging and discharging of PCM at these months of the year.

Figure 3.5 Zone mean air temperature from 1st to 4th of April in Melbourne weather

In the mild temperate climate zone like Adelaide, best PCM performance was observed
during March – May (Autumn) and September – November (Spring). Unlike the
previous weather zone, PCM also exhibited good performance during the other times of
the year (ATFR value 1.5°C-2°C), especially during the winter season (May – September).
In the warm temperate climate zone like Sydney and Perth, the ATFR values suggest
that the effectiveness of PCM was reduced in summer (November – February) while
other months showed higher average temperature reduction (2.5°C or above). This is
because the night-time temperature during summer may not always drop below the
PCM solidification point, and thus PCM effectiveness is reduced. A similar trend was
seen in Brisbane, which is in warm humid summer and mild winter climate zone (Figure
In this city, the PCM performance was observed for a longer period, from April to October where the ATFR values were mostly between 3°C – 4°C. The humid summer has smaller diurnal temperature fluctuation with higher night time temperature due to which PCM was mostly inactive (mostly less than 1°C) during November – February (summer). The Darwin City is in high humid summer and warm winter climate zone where PCM was found mostly ineffective (ATFR values below 1°C). Because, similar to previous climate zone, the diurnal temperature in Darwin does not drop enough throughout the year to solidify the PCM and thus the average temperature reduction was minimal. Only during June – August (winter) the temperature fluctuation was enough to create ATFR values above 1°C due to PCM application (Figure 3.6).

Figure 3.6 also reveals that the performance of PCM with different melting temperature was different for different times of the year. For example, the best-performed PCMs regarding ATFR in Adelaide are: 25 PCM during December – March, 23 PCM on April and October, 21 PCM on May, 20 PCM during June – September and 24 PCM on November. Similarly, in Sydney, the 25 PCM performed better during November – April, 23 PCM on May, 20 PCM during June – July, 21 PCM on August, 22 PCM on September and 24 PCM on October. The trend from the ATFR values shows that, in general, high melting point PCM was working better during the summer time and the low melting point PCM during the winter season. The overall results from the Figure 3.6 suggest that the performance of PCM in reducing the diurnal temperature fluctuation is strongly dependent on the local weather, and no single PCM is uniformly effective throughout the year. Also, in general, PCM with high melting temperature is more suitable for warm temperate climate whereas low melting point PCM is for the cool temperate climate.
Figure 3.6 Average temperature fluctuation reduction in different Australian cities.
3.4.2 Effect of PCM on Annual Energy Consumption

To study the annual energy consumption, the simulation of models similar to the previous section (Section 3.4.1) were carried out with the inclusion of HVAC system. Figure 3.7 shows the percentage of annual energy consumption reduction with the application of PCM. The percentage of energy reduction was calculated by using the following formula:

\[
\text{% of energy consumption reduction} = \left( \frac{\text{energy consumption without PCM} - \text{energy consumption with PCM}}{\text{energy consumption without PCM}} \right) \times 100
\]

By comparing the Figure 3.6 and Figure 3.7 it can be observed that the profiles of the energy consumption reduction are very similar to the profiles of the ATFR values. This indicates that the average temperature fluctuation reduction was mainly contributing to the reduction of energy consumption. Also, in general, higher energy consumption reduction was found for the corresponding higher ATFR values of all cities.

The results from the Figure 3.7 shows that the energy consumption reduction was higher during summer in the cool temperate climate zones whereas in the warm temperate climate zone, it was higher during the winter season (similar to ATFR values). Moreover, the PCM with lower melting point reduced more energy consumption during the winter season than others whereas PCM with high melting point performed better in reducing summer-time energy consumptions. This trend is also similar to the ATFR values described in Section 3.4.1. For example, at Adelaide city in January, the highest value of ATFR was found as 2.3°C which was from 25 PCM and the highest reduction in energy consumption, i.e. 12% was also resulted from the same PCM. Similarly, during September, the 20 PCM was the most effective with 3.1°C average reduction of temperature fluctuation and 42% reduction of corresponding energy consumption.

However, the similarity between the results of ATFR values and energy consumption reduction is not always true. Because the difference between free simulation (without HVAC) and simulation with HVAC are that the dual thermostat setting was used for the latter case, i.e. heating and cooling thermostat settings. Table 3.3 shows the thermostat
settings for all simulated cities of Australia as recommended by Australian Building Code Board (ABCB) [241]. The heating thermostat is same for all cities, but the cooling thermostat is different for different cities. Now if a better-performed PCM in ATFR values has the melting point outside the thermostat settings, it may not have similar effectiveness in energy consumption reduction. For example, in Melbourne city, the 25 PCM was most effective in average temperature fluctuation reduction during January – March whereas in the case of energy consumption reduction, it was the least effective. This reason behind this is that the heating and cooling thermostat point of Melbourne city was 20°C and 24°C respectively. So when the zone temperature went above 24°C the 25 PCM was in the process of melting (phase change temperature 23°C-27°C). As the cooling set point was 24°C, the HVAC needed to cool down the zone as well as solidify 25 PCM to bring down the temperature at or below 24°C. Thus, this process required extra energy consumption which in turn reduced the performance of 25 PCM. Similar trends can be seen for the Canberra and Hobart. The heating and cooling set point for Hobart are 20°C and 23°C respectively. During January – March, the ATFR values of 23 PCM and 24 PCM was higher compared to the 21 PCM. But in case energy consumption reduction the 21 PCM was found to be the best for those months where 23 PCM and 24 PCM was found some of the least effective ones.

From the results and the discussion above, it can be concluded that the performance of PCM in energy savings depends on the local weather as well as local thermostat settings. A PCM which has high effectiveness in reducing average temperature fluctuation may not be necessarily best regarding energy savings. Furthermore, it can be also be observed that the optimum PCM melting point contributing the highest energy consumption reduction throughout the year is far from unique. PCM with different melting temperature are found to be effective at different times of the year for all the cities investigated. At this point, the optimum PCM can be selected by finding the highest contributing one to the annual energy savings in a particular city.

Table 3.4 shows the most effective melting point PCM for different cities of Australia and their respective annual energy savings percentage. It can be observed that the application of PCM was most effective in Adelaide where 23.5% of annual energy
savings was found. Darwin, on the other hand, was found to have minimal or no effect on annual energy saving (Figure 3.7) due to PCM application (not shown in Table 3.4). Further studies are required on the effective use of PCM in hot and humid climate zone like Darwin.

Table 3.4 Most efficient PCM at different cities of Australia for the studied house (ratio of wall to floor area = 2.6)

<table>
<thead>
<tr>
<th>City</th>
<th>PCM</th>
<th>Energy consumed per conditioned floor area (MJ/m²)</th>
<th>Annual Energy savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No PCM</td>
<td>With PCM (5mm PCM layer spread to a surface area of 16m² in ceiling)</td>
<td></td>
</tr>
<tr>
<td>Adelaide</td>
<td>22</td>
<td>366</td>
<td>280</td>
</tr>
<tr>
<td>Brisbane</td>
<td>23</td>
<td>430</td>
<td>357</td>
</tr>
<tr>
<td>Canberra</td>
<td>21</td>
<td>481</td>
<td>391</td>
</tr>
<tr>
<td>Hobart</td>
<td>20</td>
<td>394</td>
<td>306</td>
</tr>
<tr>
<td>Melbourne</td>
<td>21</td>
<td>411</td>
<td>332</td>
</tr>
<tr>
<td>Perth</td>
<td>22</td>
<td>422</td>
<td>336</td>
</tr>
<tr>
<td>Sydney</td>
<td>23</td>
<td>329</td>
<td>254</td>
</tr>
</tbody>
</table>
Figure 3.7 Energy consumption reductions with PCM in different Australian cities
3.4.3 Effect of PCM Surface Area and Thickness on Energy Consumption

In the previous section, the performance of different melting point PCM was discussed where PCM layer with 5 mm thickness was applied in the ceiling as shown in Table 3.2. In this section, the potential of the PCM in energy savings is explored using different location and area of application and different thickness of the PCM layer. Table 3.5 shows the location, area and thickness of PCM application as well as respective results from the PCM applications. To compare all of these different combination of PCM application, the total volume of the PCM was kept same for all the simulated case. The thickness of the layer was calculated by dividing the total volume of the PCM by the surface area of the PCM application.

From the Table 3.5, it can be observed that the PCM application in individual wall resulted in less annual energy savings compared to the one applied in the ceiling. This is because the warm air of the thermal zone always goes up because of the buoyancy effect and thus it has better interaction with ceiling compared to the surrounding wall of the zone. This increases the effective charging and discharging of PCM and thus better contribute to energy savings. Table 3.5 also shows that the performance of PCM, regarding energy savings, increases with the decrease of the PCM layer thickness and increase of the surface area of application. This is reasonable because the increase of the area of application means that the PCM has higher heat transfer area which results in higher heat transfer rate. Moreover, the thickness of the PCM layer decreases with the increase of the surface area as the total volume of the PCM is constant. The lesser thickness of PCM facilitates less time for charging and discharging. Because due to the low thermal conductivity (0.2 W/m.K), the thicker the PCM layer, the more time it would take to melt or solidify and thus would have less possibility of effective charging and discharging process during the diurnal temperature fluctuation. This is why the effectiveness of the PCM in reducing the energy consumption is increased with the larger surface area and lesser thickness of the PCM layer.

However, from Table 3.5, it can be observed that the PCM application in “all wall” with 41.4 m² surface area resulted in the highest energy savings and then it is slightly
decreased in “all wall and roof” case although the area of application is increased to 57.4 m² in the latter simulation. This happened due to the difference in thickness of the PCM in those two cases which can be explained with the Figure 3.8. The temperature of the PCM layer at the east wall is plotted in Figure 3.8 for four different cases in Sydney weather. These simulations were carried out using 23 PCM and thickness of the PCM layer is presented in Table 3.5. From Figure 3.8, it can be seen that the minimum temperatures for all the cases are low enough for the solidification (discharging) of PCM and the only difference is in daytime melting (charging) of PCM. Now among all the cases, the “east wall” has the thickest PCM layer which shows inadequate melting of PCM in Figure 3.8. Due to the thicker PCM layer, the maximum temperature of the PCM layer was in the range of the melting phase of the 23 PCM. This suggests that the PCM was not completely melted (fully charged). Thus, the corresponding energy saving was lowest among all the four cases. In the case of “east wall and roof”, the thickness of the PCM layer was less than that of the “east wall”. The resulted maximum PCM temperature was higher than the “east wall” but still in the melting range of 23 PCM. This means that, in “east wall and roof” case, the PCM was is still in the melting process, but the fraction of melted PCM was higher than the “east wall” case. Hence, the resulted energy savings was higher than that of “east wall”.

Table 3.5 Energy savings for surface area and thickness of PCM with constant volume of 0.08 m³ (Results are shown for Sydney weather)

<table>
<thead>
<tr>
<th>Location</th>
<th>PCM Surface area (m²)</th>
<th>Thickness of PCM layer (mm)</th>
<th>Annual energy consumption (GJ)</th>
<th>Annual Energy savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No PCM</td>
<td>0</td>
<td>0</td>
<td>5.28</td>
<td>0</td>
</tr>
<tr>
<td>Roof</td>
<td>16</td>
<td>5</td>
<td>4.07</td>
<td>22.9</td>
</tr>
<tr>
<td>East wall</td>
<td>12</td>
<td>6.7</td>
<td>4.30</td>
<td>18.5</td>
</tr>
<tr>
<td>North wall</td>
<td>9.5</td>
<td>8.42</td>
<td>4.43</td>
<td>16.1</td>
</tr>
<tr>
<td>West wall</td>
<td>9.5</td>
<td>8.42</td>
<td>4.48</td>
<td>15.22</td>
</tr>
<tr>
<td>South wall</td>
<td>10.4</td>
<td>7.7</td>
<td>4.42</td>
<td>16.28</td>
</tr>
<tr>
<td>North wall and roof</td>
<td>25.5</td>
<td>3.14</td>
<td>3.85</td>
<td>27</td>
</tr>
<tr>
<td>Location</td>
<td>PCM Surface area (m²)</td>
<td>Thickness of PCM layer (mm)</td>
<td>Annual energy consumption (GJ)</td>
<td>Annual Energy savings (%)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>West wall and roof</td>
<td>25.5</td>
<td>3.14</td>
<td>3.89</td>
<td>26.4</td>
</tr>
<tr>
<td>South wall and roof</td>
<td>26.4</td>
<td>3.03</td>
<td>3.87</td>
<td>26.75</td>
</tr>
<tr>
<td>East wall and roof</td>
<td>28</td>
<td>2.86</td>
<td>3.83</td>
<td>27.5</td>
</tr>
<tr>
<td>All wall</td>
<td>41.4</td>
<td>1.93</td>
<td>3.72</td>
<td>29.6</td>
</tr>
<tr>
<td>All wall and roof</td>
<td>57.4</td>
<td>1.39</td>
<td>3.75</td>
<td>29</td>
</tr>
</tbody>
</table>

In the case of “all wall”, the maximum temperature was reached to 25°C, which is just above melting range of 23 PCM. So the thickness of the PCM in “all wall” case was just enough to melt the PCM completely. This facilitates the complete daytime charging of PCM, and that’s why the annual energy savings was the highest for this case compared to the all previous cases.

However, in the case of the “all wall and roof”, where the thickness of the PCM layer was 1.39 mm, the PCM temperature rose quickly and melting period became shorter than the previous cases. Due to a thinner PCM layer, the PCM was fully melted within a short period and thus the PCM temperature was quickly increased after the phase transformation (Figure 3.8). Therefore, the PCM could not keep the zone temperature within the comfort range (20-25°C for Sydney) for a longer period and additional energy was required to maintain the comfort temperature. So “all wall and roof” yielded lower energy savings compared to the “all wall”, although the former case has a higher surface area than the latter one.

Finally, among the other results, Table 3.5 shows that despite having the same surface area of PCM application, “north wall” had higher annual energy savings than the “west wall”. A similar trend can be seen between the “north wall and roof” and “west wall and roof”. The reason might be due to the difference in the projection of solar radiation experienced by these walls.
3.4.4 Comparison with a Typical Residential House

A typical single story Australian residential house was modelled in full-scale and simulated with and without PCM application to investigate the effectiveness of PCM. The house has a floor area of 232 m², and it is a 5-star energy rated house according to the Nationwide House Energy Rating Scheme (NatHERS), Australia. The NatHERS is an energy rating system for Australian homes, by which the thermal energy efficiency of a residential house is rated (out of ten) based on its design. Figure 3.9 shows the 14 thermal zones of the simulated residential house. The dimensions and the detail construction of this house can be found from these articles [242, 243]. The energy simulation was carried out with PCM of five different melting point in Sydney and Melbourne weather using the settings described in section 3.2.2. Similar to the single house model, the PCM layer with 5 mm thickness was applied in the ceiling of the all thermal zones except the garage area.
Figure 3.9 Thermal zones of a typical single storey residential house [242]

Figure 3.10 shows the potential of different melting point PCM in reducing the annual energy consumption in the typical residential house for the two simulated weather. The figure also compares the results with that of the single room house simulation. For the single room house, the results indicated that the 21 PCM and 23 PCM has the best potential for annual energy savings in the Melbourne and Sydney weather respectively. The results from this single room house can be used to predict the energy savings potential of PCM application with the different combination as described in the previous sections. However, the Figure 3.10 also reveals that the actual percentage of annual energy savings due to the PCM application is different for the typical residential house and the single room house. This was expected because every house is different regarding internal thermal loading because of the its size, orientation, construction of the walls, roofs, windows and their materials, window size and position, etc. So the energy requirement will be different for different residential houses based on their design. But the Figure 3.10 suggests that the trend of the effectiveness of PCM application in annual energy savings would be similar. In both cases, the most effective PCM was 21 PCM and 23 PCM for Melbourne and Sydney weather respectively. Since, the main goal of this study was to find the optimum PCM melting range for the different climate zone and to
investigate the effect of different combination of the PCM applications on the annual energy savings, the single house was considered for the simulation rather than the real residential house which also contributed to lower the simulation time.

Figure 3.10 Energy saving potential of PCM in both the single room house and real house

Finally, although the best effective PCM (21 PCM and 23 PCM) for Melbourne and Sydney was similar for single room house and the typical residential house, these contributed to only 10.3% and 3.3% of the annual energy savings. This percentage can be improved by using different combinations of PCM application as described in section 3.4.3.

3.5 CONCLUSIONS

The effectiveness of PCM application on the building energy savings at different climate zones of Australia and the several factors of PCM application that influence the PCM effectiveness was investigated using the building energy simulation software EnergyPlus. PCM with five different melting ranges has been studied to find out the optimum PCM melting point for each major city. From the current study, following conclusions have been reached:
• The PCM effectiveness was found to be different for the different Australian climate zone. PCM has the potential in reducing the annual building energy consumption in Australian cities of mild temperate, warm temperate and cold temperate climate zone. It was found to have a minimal effect in building energy savings in hot and humid climate zone.

• The optimum PCM melting point resulting the highest energy savings on each month of the year is far from unique. The PCM melting point which contributes to the highest annual energy savings in a particular city can be selected as best performing PCM for that specific city.

• The efficacy of the PCM also depends on the location of PCM application, the thickness of PCM layer and surface area of application. The ceiling was found to be the best place among the ceiling and walls for the PCM application because the warmer air has more chance to interact with the ceiling than the walls. Also, for a constant volume of PCM, its effectiveness on energy savings increases with the decrease of PCM layer thickness and the increase of the surface area of application. This phenomenon happens until an optimum point after which the energy savings decreases with the increase of the surface area.

• The PCM performance also depends on the local thermostat range or comfort range. The PCM with a melting point outside the thermostat range does not provide effective energy consumption reduction although it may be the best in reducing the average temperature fluctuation under free running condition.

• The most effective PCM regarding the highest energy savings in different cities were found as follows: 22 PCM was most efficient for Adelaide and Perth, for Brisbane and Sydney 23 PCM, for Melbourne and Canberra 21 PCM and finally for Hobart 20 PCM was the most effective.

• The comparison between the single room house and typical residential house shows that the most effective PCM melting point is the same in both cases although the amount of PCM used is different. Thus, single room house can be used to find optimum PCM melting point for any city or climate zone.
CHAPTER FOUR

4 ROOM TEMPERATURE TES: EXPERIMENTAL STUDY AND NUMERICAL SIMULATION OF A REAL HOUSE WITH AND WITHOUT PCM

4.1 INTRODUCTION

The energy efficient buildings are one of the most important keys to reduce the greenhouse gas emission and to develop a sustainable society [244]. Building sector accounts for approximately 40% of total energy consumption and one-third of greenhouse gas emission around the world [245]. The energy demand in this sector is growing each year because of the increasing number of the population around the world. In 2009–2010, the energy consumption of residential building in Australia was around 25% of total energy consumptions [1] and approximately 40% of this energy was used for space heating and cooling [246]. Previous research showed that integration of Thermal Energy Storage (TES) system in buildings has great potential in reducing heating and cooling energy demand and increasing the thermal comfort [247]. In the last couple of decades, Phase Change Material (PCM) have received considerable attention as a Latent Heat TES system in building for passive heating and cooling applications in buildings [6]. PCM can store or release heat as a heat of fusion or solidification during the phase change process and in this way, it is capable of storing a large amount of thermal energy compared to its volume. It has a large heat capacity over a limited temperature range and acts as an almost isothermal reservoir of heat.
In passive application method, PCM has been extensively studied by integrating it in ceilings, walls, floors, windows, etc. of experimental rooms or test cells. Athienitis et al. [71] observed 4°C decrease in maximum room temperature using gypsum board with 25% PCM in Montreal weather. In another study, similar temperature reduction and improved thermal comfort have been observed by Kuznik et al. [9, 77] when PCM was integrated into the wall of a lightweight test room. Shilei et al. [76] investigated an experimental room in the northwest of China with PCM wallboard and found 1.15°C reduction in room temperature during winter. Ahmad et al. [99] observed 20°C decrease in the indoor temperature amplitude of the test cell through the application of a composite wallboard with vacuum insulation panel and PCM during summer in France. Cabeza et al. [14] set up two real size concrete cubicles in Lleida, Spain, where walls of one cubicle were integrated with microencapsulated PCM. The experimental results showed that in the cubicle without PCM, the maximum temperature was 1°C higher, and minimum temperature was 2.8°C lower than that with PCM. The integration of PCM also found to shift the maximum indoor temperature by 2 hours. In another study [94], the application of microencapsulated PCMs in concrete floors resulted in a reduction of maximum floor temperatures up to 16°C ± 2%, and an increase of minimum temperatures up to 7°C ± 3%. Several studies with PCM integrated into brick walls also showed great potential in reducing indoor temperature [139, 248]. Integration of PCM on the roof also found to narrow down the indoor air temperature swings [97]. Barzin et al. [249] combined the PCM impregnated gypsum boards with night ventilation and free cooling method to improve the PCM efficiency. This combination was tested in a hut in Auckland (NZ) which significantly improved the energy savings. Recently, Ramakrishnan et al. [250] developed a novel thermal energy storage composite by impregnating paraffin PCM into hydrophobic coated expanded perlite granules. Because of the hydrophobic coating, up to 50% by weight of PCM was impregnated successfully without any leakage of PCM. The results revealed that the thermal inertia and thermal energy storage of panel incorporating PCM were significantly greater than that without PCM.

Nowadays, more and more researchers are using building simulation model to investigate PCM performance, particularly using real buildings geometry and
conditions. One of the reasons might be the increase in confidence in the simulation results with the advent of high-performance simulation tools. Another reason is to investigate PCM performance in real conditions as it is sometimes difficult to conduct experiments in real buildings. Ascione et al. [251] simulated office building with PCM plaster on the inner side of the wall in five Mediterranean climates. The results showed a general trend of energy savings with the increase of PCM thickness. The highest energy saving was achieved for the city of Ankara with 7.2%. However, in naturally ventilated condition, a maximum of 22.9% improvement of comfort times was observed in Naples (US). In another study, a typical 171 m² house was simulated in Auckland (NZ) by Behzadi et al. [252] and it was concluded that the use PCM-impregnated gypsum board could lessen the indoor temperature fluctuation by 4°C on a typical summer day. From the simulation PCM integrated residential buildings in four different cities of USA, Campbell et al. [253] showed that the occupant comfort can be substantially improved by the use of PCM. Best performance was found in the Portland (Oregon) where 93% of zone hours outside the thermal comfort were reduced by using 3.1 kg/m² PCM (BioPCM™) with a melt temperature of 25°C. Based on this simulation result, Sage-Lauck et al. [254] have done another experimental and numerical study on the same house in Portland by installing 130 kg of 25°C–BioPCM™ (0.9 kg/m² floor area) on the ceiling and wall. The authors have concluded that the incorporation of BioPCM™ could reduce the zone overheated hours by about 50%. From the simulation study, Alam et al. [255] observed that effectiveness of PCM in reducing building energy consumption depends on local climate, local thermostat range, PCM applied surface area and PCM temperature range. Ramakrishnan et al. [256] presented a design optimization methodology to maximize the utilization of latent heat capacity of PCM to improve indoor thermal comfort during the summer season.

The experimental studies with the integration of PCM showed promising results in reducing building energy consumptions and increasing thermal comfort. However, almost all of those studies were carried out using either a box or a test room. Studies regarding PCM performance in real houses were mostly done using simulations. There is hardly any experimental study that reports the performance of PCM in a real house with occupants except [254]. The previous study showed that user behaviour in a real
house significantly influences the indoor temperature and thermal performance of the buildings. The performance variability associated with occupant behaviour is large relative to potential benefits from implementation of PCM [254].

The aim of the research was to investigate the effectiveness PCM in reducing the zone air temperature and improving occupant thermal comfort in an existing real house under free running condition. Both the experimental and numerical approach was applied in this study. In the experimental study, PCM was installed in the ceilings of one of the bedrooms of a modern duplex house in Melbourne and indoor air temperatures of the various rooms of the house (with and without PCM) were recorded. A building simulation model was developed using building simulation software EnergyPlus and validated using the recorded experimental temperature data. The validated simulation model was then used to investigate the PCM performance in the real house under actual user behaviour. Finally, several simulations including different user behaviour scenario (night ventilations, internal door operations) were carried out to identify the best user practice that can maximize the effectiveness of PCM.

4.2 METHODOLOGY

4.2.1 Details of Building Construction

A typical two-storey modern house from Melbourne, Victoria, was chosen to conduct the experimental study (Figure 4.1). This is a privately owned four-bedroom house with floor area of 326 m². This house has a five-star rating (out of ten) according to Nationwide House Energy Rating System (NatHERS), Australia. This means that the house was designed to consume maximum 149 MJ/m² of energy per annum for heating and cooling in the Melbourne Climate Zone.
The plan of the duplex house is presented in Figure 4.2. The house consists of one lounge, one family area with kitchen, one rumpus, one study, four bedrooms, two bathrooms, one WC and en suite and one laundry area. The external wall consists of brick veneer, wall insulation, and plasterboard. The ground is a waffle slab made of concrete (85 mm thick) and Extruded polystyrene (EPS) blocks (300 mm thick). The internal floor between first and second level consists of plasterboard, timber floor, and carpet. The internal wall has plasterboard fitted with the wooden structure, and it does not contain any insulation. The ceiling of the second floor comprises ceiling insulation and plasterboard. The details of the building materials and construction of the house are given in Table 4.1 and Table 4.2.
### Table 4.1 Thermophysical properties of the building materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Thickness (m)</th>
<th>Conductivity (W/m.K)</th>
<th>Density (kg/m³)</th>
<th>Specific heat capacity (J/kg.K)</th>
<th>R-value (m².K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick veneer</td>
<td>0.11</td>
<td>0.61</td>
<td>1690</td>
<td>878</td>
<td>0.18</td>
</tr>
<tr>
<td>Wall Insulation wall</td>
<td>0.09</td>
<td>0.045</td>
<td>12</td>
<td>883</td>
<td>2</td>
</tr>
<tr>
<td>Ceiling Insulation</td>
<td>0.176</td>
<td>0.044</td>
<td>12</td>
<td>883</td>
<td>4</td>
</tr>
<tr>
<td>Wall Plasterboard</td>
<td>0.01</td>
<td>0.17</td>
<td>847</td>
<td>1090</td>
<td>0.059</td>
</tr>
<tr>
<td>Ceiling Plasterboard</td>
<td>0.013</td>
<td>0.17</td>
<td>847</td>
<td>1090</td>
<td>0.0765</td>
</tr>
<tr>
<td>Ceramic tiles</td>
<td>0.012</td>
<td>1.2</td>
<td>2500</td>
<td>640</td>
<td>0.01</td>
</tr>
<tr>
<td>Carpet</td>
<td>0.02</td>
<td>0.0465</td>
<td>104</td>
<td>1420</td>
<td>0.43</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.085</td>
<td>1.42</td>
<td>2400</td>
<td>880</td>
<td>0.06</td>
</tr>
<tr>
<td>Roof tiles</td>
<td>0.02</td>
<td>1.42</td>
<td>2400</td>
<td>880</td>
<td>0.014</td>
</tr>
<tr>
<td>Timber (door)</td>
<td>0.035</td>
<td>0.16</td>
<td>838</td>
<td>1260</td>
<td>0.28</td>
</tr>
</tbody>
</table>

### Table 4.2 Construction details of the experimental house

<table>
<thead>
<tr>
<th>Name</th>
<th>Construction (outside to inside layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Wall</td>
<td>Brick veneer, 40 mm Air gap, Insulation, Wall Plasterboard</td>
</tr>
<tr>
<td>Internal Wall</td>
<td>Wall Plasterboard, 90 mm Air gap, Wall Plasterboard</td>
</tr>
<tr>
<td>Roof</td>
<td>Roof tiles</td>
</tr>
<tr>
<td>Name</td>
<td>Construction (outside to inside layer)</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>2nd Level Ceiling</td>
<td>Ceiling Insulation, Ceiling Plasterboard</td>
</tr>
<tr>
<td>1st level Floor</td>
<td>EPS, Concrete, Ceramic tiles</td>
</tr>
<tr>
<td>2nd Level Floor</td>
<td>Ceiling Plasterboard, 90 mm Air gap, Floor timber, Carpet</td>
</tr>
<tr>
<td>Door</td>
<td>Timber</td>
</tr>
</tbody>
</table>

**Figure 4.3 The Enthalpy – Temperature curve for BioPCM Q25**

### 4.2.2 PCM Details

In this research, a macro-encapsulated Phase change material, BioPCM™, has been used in the experimental house. The BioPCM™ is a poly-film encapsulated fatty-acid based organic PCM developed by Phase Change Energy Solutions. It has three different types depending on the melting temperatures, i.e. Q23 (23°C), Q25 (25°C) and Q27 (27°C). Again each of these has three types of mat depending on the amount or weight of PCM to cover the application area (m²), i.e. 1.5 kg/m², 2.7 kg/m² and 4.9 kg/m². This mat can be installed on the wall or ceiling. In this study, the Q25 (25°C) with “area density” of 4.9 kg/m² was used in the house. PCM with 25°C melting temperature was chosen here due to its better performance in temperature fluctuation reduction in summer weather of
Melbourne (section 3.4.1, Figure 3.6). In a total of 58.8 kg of BioPCM™ mats were spread across the ceiling of the BED 2. These mats were placed on top of the gypsum plasterboard and below ceiling insulation. The enthalpy curve for Q25 BioPCM™ shown in Figure 4.3 was supplied by the manufacturer.

### 4.2.3 Experimental Program

#### 4.2.3.1 Thermal Resistance Measurement

The design and as-built R-value of the external wall of the house was 2.44 m².K/W. To investigate the current condition and performance of thermal resistance of the wall, an experiment has been done according to ISO 9869 standard [257]. Thermistors, with an accuracy of ± 0.05°C, and heat flux sensors (Hukseflux HFP01) with an accuracy of ± 3% were used to measure temperature and heat flux through the wall. Two heat flux sensors and eight thermistors were attached to the south wall of the Family room. Four thermistors and one heat flux plate are installed on the inside surface of the wall as shown in Figure 4.4. The other four thermistors and heat flux plate were mounted on the outside surface of the in a similar fashion. The temperature and heat flux data are recorded through Voltage Sensor Logger (VSL) at 10 min interval for 18 days. The collected data were then used to calculate the R-value of the wall using ISO 9869 average method and dynamic method [257].

![Figure 4.4 Thermistors and heat flux plate on the inside surface of the wall](image)
Table 4.3 Thermal resistance of the South wall of studied house

<table>
<thead>
<tr>
<th>Design Resistance (m²K/W)</th>
<th>Measured Resistance (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISO 9869 Average Method</td>
</tr>
<tr>
<td></td>
<td>ISO 9869 Dynamic Method</td>
</tr>
<tr>
<td>Thermal resistance</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table 4.3 shows the calculated thermal resistance of the Family wall. This is similar to what Belusko et al. [5] reported where up to 50% decrease in the thermal resistance value was found. This result was attributed to three-dimensional heat flow and insulation installation defects, resulting from the design and construction method used. The thermal resistance $R=1.2$ of the wall was used in all the simulations of the house.

4.2.3.2 PCM Effectiveness Study

A Davis Wireless Vantage Pro2 (Model 6152AU) weather station was mounted at the backyard of the house (Figure 4.5) to measures outdoor dry bulb temperature, outdoor humidity, rain rate, solar radiation, wind speed and direction and barometric pressure. All these parameters were logged at a regular interval in the wireless console (Figure 4.5) placed in the Family room. The console also includes two sensors for temperature and relative humidity which were used to record the indoor temperature (accuracy ± 0.5°C) and relative humidity (accuracy ± 3%) of the Family room.

The Q25 PCM has been installed on the BED-2 (12 m² area) ceiling to investigate the PCM effectiveness. The BED-2 room was chosen due to its high internal heat gain during summer time. Two thermistors were put in the room to record the dry bulb temperature in every ten minutes. A log sheet was given to the user to record the opening or closing time of the windows and window blinds. The room was monitored from 23rd January 2015 to 13th March 2015.
This study was focused on the summer season of the Melbourne area. During this time of the year, the daily average maximum outdoor temperature is 25.9°C, and the daily average minimum outdoor temperature is 13.2°C. This large temperature variation can allow PCM to melt completely during daytime and solidify during nighttime, and thus, PCM can work efficiently.

### 4.2.4 Building Simulation Details

The experimental house was modelled using building simulation software EnergyPlus V8.3. The whole house was divided into 17 thermal zones as shown in Figure 4.2. Figure 4.6 shows the Sketchup model of the house used in EnergyPlus simulation. All the zones were simulated using Conduction Transfer Function (CTF) algorithm except the BED 2 zone. The BED 2 zone contains PCM layers, and this was simulated with Conduction Finite Difference (ConFD) algorithm. A 2 min time-step was used in the model as suggested by Tabares-Velasco et al. [233] for PCM simulation in EnergyPlus.
Figure 4.6 The model house in EnergyPlus

Schedules of window and window blind operation for different zones were created using the records of log-sheet that was given to the occupants to record the opening and closing time of the windows and window blinds. The “ZoneMixing” object was used to facilitate the mixing of air between the zones as the doors between the rooms were kept open by the users. The internal gains were taken into account in the simulation by using “People” and “ElectricEquipment” object. The house was simulated for four persons with different activities e.g. writing, sitting, cooking, reading, sleeping, etc. at different times (schedule) and zones. The lighting, TV, refrigerator, etc. were modelled with the “ElectricEquipment” object. The schedules of the internal heat gains were determined through interviewing the occupants. The heat transfer between the building floor and the ground were modelled using the GroundHeatTransfer:Slabmodule of the EnergyPlus software [239]. Infiltration in all zones was taken into account through “Design flow rate” infiltration model available in the software which calculates the infiltration according to following equation [239]:

\[
Infiltration = (I_{design} \times [A + B \times |T_{zone} - T_{odb}|]) + C \times W_s + D \times W_s^2
\] (4.1)
Here, $I_{design}$ is the air change per hour, $A$, $B$, $C$ and $D$ are equation constants, $T_{zone}$ and $T_{odb}$ are the zone temperature and outdoor dry bulb temperature and $W_s$ is the wind speed. The values used for $I_{design}$, $A$, $B$, $C$ and $D$ are 1.0, 0.2, 0.03636, 0.07 and 0 respectively for all zones except for the zones with exhaust fan. In the zones with exhaust fan, higher value of constant $A$ was used. The constants of Eqn. (4.1) were selected according to EnergyPlus reference manual [239] and personal communication with Dong Cheng who developed an infiltration model for Australian housing energy analysis [258]. The predicted average infiltration rate for the experimental house was around 0.4 ACH which is typical for a house built after 2000 in Melbourne [258]. To model the natural ventilation rate in the house, Wind and Stack model was used. In this model the ventilation air flow rate through the window is a function of wind speed and thermal stack effect, along with the area of the opening being modelled. A fraction multiplier schedule was applied to control the window opening area and time. The schedule was defined according to the input of the chart that was given to the occupant to record the window opening and closing schedule and time. The simulation was carried out for 50 days (from 23rd of January to 13th March) in free running conditions without the use of HVAC. It was difficult to incorporate an HVAC schedule because no particular temperature limit was followed by the occupants to operate the cooling system during summer.

The BioPCM™ is available in the form of square pouches attached to the mat. But in the simulation, BioPCM was implemented as a constant layer with the same weight because EnergyPlus PCM module only allows continuous layer. The Q25 BioPCM™ with 4.9 kg/m² was modelled (total 58.8 kg) as a constant layer of 0.02 m thickness which was calculated by following the procedure of Muruganatham [259]. The phase change process was applied in the model using the enthalpy – temperature curve as shown in Figure 4.3. The thermal conductivity, specific heat capacity and the density of the BioPCM™ used in the model were 0.2 W/m.K, 1970 J/kg.K and 235 kg/m³ respectively. A weather file was created for 50 days (23rd January to 13th March) by using the data recorded in installed weather station. Figure 4.7 shows the recorded outdoor dry bulb
temperature and the solar radiation data of the experimental site from 23rd January to 13th March.

![Figure 4.7 The outdoor dry bulb temperature and the solar radiation data collected from the site from 23rd January to 12th March](image)

**4.3 VALIDATION**

The developed energylplus model was validated by comparing the simulation results with recorded temperature data. Among the experimental data, the period between 25th February and 13th March was selected for the validation study because usage of the air-conditioner was minimum in this period and the developed energylplus model only capable of simulating the indoor thermal condition of the building under free running condition. Figure 4.8 shows the daily simulated and experimental temperature plot of BED 2 zone (with PCM in the ceiling) and the family zone (without PCM). Both the Bed 2 and Family zone simulation results showed good agreement with the experimental data. The RMS error of the daily temperature in Bed 2 zone was 1.1°C with less than 1°C temperature difference for 73.5% of hours.
Figure 4.8 Comparison of experimental and simulation temperature for (a) BED 2 zone (with PCM) and (b) Family zone
In Family zone, the average difference between experiment and simulation temperature was 0.7°C with the RMS error of 0.93°C. The difference was less than 1°C for the 74.8% of hours. Although the Family zone was not a PCM zone, this zone was also studied to ensure that the model can predict the zone temperature both with and without PCM with reasonable accuracy. However, significant disagreements between simulation and experiments were observed on some occasions in BED 2 zone (maximum 4.2°C) and Family zone (maximum 3.3°C) during the daytime. Such discrepancies are to be expected given the inability of the model to capture the occupant behaviour and occupancy anomalies including unoccupied periods fully. However, these differences do not undermine the conclusion that can be drawn from the validation study that the developed EnergyPlus model can be used to predict the thermal behaviour of the buildings with good accuracy.

4.4 RESULTS

After validation, the developed EnergyPlus model was used to study the effectiveness of PCM in reducing indoor temperature fluctuation and increasing thermal comfort of the studied house under real occupant behaviour. The simulations were carried out from 23rd January to 12th March (49 days) using the weather file that was created using the local weather conditions as mentioned in section 4.2.4. The results of the simulations are presented in following sections.

4.4.1 PCM Performance in the Real House

In this section, results regarding the PCM performance in the studied house have been presented. Two simulations were carried out with and without the integration of PCM in the ceiling of BED 2 zone. The data presented in Figure 4.9 for both with and without PCM case is the simulated data from validated EnergyPlus model. It should be noted that comparison of the experimental zone temperature of BED 2 zone with and without the application of PCM is certainly the best way of evaluating the performance of PCM. However, this was not possible as it is impossible to have similar outdoor air conditions for with and without PCM experimental period. Comparison of indoor air temperature of BED 2 (with PCM) with that of adjacent no PCM zones (BED 3 or BED 4) was another
option of evaluating the PCM performance experimentally. However, in that case, it would be difficult to calculate the influence of PCM on zone air temperature as, other factors such as size, window, orientation, etc., of the two rooms would also have an influence on zone air temperature. This is why validated EnergyPlus simulation model was used to investigate the performance of PCM in this study.

Figure 4.9 shows that integration of PCM has some influence on the zone temperature of BED 2. The difference in zone temperature without and with PCM (w/o PCM – w/ PCM in secondary axis) demonstrates up to 1.1°C reduction in BED 2 zone temperature with the installation of PCM in the ceiling depending on outdoor air temperature. The performance of PCM has been found to be highly dependent on local weather condition. The maximum reduction in zone temperature was achieved when the temperatures of preceding nights were low enough to solidify the PCM completely. The outdoor temperature on Figure 4.7 shows that between 5th to 28th February there were 12 days where maximum day temperature reached over 28°C and preceding night temperatures were lower than the solidification temperature of PCM (23°C). It was expected that PCM will have a significant impact on indoor zone temperature in this conditions. However, Figure 4.9 shows that only in 3 occasions, temperature reductions more than 1.1°C was achieved. This suggests that the PCM incorporated in the BED 2 zone might not have been fully solidified for most of the nights although the outdoor air temperature was lower than the freezing point. Because of higher ceiling insulation, there is very little heat transfer between PCM and attic zone air (The temperature of attic zone air is very close to outdoor air). Therefore, melting and solidification of installed PCM depend on zone air temperature instead of outdoor air.
Figure 4.9 shows that between 4th February and 23rd February where the day-time zone temperature without PCM rose to 30°C or over, integration of PCM did not give a consistent reduction in the zone maximum temperature. For example, on 16th February and 19th February the zone maximum temperature without PCM were 29.54°C and 29.41°C respectively. However, with the integration of PCM, the zone temperature reached around 29.41°C on 16th February (0.12°C reduction) and 28.27°C on 19th February (1.14°C reduction). This was because the previous night-time zone minimum temperatures were not similar on both occasions. The minimum temperature was around 25°C on 16th February which did not allow PCM to solidify completely and eventually PCM did not perform well during day-time as expected. On the other hand, the zone minimum temperature on 19th February was close to 20°C which allowed the PCM to solidify at night. From 25th February to 5th March, the diurnal BED 2 zone temperature without PCM was mostly between 21°C to 28°C. Although this temperature range was favourable for the complete freezing of PCM at night, only 0.6°C reduction in maximum zone temperature during the days was observed with the installation of PCM.
This might occur due to the very low thermal conductivity of PCM (0.2 W/mK) which prevented complete solidification of PCM during the period when zone temperature was below the freezing point of PCM. The duration of zone temperature below the freezing point of PCM needs to be long enough to allow the PCM solidify completely. This can be observed on 5th and 19th February where maximum temperature reduction was found due to PCM (above 1°C). These two days had few preceding cool days where the temperatures were mostly below 23°C. This allowed the PCM to solidify completely and thus helped in providing maximum temperature reduction. Table 4.4 summarises the performance of PCM throughout the whole study period (49 days). It shows that the reduction of zone maximum temperature in BED 2 due to the PCM was over 0.5°C for 37% of studied days. The maximum difference was in the range of (1°C ~ 1.5°C) but it was only for 4% of days. The results indicate that integration of PCM on BED 2 ceiling did not create a significant reduction in zone temperature. In the following sections, several methods of improving the PCM performance in the studied house have been explored numerically.

### Table 4.4 Performance of various PCM configuration

<table>
<thead>
<tr>
<th>Reduction of daytime maximum temperatures, ( \Delta T_{\text{max}} ) (°C)</th>
<th>PCM only</th>
<th>PCM w/ NV</th>
<th>PCM w/ NV &amp; No Mix</th>
<th>PCM in Ceiling and Wall w/ NV &amp; No Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T_{\text{max}} &gt; 2 )</td>
<td>0%</td>
<td>2%</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>( 1.5 &lt; \Delta T_{\text{max}} \leq 2 )</td>
<td>0%</td>
<td>2%</td>
<td>16%</td>
<td>27%</td>
</tr>
<tr>
<td>( 1 &lt; \Delta T_{\text{max}} \leq 1.5 )</td>
<td>4%</td>
<td>8%</td>
<td>19%</td>
<td>4%</td>
</tr>
<tr>
<td>( 0.5 &lt; \Delta T_{\text{max}} \leq 1 )</td>
<td>33%</td>
<td>49%</td>
<td>16%</td>
<td>18%</td>
</tr>
<tr>
<td>( \Delta T_{\text{max}} \leq 0.5 )</td>
<td>63%</td>
<td>39%</td>
<td>45%</td>
<td>43%</td>
</tr>
</tbody>
</table>

#### 4.4.2 PCM Performance with Night Ventilation (NV)

As mentioned before, complete melting and solidification of PCM predominantly depend on zone air temperature instead of outdoor air. Hence, the performance of PCM can be improved by lowering the night-time zone air temperature below PCM freezing point as well as increasing the duration of zone air temperature below PCM freezing point which would help to solidify the PCM completely. The weather data in Figure 4.7 shows that the night-time outdoor temperature was always below 23°C (freezing point...
of PCM) with an average of minimum 15°C during the study period which is well below the freezing point of PCM. Therefore, in the simulation, the “ZoneVentilation” object was used to keep the window open (20% of total window area) every day from 7 p.m. in the evening to 7 a.m. in the morning depending on outdoor air temperature. A schedule was used to control the window opening/closing based on outdoor air temperature. The night ventilation was not allowed when the outdoor air temperature was lower than 22°C to avoid overcooling of the zone at night which might result in thermal discomfort.

Figure 4.10 BED 2 Zone temperatures with PCM, NV and No mix comparisons

Figure 4.10 shows the BED 2 zone temperatures for “PCM only” and “PCM with night ventilation” cases. Due to the night ventilation (NV), the night-time temperature dropped sharply compared to the “PCM only” case. But the day-time temperature rise for both case is similar. Also, the peak day-time zone temperatures are almost same. This might happen for a couple of reasons. Firstly, Night ventilation cools down the thermal mass and prepares it to absorb heat during the daytime. However, there is no thermal mass inside the zone BED 2 except PCM, because the walls and ceiling are plasterboard material, and the floor is a wooden floor. Secondly, the air of BED 2 zone is continuously mixing with the air surrounding zones as the internal door is always open. As a result,
the reduction of daytime BED 2 zone temperature due to the installation of PCM is not realized fully. Zone mixing rate was included in the simulation according to the observed occupant behaviour of the studied house. Table 4.4 shows the reduction of zone maximum temperature in the “PCM with NV” case compared to “without PCM” case during the simulation period. In comparison to the “PCM only” case, there is an increase in the percentage of days in the (0.5°C ~ 1°C) range but improvements are not very significant in the higher ranges.

Finally, another simulation was carried out without air mixing amongst the surrounding zones (assuming internal doors remain closed) and with the presence of night ventilation. The BED 2 zone temperature for the “No mix” case was also presented in Figure 4.10. The figure shows that “PCM with NV and no mixing” case significantly lowers Bed 2 zone temperature compared to “PCM with NV” case.

Table 4.4 shows that in 4% of the simulated days, the reduction in maximum daytime zone temperature was over 2°C for the “PCM with NV and No mix” configuration compared to “without PCM” case. Also, in 16% and 19% of the simulated days the temperature reduction were in the range of (1.5°C ~ 2°C) and (1°C ~ 1.5°C) which are significantly higher than the previous cases. In total, 39% of the simulated days were found to have peak temperature reduction greater than 1°C compared to 4% in case of “PCM only” configuration. Hence, it can be said that the “PCM with night ventilation and no mixing” is superior to the other two configurations in increasing the effectiveness of PCM as well as reducing the daytime zone temperature.

### 4.4.3 Spreading PCM to Ceiling and Wall

If the equal amount of PCM is spread to ceilings and walls instead of integrating it only in ceilings, the melting and solidification efficiency of PCM increases due to enhanced heat transfer surface area, which in turn increases the effectiveness of PCM [255]. A similar approach has been adopted here to further improve the performance of PCM. The same amount (58.8 kg) of PCM was spread to the ceiling (35kg) and north wall of BED 2 (23.8kg). In the wall, PCM was integrated just behind the wall plasterboard. The simulation was carried out for “Night Ventilation and No Mixing” condition as this was
shown to have the higher effectiveness of PCM. Figure 4.11 shows the BED 2 zone temperature for “PCM in ceiling and wall” case along with that of other studied cases.

The figure shows a further reduction of the peak temperature compared to the “PCM with NV and No mix” case. The Table 4.4 shows that percentage of simulated days with reduced peak temperature greater than 2°C rose to 8% because of the spreading of PCM. A significant increase in the percentage of the simulated days (27%) in 1.5°C ~ 2°C range was also observed compared to “PCM with NV and No mix” case (16%). Therefore, it can be concluded that the spreading of the PCM to ceiling and walls along with night ventilation and no zone mixing condition exhibits highest reduction in zone maximum temperature than all other combinations investigated in this study.
4.4.4 Thermal Comfort

In this section, the performance of PCM on the thermal comfort of the zone was analysed using the standard ASHRAE-55 Adaptive Comfort Model [260]. This model specifies a range comfortable indoor temperatures corresponding to the prevailing mean outdoor temperature. The daily mean outdoor temperatures were calculated from recorded the weather data of the experimental house. The prevailing mean outdoor air temperature was determined from the weighted mean of seven sequential days prior to the day in question with the most recent day’s temperature heavily weighted.

Figure 4.12 shows the BED 2 zone temperatures for the “without PCM” and “PCM with NV and No mix” case compared to the ASHRAE-55 comfort ranges. It shows that the number of hours outside the 80% acceptability limit is reduced due to the use of the PCM. Figure 4.13 summarises all the analysed cases in terms of hours outside the 80% acceptability limit. The base case without PCM results in 342 hours beyond the 80% acceptability limit. On the other hand, “PCM only” configuration creates a more comfortable scenario which reduces it to 226 hours. The “PCM with NV” case improves the comfort a little bit, but it is close to the “PCM only” case, which is consistent with the diurnal temperature results. Significant improvement occurs with the “PCM with NV and No mix” condition which decreases the uncomfortable hours to 163. As observed in the zone temperature results the spreading of the amount of PCM to ceiling and wall further improves the PCM performance and hence the thermal comfort. The hours over 80% acceptability was found to be 149 for this case which is 193 hours less than the “without PCM” case. This is the lowest among all the simulated cases, and it suggests that with increased surface area, NV, and No mix condition PCM may exhibit the best performance in a real house.
Figure 4.12 BED 2 Zone temperatures (a) without PCM (b) PCM with NV and No mix simulation compared to ASHRAE 55-2013 [260] Adaptive Comfort model
Figure 4.13 Number of hours 80% acceptability not met according to ASHRAE 55-2013 [260]

Adaptive Comfort model (total analysis was 1175 hours)

4.5 DISCUSSION

This study investigates the effectiveness of PCM as a potential retrofitting option to reduce the daytime peak zone temperature and increase zone thermal comfort in a real 5-star energy rated duplex residential building in Melbourne Australia. PCM was integrated into the ceilings of BED 2 zone underneath the insulation. Several issues have come out from this investigation. First of all, user behaviour has been found to have an influence on the performance of PCM. In the present study, when no change in the existing user behaviour (windows remain closed and internal doors always open) was considered, incorporation of PCM in the ceiling reduced the thermal discomfort hours by 116 hr (Figure 4.13), which is 34% reduction of thermal discomfort hours compared to the “without PCM” case according to ASHRAE 55-2013. However, if the occupants open the window at night when the outdoor air is favourable to solidify the PCM and keep the internal door closed during the day (PCM with Night ventilation and No mix case), thermal discomfort hours in BED 2 zone reduce by 179 hr (Figure 4.13), which is
52% reduction of thermal discomfort hours compared to the “without PCM” case. And this is significantly higher than the previous PCM cases.

Spreading of PCM in wall and ceiling is shown to be the best options in terms of increased thermal comfort and peak daytime temperature reduction. However, integration of PCM in the wall might not be realistic in most retrofitting cases compared to PCM integration in the ceiling as it may require removal of the plasterboard from the wall. This may increase the cost of PCM installation in the residential house as it requires removal of the wall plasterboard, integration of the PCM and reinstallation of the wall plasterboard. Hence, although spreading of PCM in wall and ceiling shows great potential, it might not be a feasible retrofitting option for this type of residential houses.

Complete solidification of PCM at night is important for better effectiveness during the day. The present study revealed that melting and solidification of PCM is more dependent on zone temperature instead of outdoor temperature. The attic zone temperature (close to outdoor temperature) does not influence the PCM temperature as it is covered by R4.0 insulation (Table 4.1). Therefore, if the zone temperature is favourable to solidify the PCM at night, the performance of PCM would be better on the following day. Night ventilation in the zone through opening the window improves the solidification rate of PCM at night. However, if the windows are kept open at night when the outdoor temperature is too low, it negatively affects the thermal comfort of the zone at night although this condition is suitable to solidify the PCM. Therefore, the arrangement should be made to cool down the PCM at night without compromising the night time comfort of the room.

In addition to night ventilation, improving the thermal conductivity of PCM could be another way of increasing the solidification rate at night. It was observed in the present study that although the zone temperature was below the freezing point of PCM in a number of cases, the duration of zone minimum temperature was not enough to completely solidify the PCM. The conductivity of PCM used in the present study is 0.2 W/m.K. An increase in thermal conductivity can enhance the solidification rate of PCM. Various techniques have been proposed in the existing literature to enhance the thermal conductivities of PCM using highly conductive nanoparticles [121], carbon fibres or
metallic fillers [122, 123], application of metal fins and honeycombs [126, 127, 261] and metal foams [129, 262]. However, these methods have not been utilized yet in commercially available PCM.

Previous modelling studies of PCM installations demonstrated significant energy savings and thermal comfort [14, 94, 99, 255]. However, the effectiveness of the real-life installation did not match up to the expectation due to the following reasons:

(1) The installation was carried out in a 5 star rated house where the temperature fluctuations were already low prior to PCM installation. In this type of houses, the PCM performance appears low.

(2) The type of passive application used need improvement to extract more effectiveness from the PCM. The ventilated ceiling integrated with PCM proposed by Helmut et al. [263] can be one option. In this approach, the ventilation is purely in circulating operation during the day, while cool outside air was used during the night to regenerate the PCM. More research is needed in exploring installation methods which provide higher PCM effectiveness.

4.6 Conclusion

The feasibility of passive integration of PCM as a potential retrofitting option to reduce peak zone temperature and enhance occupant thermal comfort in a modern 5-star energy rated house was investigated both experimentally and numerically. The numerical model was developed using building simulation software EnergyPlus and validated against the recorded internal zone temperature data. The analysis showed that effectiveness of PCM in reducing peak zone temperature and thermal comfort depends on the behaviour of the occupants (operation of windows and internal doors). In this study, the incorporation of PCM in the ceiling was found to be most efficient when the windows were kept open on the previous nights and internal doors remain closed all the time. Hence, occupant should have some knowledge about what they need to do to maximize the PCM efficiency. Finally, it was observed that the effectiveness of passive integration of PCM in a real 5-star energy rated house is lower compared to those reported in previous modelling and laboratory scale studies. Therefore, selection of
proper PCM integration method is required to achieve higher PCM effectiveness in this type of 5-star energy rated residential building. Also, further research is recommended to investigate the relationship between house energy rating and PCM effectiveness.
CHAPTER FIVE

5 ROOM TEMPERATURE TES: INCORPORATION OF PCM IN HOLLOW CORE SLAB SYSTEM

5.1 INTRODUCTION

The rise of energy demands and the increase of greenhouse gas emission are creating pressure to reduce the dependency on the conventional heating, ventilation and air-conditioning (HVAC) systems in office buildings. Thus, the thermal energy storage (TES) is becoming an attractive option for efficient space heating and cooling system. It plays an important role in enhancing the performance of the renewable energy sources. The availability of the solar radiation is time dependent. Also, the demand of heating and cooling in a building varies with time and most of the time it does not coincide with the availability of energy. The TES works as an energy reservoir and balance the mismatch so that energy is used efficiently according to the requirements.

The building materials can be utilised as a TES by using different methods, e.g. sensible heat, latent heat energy storage [7]. In the sensible heat storage method, the energy is stored by changing the temperature of the storage mediums (e.g. masonry walls, concrete, rock beds, etc.). On the other hand, in the latent heat storage method, the material stores heat by changing its phase. The material is known as Phase Change Material (PCM).
One of the ways to use the building fabric as a sensible thermal storage is to pass the cold/hot heat transfer fluid through precast hollow cores in the ceiling or floor slabs (hollow core slabs). The earliest development of hollow core slab was reported in Sweden in late 1970s which was later commercialised in the UK as “TermoDeck®” System [264]. It consists of a patented arrangement of interconnected hollow cores making an air passage within a precast concrete plank (Figure 5.1). In the hollow core concrete slab system, air is used as a heat transfer fluid. The air passes through the several cores back and forth utilising the increased heat transfer area of the inside surface of the cores. This allows a higher rate of heat transfer for a prolonged time even for the small temperature difference between air and the slab. During the summer nights, the cool ambient air removes the heat from the slab as it passes through the hollow cores, lowers its temperature ready for the day time use. During the day, warmer outside air is cooled down as it circulates through the cores of the slab before entering the occupied space. Moreover, the cooler slab provides a radiant cooling effect to the conditioned space. If the cooling load demand is high, the hollow core slab may not reduce the air temperature to adequate comfort but nonetheless it would reduce the chiller load of the mechanical HVAC system. The hollow core slab can also be used during the winter season when it can be heated by mechanical HVAC system during off-peak times (night) and the stored heat can be used during the peak period (day).
The supply air is distributed to the hollow core slabs with a central distribution air duct which runs perpendicular to the slabs (Figure 5.2). Each of the slabs is connected to this air duct. The supply air directly from the outside or from the HVAC system is sent through the distribution duct to the slab, and then through the hollow cores to the conditioned space.

Various studies have been carried out regarding the design, modelling, and application of hollow core ventilated slabs [23]. Winwood et al. [156] performed a three-dimensional (3D) Computational Fluid Dynamics (CFD) analysis of hollow core slab with a simplified geometry. The simulation was carried out by using the “PHONICS” software. The results showed that the model could reproduce the pattern of the heat transfer in the hollow core slab similar to the experimental data with 2.0% (outlet temperature) of accuracy. The effects of various parameters e.g. insulation on the surface, a variation of thermal conductivity of the slab, air flow rate, etc. on the heat transfer of hollow core slab were also investigated. Winwood et al. [157] also reported an application of TermoDeck® slab in a real office building (Weidmuller Building) in UK which suggested that with better control, efficient fans and improved night heating, the building could reach energy target of 50 to 70 kWh/m² depending on the heat gain, heat loss characteristics and local weather. Willis and Wilkins [158] investigated an experimental office room with two TermoDeck® slab, which suggested that the slab offers not only an
enhanced alternative to mechanical ventilation system but also match the performance of comfort cooling or conventional air conditioning system. Zmeureanu and Fazio [161] presented a mathematical model of the hollow core slab which was simulated for a single zone office in Montréal, Canada. The simulation result showed that the hollow core slab can save average cooling load from 28.4 W/m² to 44.2 W/m² compared to the mechanical system, and it can provide thermal comfort without the mechanical system in the studied weather. Ren and Wright [162] developed a dynamic thermal model using lump parameter model for the hollow core concrete slab. With the assumptions of heat transfer coefficient of the bend area 50 times higher than that of straight hollow cores, the model was able to validate experimental data with the RMS error of 0.5°C for average slab temperature and 1.0°C for zone air temperature. Russell and Surendran [164] presented a two-dimensional finite difference model of hollow core slabs to simulate the cross-section of the slab. An active slab with a different number of cores and their position in the slab were investigated to study their effect on cooling capacity. The study also established a correlation between the air temperature through the slab and the cooling potential for different configurations of the slab. Corgnati and Kindinis [165] coupled the hollow core slab with the night ventilation and compared the result with the traditional mixing ventilation system. The simulation was carried out with the Simulink® dynamic model, and the result showed that night ventilation coupled with thermal mass activation can reduce the average operative temperature and improve the thermal comfort. Chae et al. [166] developed a computational model of hollow core slab and investigated its influence on the whole building operation. The model included an auxiliary air handling unit, radiant slab with hollow cores and various control option to provide conditioned air when desired. The model, simulated with the EnergyPlus building simulation program, showed agreement with a previous study for both indoor temperature variance and cooling energy potential.

Some studies were also reported on the improvement of hollow core slab by incorporating PCM. Whiffen et al. [19] worked on a prototype of hollow core slab with PCM enhancement and investigated energy savings and comfort benefits under laboratory conditions. Due to the PCM incorporation, additional 0.1 kWh energy was saved per day, with 1.2 h thermal delay and 1.0°C reduction of room temperature were
reported compared to the original hollow core slab. Pomianowski et al. [106] carried out a full-scale experiment of a different hollow core slab with water circulation system for mass activation and an additional microencapsulated PCM layer to enhance the thermal performance. The results of the experiment indicated that the incorporation of PCM layer in the hollow core slab reduced its cooling capacity which was attributed to the low thermal conductivity of the PCM or the experimental error. Navarro et al. [8] presented an innovative hollow core slab system with macro-encapsulated PCM in the cores used as a thermal energy storage. In the case of control temperature experiment, the study reported energy savings of 30% - 55% under mild conditions and 15% - 20% under severe conditions in the HVAC system compared to the reference cubicle. Gunay et al. [266] carried out a numerical study of the hollow core slab mixed with microencapsulated PCM in which an improvement of both peak load reduction and phase shift was predicted.

PCM was also used in the ventilation system, especially in the air duct, as a latent heat thermal energy storage (LHTES) to condition the air and increase thermal comfort [7, 267]. Lopez et al. [111] developed a numerical model of PCM – air heat exchanger where several layers of PCM was placed in the air duct along the lengthwise direction. The model was validated with the experimental work with good accuracy. Based on this model, Borderon et al. [110] developed a PCM/air system and integrated it in ventilation circuit to allow a forced convection between air and the PCM which would increase the heat transfer and hence improve the latent heat storage capacity of PCM. A house modelled in TRNSYS® coupled with this PCM/air system in Matlab® was used in this study which reported 8% - 15% improvement in reduction of overheated hours. Arkar and Medved [112] investigated a LHTES device integrated into mechanical ventilation system for free cooling of the low-energy building. Macro-encapsulated PCMs in the form of spheres were used in the system. A validated numerical model showed that free cooling with LHTES device is an effective cooling method, and suitable comfort can be achieved for Slovenian weather. Turnpenny et al. [113, 114] developed a fan assisted LHTES incorporating heat pipe embedded in PCM for low energy cooling of the building. The authors demonstrated that the system coupled with night ventilation would provide sufficient storage to eliminate overheating and thus significant energy
savings in UK summer weather. A ventilation air duct with PCM packed bed system coupled with night ventilation was proposed by Yanbing et al. [108]. The experimental results demonstrated that the system can reduce the room temperature as well as energy consumption. Stritih and Butala [115] carried out an experimental investigation of the free cooling system with PCM cold storage for cooling buildings. From the results, it was reported that the PCM could cool an air flow with 26°C temperature and 1m/s velocity to 24°C for more than 2.5 h.

The purpose of this study is to investigate the effectiveness of PCM incorporated air duct (PCM – air duct) coupled with the existing hollow core based concrete slab TES. The PCM – air duct is used as an extra thermal storage to the hollow core slab which would improve the overall hollow core slab system by further reducing the temperature swing of mainly summer weather of Melbourne. In this analysis, the hollow core slab system is used independently without any supplementary HVAC system (free running) to study its influence in reducing the indoor temperature swing. Unlike summer, the winter operation of hollow core slab requires off-peak HVAC operation or Solar collector to store the heat. Therefore, this study mainly focuses on summer operation of hollow core slab, although free running winter operation is also explored.

5.2 Methodology

5.2.1 Experimental Investigation: PCM Incorporated Air Duct

A 2 m long rectangular shaped (300 mm x 300 mm) aluminium air duct was used in the experiment to represent the supply air duct of a hollow core slab system. The PCM was installed approximately in the middle of the air duct. Macro-encapsulated BioPCM™ Q21 was used in this study. BioPCM™ is a polyfilm encapsulated fatty-acid based organic PCM developed by Phase Change Energy Solutions. The BioPCM™ comes like a sheet or mat as shown in Figure 5.3. In this experiment, a 300 mm x 1200 mm PCM mat was used which has an area density of 1.5kg/m². The phase change of the BioPCM™ (Q21) occurs in the temperature range from 18°C (melting starts) to 23°C (freezing starts). Figure 5.4 shows the enthalpy-temperature curve for Q21 BioPCM™ as supplied by the manufacturer.
A portable reverse cycle air-conditioning (A/C) unit was used in the experiment to provide an air flow with different temperatures. This unit can provide air flow both in cooling mood or heating mood with temperatures from 10°C to 35°C. The experimental setup with PCM-duct and A/C unit is shown in Figure 5.5. The air duct was covered by insulation material to minimize the heat transfer through its wall. To monitor the air temperature at the inlet and the outlet, three sets of thermistors (accuracy ± 0.1°C) were
installed each of the position 1 and 2 (Figure 5.5). The temperatures were recorded at each second through a data logger. The velocity of the air flow was also measured by using a hot-wire anemometer. Three sets of experiments were performed with different PCM arrangements in the air duct: (i) air duct without PCM (No-PCM), (ii) PCM on single surface arrangement (PCM-SSA), and (iii) PCM on all surfaces arrangement (PCM-ASA) (Figure 5.6). On both PCM-SSA and PCM-ASA case, the amount of PCM were kept same. All the experiments were carried out for 2 hours (120 min).

Figure 5.5 Schematic and the picture of the experimental set-up
Figure 5.6 Schematic of BioPCM™ arrangement inside the air duct (a) PCM-SSA (b) PCM-ASA

Figure 5.7 Typical inlet temperature profile for cooling and heating mode

To study the response of PCM – air duct in an increase or decrease of the inlet temperature, the experiment was carried out in two modes i.e. cooling mode and heating mode. Figure 5.7 shows typical inlet temperature profiles for the two modes. In the cooling mode, at first, the inlet temperature was kept around 27°C for some time and then it was decreased to around 10°C. On the other hand, the heating mode was carried out by increasing the temperature from around 12°C to 32°C. Here, in both cases, the initial temperature was chosen in a way that it would cause the PCM to fully melt (cooling mode) or solidify (heating mode) before the experiment starts. Then the inlet temperature was decreased (cooling mode) or increased (heating mode) so that it crosses...
the PCM melting or solidification range (18°C – 23°C). These arrangements would maximize PCM utilisation in the PCM – Air duct. In both cooling and heating mode, the inlet and outlet temperatures were recorded, and the difference between them was calculated to see the effect of the PCM.

5.2.2 CFD Simulation Details: PCM- Air duct and Hollow Core Slab

5.2.2.1 PCM - Air Duct Model:
A CFD model of the experimental air duct was developed using the ANSYS® CFX software. Among the experimental cases, No-PCM and PCM-ASA case was modelled. Due to the axisymmetric nature of the airflow through the air duct, one-fourth section (150 mm x 150 mm) of the duct was considered in the model with symmetric boundary (Figure 5.8a and Figure 5.8b). This makes the flow domain smaller i.e. less number of cells, which requires less simulation time. The length of the air duct was kept same as the experimental one i.e. 2 m. The model includes three domains: air flow domain (fluid region), aluminium body and PCM (when included) domain (solid region). The mesh of the modelled region was shown in Figure 5.8c. The mesh has elements from 20,000 to 75,000 depending on the different configuration of the PCM- air duct.

The thickness of the aluminium shell was 0.4 mm. The PCM layer was considered as a flat layer as used by Muruganantham [240] rather than a sheet of square pouches, to make smoother and convenient mesh generation. The thickness of the PCM layer used in the simulation was 6.4 mm which was calculated using the area density 1.5 kg/m² and material density 235 kg/m³ of BioPCM™. The area of the PCM layer was kept same as the area of the BioPCM™ mat used in the experiment (300 mm x 1200 mm for PCM-ASA). The specific heat capacity curve of PCM used in this simulation is shown in Figure 5.9.
Figure 5.8 The PCM – Air Duct (a) Cross-section (schematic) (b) Full length duct (2m long) and (c) the mesh

Figure 5.9 Specific heat capacity curve for BioPCM™ Q21
The outside wall of the air duct was set as an adiabatic wall to assume zero heat transfer through the wall. The average air flow velocity measured in the experiment was about 0.5 m/s which was used as an inlet velocity in the simulations. The recorded inlet temperature with time from the experiment was applied as the inlet temperature profile of the air in the CFD model. The outlet boundary condition was set as an outlet to atmospheric pressure (zero relative pressure). The k-epsilon turbulence model was used in the simulation to model the turbulent flow.

The air flow profile through the air duct is not changing with time but only the temperature. The heat transfer also occurs with few degree Celsius temperature difference. The heat transfer due to convection is also negligible. That is why the simulation was done in two steps. In the first step, the fluid flow was solved in a steady state simulation. Once the fluid flow was established, the transient heat transfer problem was solved. This facilitated to run longer flow simulation time. A 1-minute time step was used in the transient heat transfer problem.

During the validation of the simulation work, the PCM – air duct model was kept similar to the experimental condition. Later some parameters (e.g. PCM thickness, Phase change temperature) were changed to see their influence on changing the effectiveness of PCM on the air flow. In those cases, the inlet temperature was kept same. Afterwards, some simulations were carried out by changing the inlet temperature to that of some averaged seasonal, diurnal temperature variation of Melbourne weather. This time the outlet air temperature of the PCM – air duct model was extracted and used as the inlet condition of the hollow core slab model to see the overall effect due to the introduction of PCM – air duct. Finally, a real weather data of outside dry bulb temperature was passed through the PCM – Air Duct and hollow core slab and the results were analysed. In all these cases, the average surface temperature at inlet and outlet was calculated and compared.

5.2.2.2 Hollow Core Concrete Slab Model:
A hollow core slab model was also developed using the ANSYS® CFX model. This model was built for a standard hollow core slab operation where three middle cores are active cores i.e. air flows only through three middle cores [268]. They are interconnected
through sideways. The two side cores are disconnected and remain idle. They were not used for the air flow. All the cores were closed at the both ends.

There are many different sizes of the precast hollow core slab. In this study, the geometry of the hollow core concrete slab (Figure 5.10) was built similar to the dimensions given by Winwood et al. [268]. The model is divided into two regions: solid region – concrete, and the fluid region – air passage or cores. The mesh of these two regions is shown in Figure 5.11. The mesh consists of 640,000 elements.

The slab surface which contains the inlet and outlet boundary was assumed to interact with the conditioned room. In this CFD model no room was considered, instead, the surface was exposed to the same ambient temperature as the outlet temperature assuming that the room temperature would be the same as the outlet shortly. The convection heat transfer coefficient of the exposed surface was used as 1 W/m.K, as limited convection heat transfer was expected from the downward faced surface due to the smaller temperature differences. The other surfaces of the slab were modelled as an adiabatic wall to limit the heat transfer in those directions.

Figure 5.10 The geometry of the hollow core slab
Figure 5.11 The mesh of (a) solid region and (b) fluid region of the hollow core slab model
The velocity of air at the inlet boundary was set to 1 m/s [156]. For the validation case, the temperature profile at inlet boundary was taken as the experimental inlet temperature. In all other cases, two sets of simulation were carried out for each diurnal outdoor condition, i.e. Slab only case and PCM – air duct - hollow core slab combination case. In the slab only case, the diurnal temperature fluctuation profile or the outside dry bulb temperature was directly assigned to the inlet boundary. In the case of the PCM – air duct - hollow core slab combination, the outlet temperature profile from the PCM – air duct simulation was used as the inlet temperature of the hollow core slab. The outlet boundary condition was set as an outlet to atmospheric pressure. In each case the outlet temperatures were extracted and then this is compared between slab only case and the combination case.

Similar to the PCM – air duct model, the hollow core slab model was also solved in two steps. The first step was to solve the fluid dynamics problem in a steady state simulation. Then transient heat transfer problem was solved in the second step. The time-step was set to 5 min, a bit higher than the PCM – air duct model, as there is no PCM in the slab. The k-epsilon model was used for turbulence modelling.

5.3 EXPERIMENTAL RESULTS AND MODEL VALIDATION

5.3.1 PCM – Air Duct Experiments

The experiment of the air duct was carried out in cooling mode and heating mode. Each mode consists of three experiments, i.e. No-PCM, PCM-SSA, and PCM-ASA. The Figure 5.12 shows the difference between outlet and inlet temperatures for the three PCM arrangements in cooling mode. In this mode, the inlet temperature was dropped from 27°C to approximately 10°C (Figure 5.7). The recorded outlet temperature response was different for different PCM arrangement which can be clearly observed from the (outlet – inlet) temperature difference plot (Figure 5.12). Initially, there is a peak in the temperature difference for all three cases which represents the initial delay in outlet temperature in response to the inlet temperature. Afterwards, the temperature gap drops sharply in the No-PCM case, i.e. outlet temperature closely follows the inlet temperature because there is no thermal storage or thermal mass in the air duct. In this
case, although ideally there should not be any temperature difference afterwards but there still was (~0.18°C) which could be due to some experimental noises, e.g. leakage, sensor accuracy, etc. On the other hand, PCM-SSA and PCM-ASA case exhibits a slower descent in the temperature difference plot which is due to the presence of PCM. In the cooling mode, when inlet temperature of the air drops from 27°C to 10°C, the PCM changes its phase from liquid to solid. During this phase change, it releases the heat to the flowing air which makes the outlet air temperature higher than the inlet temperature. Now, although the same amount of PCM was used in both PCM-SSA and PCM-ASA case, the temperature difference was higher for PCM-ASA case. Also, it was maintained for longer period. This is due to the difference in PCM arrangement in those two cases. In PCM-SSA case, the BioPCM™ sheet was placed on the bottom surface of the air duct (Figure 5.6-a). This arrangement allows PCM to interact with the air only from one side. On the other hand, in PCM-ASA case the PCM was laid out on all the four surfaces (Figure 5.6-b) which increases interaction of PCM with the air in all directions. Eventually, this arrangement produces higher temperature difference for a longer time compared to the PCM-SSA case.

![Figure 5.12 Outlet-Inlet Air temperature difference in case of cooling mode](image)

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Figure 5.12 Outlet-Inlet Air temperature difference in case of cooling mode
In the heating mode, the inlet temperature was raised from 12°C to 32°C (Figure 5.7) and the corresponding outlet temperature was recorded. The Figure 5.13 shows the temperature difference between inlet and outlet for the three cases. This time, the inlet temperature was higher than that of the outlet, that’s why “inlet – outlet” difference is shown in the Figure 5.13. Similar to the cooling mode, the results demonstrated initial delays in all but PCM-ASA case. In the PCM-ASA case, the temperature sensor might have missed the initial delay while recording the temperatures. After the peak of the initial delay, the temperature difference of No-PCM case falls sharply to approximately 0.2°C as there was no PCM material to keep the difference. Similar to the cooling mode, here also PCM-ASA demonstrated higher temperature difference for a longer time compared to the PCM-SSA case. This time, PCM changes the phase from solid to liquid by taking the heat from the flowing air which eventually lowers the temperature at the outlet.

In the heating mode, the A/C was raising the air temperature by using its internal heater which was not as smooth as the cooling mode. That’s why the temperature response of the heating mode was a little bit different than the cooling mode (e.g. No-PCM case).
5.3.2 Validation of CFD Simulation of PCM – Air Duct

The developed CFD model was validated by comparing the simulation results with the experimental ones. The PCM-ASA was observed to be performing better in the experimental study than PCM-SSA. That’s why only No-PCM and PCM-ASA model was developed and validated here. Although the simulation would be compared with the full experimental data, it is important to focus the comparison on the on the portion of the graph after an initial delay. Figure 5.14 shows the comparison of experimental and simulation temperature difference of No-PCM case for the cooling mode. The simulation profile captures the initial delay (up to 13 min) pretty close to experimental one with an average error of 0.22°C. Afterwards, the simulation temperature difference drops to zero, which is more sensible as there is no PCM and so there is no difference in the inlet and outlet temperatures. On the other hand, the experimental profile stays on 0.18°C, keeping this difference with the simulation all the way. This might be due to some experimental noises coming from the sensors, leakage, etc. as explained in the previous section. Figure 5.15 also compares the temperature difference of No-PCM case for experiment and simulation and this time it is in heating mode. The initial delay (up to 15 min) was sharper in the experiment than the simulation and the difference between them is higher than the cooling mode. The average error was 0.4°C with maximum 0.8°C in this range. Interestingly, here the initial delay in the simulation is more consistent with that of cooling mode. After the delay, the simulation gradually drops to zero, while maintaining an average error of 0.16°C and maximum of 0.3°C.

The experimental and simulation results of PCM-ASA configuration in cooling mode was compared in the Figure 5.16. From the figure, it is apparent that the both the experiment and the simulation profile follows a similar trend. The initial delay in the simulation results has a lower peak than that of the experimental result. After this, both experimental and simulation profile of temperature difference gradually drops to around 0.5°C and maintains it till the end. The average error in simulation results was about 0.09°C, although the maximum error was about 0.5°C, which is near the peak of the delay period. The overall RMS error was 0.14°C. The Figure 5.17 shows the comparison of results for the same configuration in heating mode. Although the peak of
the initial delay was missing in the experimental result, it is present in the simulation temperature difference profile. After the peak, the simulation profile gradually reduces to around 0.5°C where experimental result further drops to 0.4°C. The average disagreement between the experiment and the simulation results is 0.13°C with the maximum of 0.8°C, which was near the initial delay period. The overall RMS error was 0.17°C. Nonetheless, the simulation result of PCM-ASA in this heating mode is more consistent with the cooling mode where experimental results in this two modes differ. The reason might be due to the difference in melting and solidification process of PCM which was not considered in the simulation.

Figure 5.14 Comparison of experimental and simulation temperature difference for No-PCM configuration in cooling mode
Figure 5.15 Comparison of experimental and simulation temperature difference for No-PCM configuration in heating mode

Figure 5.16 Comparison of experimental and simulation temperature difference for PCM-ASA configuration in cooling mode
Validation of Hollow Core Slab CFD model

The hollow core CFD model developed to perform standard hollow core slab operation was simulated with an inlet condition of the experiment reported by Winwood et al. [268]. This was a diurnal temperature fluctuation over a period of 24 hours. The comparison of the outlet temperatures of experiment and simulation results are presented in the Figure 5.18. The outlet temperature was calculated by taking a surface average of temperatures at the simulated outlet surface. The overall trend of the simulation result has a good agreement with the experimental outlet temperature profile. The average difference in temperature of simulation and experiment was 0.24°C with the maximum difference of 0.77°C and RMS error was 0.32°C.
Figure 5.18 Transient inlet and outlet temperature profile of the simulated hollow core slab compared with the experimental data reported in Winwood et al. [268]

Figure 5.19 Velocity distribution on the mid-horizontal plane of hollow core slab
Along with the temperature graphs, some of the surface plots of velocity, temperature, etc. are also presented here. The Figure 5.19 and Figure 5.20 show the velocity distribution inside the hollow core slab on mid-horizontal and vertical planes. Although the average velocity inside the core is around 0.9 – 1.0 m/s, it is significantly higher near the entry and the interconnection. In these regions, the airflow is changing the directions which create lots of turbulence and therefore increases the air velocity as high as 1.8 m/s. In the Figure 5.21 and Figure 5.22, two surface temperature plots of the hollow core slab are presented at two different times, t = 5h (night) and t = 17h (day). During the daytime (Figure 5.22), the hot air (25°C) transfers the heat to the relatively cool hollow core slab (20°C) as it passes through the cores. The air temperature drops to 22.5°C while it lefts the outlet surface. Thus, the hollow core slab acts as a thermal energy storage by absorbing the heat from the hot outdoor air during the day time. Opposite incident happens during the night time (Figure 5.21). This time, the slab is relatively hotter (21°C) than the outside night time cold air (18°C). So, it is cooled down as the cold air circulates through the cores. This makes the slab ready for the next day operation. The temperature distribution at the bottom surface of the slab at t = 20h is presented in the Figure 5.23. The time is chosen as 20h to have a good contrast of temperature at the surface. From the plot, it is evident that most of the heat transfer is occurring near the
entry and the interconnection regions of the cores. This is because of the increased turbulence (Figure 5.19) which was reported in many previous studies [156, 159, 162].

Figure 5.21 Cold air is used during night time to activate the thermal mass (time = 4h)

Figure 5.22 Hot air is being cooled by hollow core slab during day time (time = 17h)
5.4 Results

At first, two sets of analysis were carried out with PCM – air duct CFD model (PCM-ASA) to study the influence of some parameters e.g. PCM arrangement, PCM phase temperatures, etc. on the PCM effectiveness. Then a range of simulations were carried out by combining the PCM – air duct and hollow core slab model (combined case) in different weather condition, to analyse the PCM on the whole system. All of these simulations were investigated by comparing the change in respective outlet temperatures (surface averaged).

5.4.1 PCM – Air Duct CFD Simulation

5.4.1.1 PCM Arrangement: Thickness Increase vs. Spreading

The average daily outdoor temperature fluctuation of January in Melbourne weather was chosen for this PCM analysis. The average maximum and minimum outdoor temperature is 27.1°C and 14.3°C respectively. A sine curve was made with these two peaks which was used as an inlet of the PCM – air duct. Four different arrangements were studied with the PCM – air duct model (PCM-ASA) which are presented in the Figure 5.24. Firstly, PCM with 6.4 mm thickness (BioPCM™ Q21) was spread throughout a 2 m long air duct. The resulting outlet temperature of the air duct (Figure 5.24) exhibits
a reduction in temperature swing. The minimum temperature was raised to 0.73°C and the maximum temperature reduced by 0.75°C. In the second simulation, the weight of PCM used was doubled the previous amount, resulting a 13.1 mm PCM-layer throughout the 2 m air duct. Interestingly, this time, the outlet temperature (Figure 5.24) showed no observed difference compared to the previous (6.4 mm layer) case. Although the PCM amount is twice, it had the same effect as the previous case. The reason might be that the amount of air which was coming in, interacting with PCM and going out through outlet was same for both cases (same velocity). Also, this same amount of air was exchanging heat with the PCM through the same surface area which resulted in a similar temperature profile.

![Figure 5.24 Inlet and Outlet Temperature for different arrangements of PCM in air-ducts](image)

The third simulation was carried out by spreading a 6.4 mm layer of PCM in a 4 m air duct. Although the amount of PCM here is essentially same as the second simulation (13.1 mm layer – 2m duct), the result showed a significant difference in outlet temperature. The minimum temperature was increased by 1.29°C where the maximum temperature was reduced by 1.31°C from the inlet temperature. By spreading PCM in a length of 4 m gives the flowing air more surface area to interact with the PCM. Thus,
each volume of air has the opportunity to exchange more heat as it passes through the air duct and hence PCM is used more effectively. This resulted in smaller thermal swing compared to the previous cases. Finally, this was further confirmed by taking a 6 m long air duct with same 6.4 mm layer of PCM which yielded 1.88°C reduction of maximum temperature and 1.68°C increase in minimum temperature. Therefore, PCM can be more effectively used if it is spread along the length of the duct as much as possible rather than the large amount of PCM putting in a small portion of the air duct.

5.4.1.2 PCM Phase Temperature
The PCM (BioPCM™ Q21) used so far changes phase in a temperature range of 18°C – 23°C. The average phase change temperature can be assumed as 21°C (PCM–21). This PCM-21 was used assuming that it would have better effectiveness in the Melbourne summer weather. In this section, two more PCM was compared with the PCM-21, whose average phase change temperatures were 18°C (PCM-18) and 23°C (PCM-23) respectively. Three simulations were carried out for these three types of PCM with 6.4 mm layer in a 6 m air duct. The inlet and outlet temperature from these simulations are plotted in Figure 5.25. The inlet temperature fluctuation was same as the previous simulation (27.1°C - 14.3°C). The night time outlet temperature of PCM-18 was slightly lower (0.4°C at the minimum point) than the PCM-21. During the day time, the outlet temperature of PCM-18 followed PCM-21 closely. But after 17h, the inlet and outlet became same which suggests that the PCM is fully melted and not acting as a thermal storage. Opposite scenario appeared in the case of PCM-23 simulation. PCM did not work during the night time because it is already solid at this time, whereas daytime outlet temperature was slightly higher (0.5°C at the maximum point) than that of PCM-21.
Figure 5.25 Influence of PCM melting temperature on the outlet temperature through 6m long PCM – air duct

The average phase temperature PCM-21 was closest to the average of the inlet temperature fluctuation (27.1°C - 14.3°C) i.e. 20.7°C. That’s why it performed both in day and night time better than PCM-18 and PCM-21. Other two PCM had their phase temperatures close to night time minimum or daytime maximum temperature which resulted in little or no effectiveness due to their fully solidified or melted phase during those times.

5.4.2 PCM–Air Duct – Hollow Core Slab Simulation: Combined Case

5.4.2.1 Simulation with Monthly Weather Variation

Although the PCM – air duct was designed to increase the total effectiveness of hollow core slab system in the summer season, a range of monthly weather conditions were studied to see how PCM – air duct response to different weather conditions. In these combined simulation cases, 6 m air duct with full 6.4 mm PCM layer (PCM-21 with PCM-ASA configuration) was used as a PCM – air duct. A 20 years average of the diurnal maximum and minimum temperatures of Melbourne’s monthly weather was retrieved from the Bureau of Meteorology (BOM), Australia [269]. Using these data, a sinusoidal
curve was constructed for each month to represent the average diurnal temperature fluctuation (Figure 5.26). From the Figure 5.26, it can be seen that some months have very similar temperature fluctuations to others e.g. Jan and Feb, March and Dec, etc. Thus, five sets of monthly temperature fluctuation of the different range were chosen for the simulation, and these were used as inlet temperature of the PCM – air duct. The outlet temperature from the PCM – air duct simulation was extracted and assigned as inlet temperature of the hollow core slab. Finally, the outlet temperature of the hollow core slab was recorded from the simulation and compared with the only hollow core slab simulation without any PCM – air duct. All the simulations were carried out for 48h to eliminate the influence of initial condition and results of the 2nd day were considered here as it would be more consistent.

![Figure 5.26 Average Diurnal Temperature Fluctuation of Melbourne’s Monthly weather](image)

The months that are chosen for the simulations are (from warmest to coolest) January, March, November, October, and July. Other months are closest to these months, and they may produce very similar results, and hence, they are ignored. Figure 5.27 presents the results obtained from the simulation of January diurnal temperature fluctuation. The outlet temperature fluctuation from the PCM – air duct suggests that the average
reduction of maximum temperature was 1.86°C, and the average increase of minimum
 temperature was 1.76°C. When the air flow of this temperature passed through the
 hollow core slab, the resulted final temperature swing was further reduced due to the
 thermal mass of the slab. The change in maximum and minimum temperatures was
 found as 4.7°C and 4.22°C respectively compared to the initial inlet temperature of
 January weather. Figure 5.27 also shows the results of outlet temperature from the
 hollow core slab only simulation without any PCM – air duct. In this case, the reduction
 in maximum temperature was 3.9°C and increase in minimum temperature was 3.45°C.
 Interestingly, the difference between the final outlet temperatures from this slab only
 case and the combined case was not as much as expected. Although the PCM – air duct
 was able to change the maximum and minimum temperature by 1.86°C and 1.76°C, the
difference in the final outlet temperature between the combined case and the slab only
 case was only 0.8°C and 0.77°C at the maxima and minima respectively. This suggests
 that the reduction in temperature swing due to the thermal mass of the slab was not
 same for the two cases. The reason might be due to the difference between the average
 slab temperature and the respective slab inlet temperature. The higher the difference
 between these temperatures, more heat transfer, would occur between the slab and the
 air. From the simulation, it was found that the average slab temperature was 20.3°C for
 both combined and slab only case. Now for the slab-only case, the temperature
 fluctuation of January was used as an inlet. On the other hand, for the combined case the
 outlet temperature swings of PCM – air duct was used as the inlet which was already
 reduced from the January temperature profile. So the temperature difference between
 the inlet air and slab was higher in the slab-only case than the combined one which cause
 a higher rate of heat transfer. That’s why the rate of temperature reduction through the
 slab was not same for the two cases.
Figure 5.27 Comparison of Outlet temperatures of combined case and slab only case for the month of January

Figure 5.28 Comparison of Outlet temperatures of combined case and slab only case for the month of March
Figure 5.27 also shows the average PCM temperature in the PCM – air duct, which did not change much throughout the simulation. This suggests that PCM was not fully solidified or melted during the simulation.

Among the next warmest months (March and December), the diurnal temperature of the March weather was simulated. Figure 5.28 shows the results of the simulation for both combined and the slab only case in March weather. The night time temperature of the March is mostly in the solid region of PCM. Thus, during the night time, PCM in the PCM – air duct quickly solidified and resulted in a smaller change (0.88°C) in night time outlet temperature (2\textsuperscript{nd} day) of PCM – air duct. On the other hand, during the day time the temperature difference between the inlet and the PCM – air duct outlet was found to be 1.31°C. This is smaller than that of January simulation. The reason might be because the daytime temperature was not as high as January to melt the PCM further. So the PCM was not utilised here as much as January. Finally, after the hollow core slab simulation, the temperature difference between the slab outlet of combined and slab-only case was found to be 0.61°C and 0.28°C at maximum and minimum peak respectively.

Figure 5.29 Comparison of Outlet temperatures of combined case and slab-only case for the month of November
Similar results yielded when the diurnal temperature of November weather was simulated (Figure 5.29). No change was found in the minimum temperatures during the night time. The reduction of maximum temperature was found 0.97°C after PCM – air duct from the inlet. Also the difference of outlet temperature after the slab between combined and slab-only case found to be 0.44°C.

Among the cold weathers, the diurnal temperature fluctuation of the October and July was also simulated and presented in the Figure 5.30 and Figure 5.31 respectively. In both simulations the results show little or no change in the temperature swing after the PCM – air duct because at these temperatures PCM is already solidified and had not been acted as a thermal storage. Thus, the outlet temperature from the combined and slab only case did not have any difference.

![Figure 5.30 Comparison of Outlet temperatures of combined case and slab only case for the month of October](image)
In the previous section, sinusoidal temperature fluctuation of monthly Melbourne weather was simulated. Now in this section, a real summer temperature data would be considered for the combined case. An hourly outdoor dry-bulb temperature data was recorded through a weather station in Scoresby, Melbourne from 25 January 2015 to 13 March 2015 (49 days). This recorded temperature data was used as an inlet of the PCM – air duct for combined case and the inlet of the hollow core slab for the slab-only case. The slab outlet temperatures from the both cases are compared in the Figure 5.32. From the outlet temperature of the PCM – air duct it can be observed that PCM worked better on those days when previous night time temperature was below 18°C and the next daytime temperature reaches beyond 23°C. This is because the PCM used in the simulation has a phase change temperature range from 18°C to 23°C. So when the temperature fluctuates beyond this two temperatures, it allows the PCM to solidify at night (charging) and melt during the next day (discharging) and hence maximise the PCM utilisation.
Figure 5.32 Comparison of Outlet temperatures of combined case and slab only case for the real summer weather of Scoresby, Melbourne

Table 5.1 The difference in outlet temperatures between PCM air duct and inlet and between PCM-air duct-slab combination and slab only simulation

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>PCM Duct - Inlet</th>
<th>PCM Duct Slab - Slab Only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>∆T ≤ 0.5°C</td>
<td>22 44.9%</td>
<td>15 30.6%</td>
</tr>
<tr>
<td>0.5°C &lt; ∆T ≤ 1°C</td>
<td>9 18.4%</td>
<td>11 22.4%</td>
</tr>
<tr>
<td>1°C &lt; ∆T ≤ 2°C</td>
<td>17 34.7%</td>
<td>13 26.5%</td>
</tr>
<tr>
<td>2°C &lt; ∆T ≤ 3°C</td>
<td>1 2.0%</td>
<td>7 14.3%</td>
</tr>
<tr>
<td>3°C &lt; ∆T ≤ 4°C</td>
<td>0 0.0%</td>
<td>2 4.1%</td>
</tr>
<tr>
<td>4°C &lt; ∆T ≤ 5°C</td>
<td>0 0.0%</td>
<td>1 2.0%</td>
</tr>
</tbody>
</table>

Furthermore, the difference in the slab outlet temperature of combined case and slab only case also varies according to the PCM effectiveness. However, like the previous simulations, the amount of temperature reduction by combined case from the slab only case was not similar to the reduction by PCM – air duct from the inlet (explained in the previous section). The differences between these temperature reductions were presented in the Table 5.1 with various temperature ranges. From the table, it can be seen that PCM...
air duct managed to reduce the maximum temperature more than 1°C for the 47% of the simulated days, among which 20% of days had reduction more than 2°C. The maximum temperature reduction was found to be 4.2°C on 6th Feb. Similar trends seen in increase in the minimum temperature by the PCM – air duct where more than 1°C were increased in 37% of the simulated days. On the other hand, when the temperatures from the combined case and slab only case compared, the combined case was found to reduce the maximum temperature more than 1°C in 14.3% of the simulated days. Also about 33% of days were in the range of 0.5°C ~ 1°C. The minimum temperature reduction was mainly in the range of 0.5°C ~ 1°C (31% of days). It was also observed from the simulation results that the temperature difference between the combined case and slab only case was 50% – 60% less than the temperature reduction originally contributed by PCM – air duct from the inlet.

5.5 DISCUSSION

In this study, the effectiveness of the PCM installed air duct, integrated with the hollow core slab system, was investigated in reducing the daily thermal swing. CFD models were developed to simulate the air flow through the PCM – air duct and hollow core slab and results were compared with the slab only model. Several findings have been come out in the investigation which will be discussed in this section.

Firstly, the interaction between the air and the PCM is important for efficient heat transfer. Thus, when PCM was placed on all four surfaces of the air duct (PCM-ASA), it yielded better results in changing temperatures than the one with PCM spread on only one surface (PCM-SSA). Because although the surface area and the amount of the PCM for both cases were same, the interaction between the PCM and the air in PCM-ASA would happen in all four directions. This would allow more air particles to interact with PCM than the PCM-SSA case in a given volume of air. Thus, PCM-ASA was found to be more efficient than the PCM-SSA.

Secondly, the heat transfer area of PCM plays a vital role in the heat transfer rate. The air and the PCM transfers heat in convection mode. And in the case of convection mode, the higher the heat transfer area, the higher the heat transfer rate. Therefore, only
increasing the thickness of PCM layer spread over a certain length of the air duct would not increase the PCM effectiveness. Because, in that case, the heat transfer area is not increased. The volumes of air which are passing through the air duct would have the same area to interact with although the thickness of PCM is increased. Hence, the heat transfer rate between them is same. On the contrary, rather than increasing the thickness, if the same amount of PCM is spread over a longer length of an air duct, it would essentially increase the heat transfer area. For any volume of air, the heat transfer would then occur for a longer period due to the increased area. This would create a bigger difference in temperature swing, and hence, PCM in air duct is utilised more effectively.

The reduction of daily temperature swing also depends on the temperature range at which phase change of the PCM occurs. Thus, PCM with suitable temperature range is needed to be chosen which would work better in a certain weather condition. In this study, PCM-21 was chosen for the summer weather of Melbourne. Because the operation of hollow core slab in summer is focused on reducing the temperature swing of outdoor air where PCM – air duct would be used to improve it. On the other hand, the winter operation of hollow core slab is mainly aimed at retaining the internal heat.

In a real weather condition, PCM was found to be more effective in those days where large diurnal temperature fluctuation occurs, especially when it stretches beyond the phase change temperature range of PCM. A cool night with a temperature below PCM’s freezing temperature lets the PCM solidify properly and make it ready (charged) for the next day. The cooler the night temperature the more chance the PCM has to solidify completely. Now if the next day time temperature goes higher than the melting temperature of PCM, the PCM would start to melt (discharge). During melting, PCM would absorb the latent heat required for the melting process which would eventually reduce the temperature swing. This process is maximised only when there a preceding cooler night to charge the PCM properly. So PCM effectiveness would be higher in those weather where the most of the days have larger temperature swing to facilitate the charging and discharging process of PCM.

PCM – air duct has the potential to improve the overall hollow core slab operation in reducing the diurnal temperature fluctuation. In real weather condition, PCM – air duct
was found to have reduced the daytime maximum temperature more than 1°C for 47% of simulated days. The highest reduction was found to be 4.2°C. It is important to note that these results correspond to the configuration used in the simulation, i.e. 6.4 mm PCM layer spread over 6 m long air duct. One can have better results if more PCM is spread over a longer length. Now although PCM – air duct was able to reduce the temperature swing as much as 4.2°C, the final outlet temperature from the slab did not retain the similar difference from that of slab only case. In fact, it was found that the temperature difference between the slab outlet temperatures can be 50% - 60% smaller than the temperature reduction already contributed by PCM – air duct. This is because the reduction of temperature swing through the slab is not always same, and it depends on the difference in the average slab temperature and the inlet temperature swing. The higher this difference is, the more heat transfer occurs in the slab and thus results in more reduction of the temperature swing. That’s why the reduction of the temperature swing through the slab for combined case was not same as the slab only case. Because the inlet temperature swing was already reduced by PCM – air duct. Therefore, improvement of PCM – air duct was not fully reflected in the final outlet of the temperature of the slab.

Finally, although the PCM – air duct was modelled for the hollow core slab system, the model can easily be used in any HVAC system to improve its efficiency and hence reduce the overall energy consumption.

5.6 CONCLUSION

The study of the PCM integrated air duct combined with hollow core slab system has led to the following conclusions:

- The PCM – air duct can improve the overall hollow core slab operation in reducing the diurnal temperature fluctuation of summer weather and it can depend on the chosen PCM configuration inside the air duct.
- Air duct with PCM-ASA configuration can increase the air-PCM interaction which potentially increases the heat transfer for a given volume of air and PCM.
• The more PCM is spread along the flowing path of the air in the air duct, the more heat transfer occurs due to the increase heat transfer area or area of interaction for a given volume of air.

• PCM can be properly utilised by choosing PCM of suitable phase change temperature which would work well with the temperature fluctuation of respective summer weather.

• Weather with large diurnal temperature swing is better to maximise the effectiveness of PCM especially if it is stretched beyond the phase change temperature range of the PCM.

• The reduction of temperature fluctuation by the hollow core slab depends on the difference in amplitude of the fluctuation and the average temperature of the slab. The higher the difference is, the more heat transfer would occur between the slab and the air which would result in smaller temperature swing.

• The effectiveness of the combined PCM-air duct-hollow core slab system is not equal to the individual performance of the PCM-air duct and hollow core concrete slab for a given inlet temperature fluctuation. The contribution of the PCM-air duct was found to be reduced by 50%-60% after the hollow core concrete slab.
CHAPTER SIX

6 HIGH TEMPERATURE TES: EXPERIMENTAL STUDY OF THE THERMAL PROPERTIES OF GEOPOLYMER AT ELEVATED TEMPERATURES

6.1 INTRODUCTION

High-temperature Thermal Energy Storage (TES) has been used to store excess heat from the renewable sources, industrial processes, etc. which is important to even out the difference between supply and demand of the thermal energy. In the temperature range of 100°C – 1000°C, there are a very limited storage technology available and many researches has been ongoing to find efficient and economically viable storage media [28]. One of the applications in this high-temperature range is the thermal storage for parabolic trough solar thermal power plant. The two-tank molten salt thermal storage is currently being used in the parabolic trough power plant. But it has a high freezing point and also has high investment and maintenance cost. Recently, a concrete storage technology is developed and tested by German Aerospace Center (DLR) [27]. This is found to be an attractive option as a solid media thermal storage system because of its low investment and maintenance cost, easy handling and availability around the world. But this type of concrete storage is tested and will work for temperatures as high as up to 500°C. Because the OPC concrete undergoes a physical and chemical change at an elevated temperature which eventually decreases its strength through disintegration.
Geopolymer, newly emerging cementitious material, has the potentials to supplement the Ordinary Portland Cement (OPC) in this regard. The potential use of Geopolymer as a cement and concrete has been investigated and summarised in many studies [195, 270-272].

Geopolymer has a ceramic-like property for which it shows a far better thermal stability at elevated temperatures than the conventional OPC [31, 32]. Moreover, geopolymer gains strengths at higher temperature due to the further geopolymerisation reaction [273, 274]. Also, geopolymer has superior fire resistance originating from its inorganic polymeric structure [275]. Zhao et al. [29] have shown that compared to OPC no spalling occurs to geopolymer concrete in sudden fire exposure which was attributed to the higher porosity of geopolymer.

The thermo-physical properties, e.g. thermal conductivity, density, specific heat capacity, the coefficient of thermal expansion, etc. of the thermal storage material are very important. Higher thermal conductivity means a higher rate of conduction through the material. Higher heat capacity will allow higher storage capability of the material. Many researches have been carried out to investigate the mechanical properties and thermal behaviour (e.g. thermal expansion, mass loss, etc.) of geopolymer at or after elevated temperature exposure [32, 217, 273, 276, 277]. But no studies focus on the thermal conductivity and heat capacity of geopolymer. These properties are important to understand the thermal behaviour of the geopolymer at elevated temperatures or sudden fire exposure. Because of the high temperature withstand capability; the geopolymer has the potential to be used as a thermal storage material at a higher temperature range. Thermal properties will be helpful to develop computer models to analyse the thermo-physical behaviour and transient heat transfer in the geopolymer in these contexts.

In this study, the thermal conductivity was measured at elevated temperatures of up to 800°C. Then from the collected data from the experiment, specific heat capacity of geopolymer was calculated. In this experiment, only fly-ash based geopolymer were used because it has proven to have better performance than the metakaolin based geopolymer when exposed to higher temperature[229].
6.1.1 Method of Measurement of Thermal Properties

The main thermal properties that can help understanding the thermal behaviour of a material are thermal conductivity \( k \), thermal diffusivity \( \alpha \) and specific heat capacity \( C_p \). They relate each other by the following equation,

\[
\alpha = \frac{k}{\rho \cdot C_p} \tag{6.1}
\]

Here both thermal conductivity \( k \) and specific heat capacity \( C_p \) may change with temperature, specially in case of wider temperature range. The higher is the thermal conductivity, the faster is the heat-flow through a material. A high heat capacity \( C_v = \rho \cdot C_p \) will allow more heat to be stored in a material.

There are many international standard methods for measuring the thermal conductivity of solids e.g. hot wire method (ISO 8894-2, ASTM C1113), calorimeter method (ASTM C201-93), hot plate method (ASTM C177), etc. The suitable one is chosen depending on the type and the thermal behaviour of the material, temperature range, etc. The conventional cement paste and concrete are porous, and usually, the pores contain moisture. They behave in a complex way during heating due to the moisture movement in the pore. For this nonhomogeneous behaviour of the conventional cement and concrete, transient method like hot-wire method (ISO 8894-2) has been suggested and used successfully [278, 279]. Due to the similar nature, the geopolymer has been tested with hot-wire method to determine the thermal conductivity at different elevated temperatures.

The hot-wire method (ISO 8894-2) is a transient measurement method where the change of temperature is measured at a certain location and at a specified distance from the linear heat source (hot-wire) which is place between two specimens [280]. The experimental arrangement is shown in Figure 6.1. The test specimen pair is placed in a furnace to heat-up to a desired temperature at which the thermal conductivity is to be measured. Then the temperature is maintained for some time to let the specimen fully saturated with the heat. A hot wire is embedded between the two specimens to provide further local heating, heated by an electrical current of known power. The measurement
thermocouple (Figure 6.1) is also placed 15 mm away from the hot-wire, with the thermocouple leads parallel to the wire. There is also a reference thermocouple placed at the top of the upper specimen. The difference of signal from the reference and measurement thermocouple is fed to the computer. The temperature increase in time at the specified distance from the hot-wire is the measurement of thermal conductivity. The following equation is used to calculate the thermal conductivity in the hot-wire method \[ \text{(6.2)} \]

\[
k = \frac{P_r}{4\pi l} \times \frac{-Ei\left(\frac{-r^2}{4\alpha t}\right)}{\Delta \theta(t)}
\]

Where \( P_r \) is the rate of the energy transfer, in watt, within the length of hot-wire, \( l \) is the length, in meter, of the hot-wire, \( t \) is the time, in seconds, from the moment of heating switch turned on, \( \alpha \) is the thermal diffusivity in \( \text{m}^2/\text{s} \), \( r \) is the distance, in meters, from the hot-wire to the measurement thermocouple and \( \Delta \theta(t) \) is the temperature difference, in kelvin, between measurement and reference thermocouple at time \( t \). \( Ei\left(\frac{-r^2}{4\alpha t}\right) \) is the exponential integral, the value of which can be calculated from \( \Delta \theta(2t)/\Delta \theta(t) \) by using the table given by Grosskopf et al. \[ \text{(281)} \].
The exponential integral term in the form of $-Ei(-x)$ can also be calculated by using the special Matlab® function “expint()” [282]. The “expint()” function represents $E_1$ [283] where,

$$E_1(x) = \int_x^\infty (e^{-u}/u)du = -Ei(-x)$$ for $x > 0 \quad (6.3)$$

Then thermal diffusivity ($a$) can be obtained from the back calculation of exponential integral term $-Ei(-r^2/4\alpha t)$ by using the function “expint()” on Matlab®. So from the equation (6.1), the specific heat capacity ($C_p$) can be calculated provided that the density of the material is known.

**6.2 Sample Preparation and Experimental Procedure**

**6.2.1 Material**

The geopolymer can be made from the reaction of a pozzolanic compound or aluminosilicate source material and highly alkali hydroxide or silicate solution. In this study the low calcium (class F) fly ash was used as a primary source of aluminosilicate for the geopolymer paste synthesis. The source of the fly ash was Gladstone Power Station, Australia. It was generally glassy with some crystalline inclusion of mullite, hematite, and quartz. The fineness of the fly ash was 89% passing through 45$\mu$m sieve.

The alkaline activator used in this experiment was combined with alkali silicate and hydroxide solution. The Alkali silicate was a laboratory grade D sodium silicate solution ($Na_2SiO_3$), supplied by PQ Australia, with the chemical composition of $Na_2O=14.7\%$, $SiO_2=29.4\%$ and water = 55.9\% by mass. The specific gravity was 1.53. The sodium hydroxide ($NaOH$) beads of 26.2\% by weight were mixed with 73.8\% of distilled water to make 8.0 M concentration of hydroxide solution.

**6.2.2 Mixture ratio**

The fly ash has its very fine spherical shape particles which allow us to use comparatively higher solid-to-liquid ratio in the mix. In this experiment, the solid-to-liquid ratio was 4.0 which was fixed after some trial mixes to provide optimum strength.
and workability. If the solid-to-liquid ratio is more than 4.0, then this affects the workability, creates difficulty in compaction and decreases the strengths of the mix.

6.2.3 Specimen preparation

The fly ash and the alkaline silicate were blended by a small mortar mixer to mix for five more minutes. Two wooden moulds were prepared to make the brick-shaped specimen with dimensions 230 mm x 114 mm x 65 mm. These moulds were placed in a vibrator and mix was poured into it while vibrating to allow the trapped air-bubble come out. The vibration continued for 5 min, and then specimens were made ready for curing.

Figure 6.2: Specimen in the oven for curing

Figure 6.3: Cured specimen taken out from the mould
6.2.4 Curing regime

The specimens were put in an oven at 60°C for 24h for curing (Figure 6.2). At the end specimen was removed from the mould and allowed to cool down. Then the weights of the specimens were measured to get the bulk density. Figure 6.3 shows a finished specimen with two grooves imprinted on it; one is along the centreline of the surface for the hot-wire, and another is at 15 mm offset from the previous one to facilitate the measurement thermocouple.

6.3 EXPERIMENTAL PROGRAM

The RXD-03 Thermal Conductometer was used for thermal conductivity measurement. This is an automated machine, which can be programmed through the computer software. A set of five temperatures can be programmed in one go to measure the thermal conductivity at those temperatures. The difference from one temperature to other can be no less than 10°C. The machine uses the electric furnace to heat the specimen up to maximum 1250°C.

![Heating Curve](image)

Figure 6.4: Heating curve for the 1st set of experiment (20°C to 125°C)

The two specimens were placed in the machine with the embedded arrangements of hot-wire and thermocouples between the specimens. The machine was then programmed to four sets of 17 different temperatures (20, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300,
400, 500, 600, 700 and 800°C) to measure the thermal conductivity. The heating rate was set to 10°C/min. Each temperature was maintained up to 6 hours so that the specimens were evenly heated and then three measurements were taken for the thermal properties. So it took approximately 10 hours to finish measurements at each temperature (Figure 6.4). From 20°C to 300°C the temperatures were taken 25°C apart, because within this range some changes like vaporization of moisture, moisture loss, high-temperature sintering reaction, etc. occurs in geopolymer which might significantly change the thermal properties.

6.4 RESULT AND DISCUSSION

6.4.1 Thermal Conductivity of Geopolymer

The fly-ash based geopolymer contains a large number of small pores which helps the moisture movement and escape during heating [229]. There are three types of water in the hardened geopolymer that can escape while heating [284-286]. These are physically bonded water, chemically bonded water and hydroxyl group (OH). These types of water can be released through dehydration and dehydroxylation at high temperatures. The effects of these processes on the thermal properties are evident from the experiment.

Figure 6.5 shows the thermal conductivity of the geopolymer at different temperatures. At the room temperature (20°C) the thermal conductivity of the geopolymer is about 1.06W/m.K. Within the range of 20°C – 100°C, the thermal conductivity shows a linear increase up to 25%. In this period, the geopolymer together with the physically bonded water acts as a compound material. The water takes the heat, increases its temperature and migrates through the pores due to the thermal gradient. This helps in increase of overall heat transfer process, and that is why an increase in thermal conductivity is seen in this region. The moisture finally reaches the phase transition temperature (100°C) and eventually it becomes vapour and escapes the matrix. The dehydration can also be realised from the Differential Thermal Analysis (DTA) (Figure 6.7) and Thermo-Gravimetric Analysis (TGA) (Figure 6.6) results of the geopolymer. The DTA results (Figure 6.7) illustrates that the geopolymer paste is in endothermic phase between 20°C to 250°C. Moreover, in TGA (Figure 6.6), the total weight loss of the geopolymer is 11%
due to the heating up to 800°C, where 6% weight is lost between 100°C – 200°C. These suggest that the physically bonded water is taking the heat as a latent heat and transforming to vapour which then leave the geopolymer paste resulting the mass loss (Figure 6.6). It is found that as much as 70% of total moisture loss can happen at this temperature range [284]. This dehydration of the physically bonded water causes a drop in the thermal conductivity in between 100°C – 200°C. Other studies [31, 276, 287, 288] reported similar mass loss with sharp shrinkage, internal micro-cracking and strength loss, all of which attributed to the rapid migration and removal of bound moisture.

![Figure 6.5: Thermal conductivity of geopolymer with temperature](image)

Figure 6.5: Thermal conductivity of geopolymer with temperature
From 200°C – 500°C, the result shows a slight increase in conductivity with a magnitude of 0.2 W/m.K. On the other hand, the DTA curve shows an exothermic phase in this temperature range. This is due to the geopolymerisation reactions in geopolymer which was also observed in previous studies [274, 289]. Moreover, dehydroxylation of chemically bonded water occurs in this range [218, 288] which contributes 2 – 3% weight loss of geopolymer found in the TGA result. The effect of these phenomena was not
significant in the thermal conductivity plot. It may be due to their insignificant nature which would just contribute to a minor increase of the thermal conductivity of geopolymer.

The Thermal conductivity of geopolymer shows a little bit higher rate of increase in the range of 500°C – 800°C than the previous range. At these temperatures, especially after 600°C, the densification of the gel phase occurs which is caused by sintering and viscous flow of the gel [229, 276, 290, 291]. Due to this sintering, the interconnectivity of the geopolymer microstructure improves which lead to a higher strength than the ambient. This change of microstructure also contributes to the increase of thermal conductivity of geopolymer (Figure 6.5) up to around 1.2 W/m.K at 800°C.

6.4.2 Specific Heat Capacity of Geopolymer

The specific heat capacity of the geopolymer is also calculated by utilising the data available from the hot-wire method and the equation (6.2). From these data the values of the exponential integral term \(-Ei(-r^2/4\alpha t)\) is collected for each temperature. A Matlab® code is written to evaluate the thermal diffusivity (\(\alpha\)) with temperature from the exponential integral values. The bulk density of the geopolymer is calculated 1800 kg/m³ from the weight and volume measurement of the specimen. The specific heat capacity is then determined from the equation (6.1).

It is important to mention here that the specific heat capacity is calculated from the data of hot-wire method where the specimen is kept at the measurement temperature for approximately 6 hours before taking the measurement. So this specific heat capacity is not an instantaneous one. And that’s why only the major heat gain/loss like phase change can be seen in the results.

Figure 6.8 shows the change of specific heat capacity with temperature. At room temperature (20°C) the specific heat capacity of the geopolymer is found to be around 1500 J/kg.K. Then it increased up to a maximum of about 1900 J/kg.K at 100°C. This rise of specific heat capacity was related to the phase change of the moisture inside the geopolymer. Afterwards, the heat capacity dropped sharply to 1125 J/kg.K at around 200°C. Then, it didn’t change much till the temperature reached to 400°C and then fall a
little bit to 1000 J/kg.K when it reaches to 600°C. This little drop may signify the end of the geopolymerisation reactions which occurs after 200°C (discussed in section 6.4.1).

The rise of the heat capacity after 600°C suggest the viscous transformation or the glass transition of the geopolymer for which it increases up to 1300 J/kg.K at 800°C.

![Figure 6.8: Specific Heat capacity of geopolymer with temperature](image)

**6.4.3 Thermal Conductivity of Geopolymer Concrete**

After the experiment of geopolymer (paste), geopolymer concrete specimen is made to measure the thermal conductivity. The paste composition is kept same as the previous experiment (section 6.2). The aggregate (coarse and fine/sand) to fly ash ratio used in the specimen is 1.8 where 10% is coarse aggregate, and the remaining is sand. 10% area for coarse aggregate is chosen because it will give the ratio of coarse aggregate to sand with a range of 1.5 – 2.0. The amount of the coarse aggregate is determined by using specific surface area calculation. The specific area of the coarse aggregate and sand are 0.4 m²/kg and 6.5 m²/kg respectively [292].
Two pairs of geopolymer concrete specimen are made for this experiment. These pairs are heated up to 800°C, and thermal conductivity is measured in a similar fashion like the geopolymer. Also, the heating and measurement are repeated two more times to study the change of thermal conductivity with repeated heating.

Figure 6.9 shows the thermal conductivity of geopolymer concrete with temperature. The plot shows the results from two specimens and the average of them. In the first heating cycle, the thermal conductivity of the geopolymer concrete at room temperature (20°C) is around 2.8 W/m.K (average) which is higher than geopolymer (1.06 W/m.K). This is due to the addition of the coarse aggregates and sand. The aggregates can have higher thermal conductivity as well as high porosity which accommodate more physically bonded water. In the range of 20°C – 100°C, the thermal conductivity of the concrete exhibits a gradual increase up to 3.7 W/m.K (average) which is a similar behaviour found in geopolymer experiment. The release of physically bonded water occurs around 100°C, after which the thermal conductivity sharply drops to around 1.87 W/m.K at 200°C.

After 200°C temperature, as further geopolymerisation occurs and chemically bonded water is released, the conductivity continues to drop but with a very slow pace up to
temperature 600°C with a value of 1.4 W/m.K. Between 600°C and 800°C the thermal conductivity does not change although viscous densification occurs during this temperature range.

As the strength of geopolymer concrete retains after heating up to 800°C, it is possible to use the specimen for more than one time. In Figure 6.9, the conductivity results are also shown for 2nd and 3rd heating cycle. It is found that the more times the concrete was heated, the less the conductivity fluctuates within the 20°C – 200°C region. This indicates that moisture/water is still available in geopolymer after 1st or 2nd heating. These are probably produced during the chemical process at the end of the previous heating cycle which did not escape the concrete at that time. Some moisture can also come from the atmosphere in concrete during the cooling process. The reduction in fluctuation of the thermal conductivity in 20°C – 200°C region indicates that the amount of free water is reduced after each heating cycle.

Also, in the temperature range of 200 – 800°C, there is a difference in the conductivity between 1st time heating and other two. This behaviour also affirms that the geopolymerisation reaction and release chemically bonded water which occurs in the first heating cycle are not repeated in the next two cycles. Therefore, the thermal conductivity is more stable in this temperature range. The results also show that the conductivity in the densification phase (600°C – 800°C) are close to each other for all heating cycle which is within the range of 1.2 W/m.K – 1.4 W/m.K.

6.4.3.1 Thermal Conductivity Model for Geopolymer Concrete

The geopolymer concrete experiment shows that the thermal conductivity continues to flatten with each heating cycle. This behaviour suggests that the irreversible physical and the chemical changes which occur inside the geopolymer are diminishing with every heating cycle. The last cycle (3rd one) from the experiment shows that the conductivity is almost levelled, the average value of which is 1.2 W/m.K. Now the thermal conductivity of the geopolymer can be written as the following for first couple of heating cycle,

\[ k(T) = k_v(T) + k_b \] (6.4)
Where, $k_b$ = Average base conductivity at which the concrete settles down after couple of heating cycles = 1.2 W/m.K and

$$k_v(T) = \text{Variable conductivity, the variations above } k_b \text{ which exist during the first couple of heating cycles.}$$

For the subsequent heating cycles, the value of $k_v(T)$ becomes close to zero. Then the eqn. (6.4) can be rewritten as,

$$k = k_b = 1.2 W/m.K \quad (6.5)$$

The Eqn. (6.5) will be useful to understand the thermal behaviour of the geopolymer concrete under a cyclic heating or cooling process which occurs in a typical thermal storage system.

![Specific heat capacity of geopolymer concrete at different heating cycle](image)

**Figure 6.10 Specific heat capacity of geopolymer concrete at different heating cycle**

### 6.4.4 Heat Capacity of Geopolymer Concrete

The specific heat capacity of the geopolymer concrete is calculated from the Eqn. (6.3) (Figure 6.10). In Figure 6.10 it can be seen that there is no peak in specific heat capacity plot to suggest any phase change or reaction. This might be due to the long heating time before taking the measurement which is necessary for the uniform heat distribution.

### 6.4.5 Geopolymer Concrete as a Thermal Storage

The thermal conductivity and the specific heat capacity of geopolymer is very close to that of blast furnace concrete used in the thermal storage study [27]. The normal concrete
storage system has a limitation on the inlet (< 400°C) and outlet temperature (315°C). One study suggested the modular storage concept to increase the outlet temperature to 350°C, which increases the maximum average storage temperature [167]. In another study, a blast furnace concrete with polyethylene fiber (N4-concrete) developed to increase the storage inlet temperature up to 500°C [27]. In the case of geopolymer, it is possible to increase both the inlet temperature up to 800°C which will eventually allow higher outlet temperature and thus a higher maximum average storage temperature. This will increase the capacity of the thermal storage to a great extent.

6.5 CONCLUSION

This study leads us to the following conclusions.

a) The moisture content in the geopolymer plays an important role in heat transfer and thus on the thermal conductivity. From room temperature to 200°C the thermal properties of the geopolymer is mainly driven by moisture presence in the pore. The movement of moisture due to the thermal gradient and its phase change considerably increases the thermal conductivity. This increase occurs linearly from 1.06 W/m.K to 1.37 W/m.K. The phase change of the moisture also gives a peak in the specific heat capacity at around 100°C.

b) In the range of 200°C – 500°C, a very slight increase of thermal conductivity occurs which may correspond to the geopolymerisation reaction and release of chemically bonded water. The glass transition or viscous sintering raises the conductivity with the relatively higher rate.

c) The thermal conductivity results of the geopolymer concrete show a similar trend like the geopolymer paste for the first heating cycle. But values are shifted to a higher range. The thermal conductivity at room temperature is around 2.8 W/m.K which linearly increased up to 3.7 W/m.K at 100°C. After this temperature, the conductivity declines all the way to 800°C to the value of 1.4 W/m.K.

d) The repeated heating of geopolymer decreases the effect of physically and chemically bonded water as well as high-temperature reactions on the thermal
conductivity. After a couple of heating cycle, it becomes less variant, average of which is found to be 1.2 W/m.K.

e) The thermal conductivity of geopolymer concrete is found to be close to the properties of concrete. This attribute coupled with high temperature withstand-ability up to 800°C makes geopolymer concrete an attractive material to be used as a thermal storage. Moreover, uniform behaviour of the thermal conductivity with the temperature after a couple of heating cycles will make the thermal behaviour of geopolymer more predictable as a thermal energy storage which involves thousands of heating cycle. The thermal conductivity of geopolymer can also be used in numerical study and simulation to inspect the material further as a thermal storage.

In this research, the geopolymer and the geopolymer concrete have been studied to examine the thermal conductivity at different temperatures from 20°C – 800°C. Further studies are required to use the geopolymer material as a thermal storage. Specially, strength test with the function of thermal cycles, the integrity of geopolymer material as a thermal storage together with tube register and other components of the storage system, experiment, and thermal modelling to find an optimum inlet-outlet temperature difference for thermal cycling, etc. are most notable ones.
CHAPTER SEVEN

7 HIGH-TEMPERATURE TES: APPLICATION OF INVERSE PROBLEM FOR THE ESTIMATION OF THERMAL PROPERTIES OF GEOPOLYMER

7.1 INTRODUCTION

7.1.1 Geopolymer

‘Geopolymer’, a term first introduced by Davidovits [293], represents a material which is produced by combining pozzolanic compound or aluminosilicate source material with highly alkaline solutions. Geopolymer has great potential to be a better alternative to Ordinary Portland Cement (OPC) because of its higher strength, stiffness, and other comparable mechanical properties. Moreover, the chemical structure of geopolymer (Al-Si-O) [30] is very different from the OPC (Ca-Si-H). Due to this difference, the geopolymer is more advantageous than the OPC in certain areas such as higher performance when exposed to elevated temperature [32]. Its superior resistance to spalling also observed under simulated fire where the highest temperature reached was more than 800°C [29]. Fly-ash based geopolymer concretes have a good endurance to sulphate attack [294, 295], lower creep [296] and shrinkage [270] compared to the OPC concrete.

The better performance of the geopolymer at elevated temperature makes it a potential material for high-temperature Thermal Energy Storage (TES) system. To understand the feasibility of the use of geopolymer as a TES, its thermal properties are needed to be
explored. Many experimental studies have been done [29, 31, 273] on geopolymer to investigate mechanical properties, damage behaviour, fire resistance properties, etc. at elevated temperature. But few researches have been reported on the thermal properties at ambient temperature [284, 288] which are of metakaolin based geopolymer. The fly ash based geopolymer that was found to have better performance at elevated temperatures in some studies [229, 297, 298], the thermal conductivity, specific heat capacity, etc. are scarce in the literature.

### 7.1.2 Measurement of Thermal Properties at Elevated Temperatures

The thermal properties are important to understand the overall thermal behaviour of geopolymer. It will help us to study high-temperature analyses, e.g. fire performance, solar energy storage, refractory usages, etc. Furthermore, by using the thermal properties, we can do numerical modelling and simulation of geopolymer structure (small or large scale) at elevated temperature.

Geopolymer paste is a porous material. It usually contains moisture inside the pore which affects the pore conductivity and heat capacity. Also, some geopolymerisation reaction occurs inside the geopolymer at around 200°C – 290°C [273, 274]. To capture these physical and chemical phenomena while determining the thermal properties, a proper method is needed for determining thermal properties.

There are some standard methods for determining thermal properties, e.g. hot-wire method for conductivity, Differential Scanning Calorimetry (DSC) for specific heat capacity, etc.

The hot-wire method (ISO 8894-2 [280]) is a widely used method to determine the thermal conductivity. In this method, the specimen is maintained at a certain measurement temperature to make the temperature uniform throughout the specimen. Then a heat pulse is given from a “hot wire”, a linear heat source embedded in the specimen. The increase in temperature as a function of time, measured from a known distance from the hot wire, is a measure of the thermal conductivity of the material of which the test pieces are made. This method applies to materials with a thermal conductivity less than 25 W/m.K at a temperature up to 1250°C. However, in this
method, it is difficult to make measurements of materials which undergo physical and chemical changes at elevated temperatures. Because this method requires pre-treatment for the materials with internal changes and long holding period at the measurement temperature to eliminate the influence of those changes in the measurement. But in the case of dynamic change of temperatures, e.g. fire exposure, heating process in thermal storage, etc. the internal changes are important to include in calculating the thermal properties. There are other similar steady-state methods, e.g. hot plate method (ASTM C177), the hot box method (ASTM C236), calorimeter method (ASTM C201), etc. which have the same problem of requiring long holding period at the measurement temperature.

The Differential Scanning Calorimetry (DSC) (ASTM E1269) method is a very simple and rapid method for determining the specific heat capacity. It measures the change of heat flow rate in a sample and a reference sample as a function of time while they are maintained nearly same temperature throughout the experiment. From the measured heat flow rate, the specific heat capacity can be calculated. The operating temperature range of this method is from 100 – 600°C, which can be extended depending upon the instruments. This method uses milligram quantities of the specimen and that is why it requires homogeneous and representative specimen. Also, this method can only be applicable to thermally stable solids and liquids. Any chemical change and mass loss during measurements will invalidate the test. So this method is not suitable for transient thermal analysis.

When modelling during a fire or different types of dynamic heating, the effects of the chemical and physical changes, which are transient, needs to be captured in thermal parameters so that the results include these effects. Therefore, in this paper, we have developed a method using an inverse calculation to estimate thermal conductivity and specific heat capacity using a newly developed numerical procedure.

Ukrainczyk [299] has used an inverse heat transfer method, the Levenberg-Marquardt iterative method [300-302] to estimate the thermal diffusivity. By using the inverse method, one can estimate unknown parameters (e.g. thermal properties, boundary heat flux, etc.) from the transient temperature distribution in a material. The algorithm
developed by Ukrainczyk [299] generates only one thermal diffusivity value for the whole range of temperature. This was reasonable as the temperature range in that study was small (5°C) and the thermal diffusivity was not expected to change in that range. But in the case of the large temperature range, thermal properties may not be the same for the whole range of the temperatures. In this study, the thermal properties of geopolymer were estimated by using the transient temperature response of a geopolymer specimen with an inverse method in the temperature range of 20°C – 800°C. The total temperature range was divided into small ranges and for each small range two thermal properties - thermal conductivity and volumetric heat capacity, were estimated simultaneously.

7.2 EXPERIMENTAL PROGRAM

7.2.1 Specimen preparation
A fly ash based geopolymer specimen was prepared for the elevated temperature experiment [32]. The low calcium (class F) fly ash was used as a primary source of aluminosilicate for the geopolymer paste synthesis. The alkaline activator used in this experiment was combined with alkali silicate and hydroxide solution. The Alkali silicate was a laboratory grade D sodium silicate solution (Na₂SiO₃). The potassium hydroxide (KOH) flakes with 90% purity was mixed with distilled water to make 7.0 M concentration of hydroxide solution. The solid-to-liquid ratio used here was 3.0 to provide optimum strength and workability.

The mould was made with cylindrical shape (Figure 7.1) with 100 mm diameter and 200 mm height. The thermocouples were placed measure temperatures at 10, 20, 30, 40 and 50 mm (centre) of the specimen at a height of 100 mm (Figure 7.2). The fly ash and the alkaline silicate were blended a mixer and then gradually filled into the mould.

The specimen was cured for 24h at room temperature. Then it was put to an oven at 80°C and 93% relative humidity for another 24h for further curing. At the end specimen was removed from the mould and allowed to cool.
Elevated temperature heating methods

The specimen was heated up to 800°C from room temperature with a heating rate of 4.4°C/min. An electric furnace was used which can heat up to 1200°C. When the specimen was reached at 800°C, it was maintained for 1h before cooling down. Figure 7.3 shows the temperature – time profile measured at different radial positions of the geopolymer specimen.
7.3 NUMERICAL METHOD

In this study, the Levenberg-Marquardt iterative method [300, 301] was used to estimate the unknown parameters in the heat transfer problem. A subroutine developed by Ukrainczyk [299] for thermal diffusivity was modified to estimate two parameters, i.e. the thermal conductivity ($k$) and the heat capacity ($C_v$) for a large range of temperature. To use the Levenberg-Marquardt method [300, 301] the heat transfer problem of this study can be arranged by direct problem and indirect problem.

7.3.1 Direct Problem

According to the experimental design, the heat transfer in the sample cylinder can be assumed as one-dimensional (1D), i.e. in the radial direction only. The system equation for 1D transient heat transfer problem of axisymmetric cylinder can be written as [303]:

$$
k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r} \frac{\partial T}{\partial r} = C_v \frac{\partial T}{\partial t} \quad \text{in} \quad 0 < r < R \quad \text{for} \quad t > 0 \quad (7.1)
$$

$$
T = T_o(r) \quad \text{for} \quad t = 0 \quad \text{in} \quad 0 \leq r \leq R \quad \text{Initial condition}
$$

$$
T = T_b \quad \text{at} \quad r = R \quad \text{for} \quad t > 0
$$
\[
\frac{\partial T}{\partial r} = 0 \quad \text{at} \quad r = 0 \quad \text{for} \quad t > 0
\]

\begin{align*}
\text{Boundary} & \quad \text{condition} \quad \text{Symmetry} \\
\frac{\partial T}{\partial r} & = 0 \quad \text{at} \quad r = 0 \quad \text{for} \quad t > 0
\end{align*}

Where, \( r = \text{radial position} \), \( R = \text{cylinder radius} \), \( t = \text{time} \), \( T = \text{temperature} \), \( k = \text{thermal conductivity} \), \( C_v = \text{heat capacity} \).

This is the direct problem, where the temperature field \( T(r, t) \) can be determined by using known values of the properties (i.e. \( k \) and \( C_v \)).

### 7.3.2 Indirect Problem

In the indirect problem, the unknown parameter vector, \( P \) (here this consists of thermal properties) is estimated in a way that it would create a similar temperature distribution at a certain position which would match the data from experiments at the same position.

The solution of the 1D conduction problem can be obtained by the minimization of least square norm given by [302]:

\[
S(P) = [M - T(P)]^T [M - T(P)] = \sum_{i=1}^{l} [M_i - T_i(P)]^2 \quad \text{(7.2)}
\]

Where, \( P = \text{Vector of unknown parameters} \)

- \( S(P) = \text{Sum of the square error for the current estimation of } P \)
- \( T_i(P) = \text{Temperature computed at time } t_i \text{ using the current estimation of } P \)
- \( M_i = \text{Measured temperature at time } t_i \)
- \( Tr = \text{Transpose of the matrix or vector} \)

\( i = 1, ..., l, \text{ and } l = \text{total number of measurements} \)

In the current study, there are two unknown parameters - thermal conductivity \( (k) \) and heat capacity \( (C_v) \). So the vector of unknown parameters \( P \) can be written as \( P = [P_1, P_2] = [k, C_v] \).

To minimize the least square norm (Eqn. (7.2)), a sensitivity matrix or the Jacobian matrix, \( J(P) \) can be defined [302] as follows,
\[
J(P) = \left[ \frac{\partial T^{Tr}(P)}{\partial P} \right]^{Tr}
\] (7.3)

In the explicit form, this can be written as,

\[
J(P) = \begin{bmatrix}
\frac{\partial T_1}{\partial P_1} & \frac{\partial T_1}{\partial P_2} \\
\frac{\partial T_2}{\partial P_1} & \frac{\partial T_2}{\partial P_2} \\
\vdots & \vdots \\
\frac{\partial T_l}{\partial P_1} & \frac{\partial T_l}{\partial P_2}
\end{bmatrix} = \begin{bmatrix}
\frac{\partial T_1}{\partial k} & \frac{\partial T_1}{\partial C_v} \\
\frac{\partial T_2}{\partial k} & \frac{\partial T_2}{\partial C_v} \\
\vdots & \vdots \\
\frac{\partial T_l}{\partial k} & \frac{\partial T_l}{\partial C_v}
\end{bmatrix} = [J_k \ J_{C_v}]
\] (7.4)

Where \( l \) = total number of measurements, \( J_k \) and \( J_{C_v} \) are the component vector of the sensitivity matrix which are related to \( k \) and \( C_v \). The i-th term of these vectors can be written as,

\[
(J_k)_i = \frac{\partial T_i}{\partial k} \quad \text{and} \quad (J_{C_v})_i = \frac{\partial T_i}{\partial C_v}
\] (7.5)

These terms are called sensitivity coefficients. Once the sensitivity matrix is constructed, the Levenberg – Marquardt method can be used to estimate the unknown parameters, (i.e. \( k \) and \( C_v \)). The iterative procedure can be written as [302],

\[
P^{n+1} = P^n + ([J^n]^{Tr}J^n + \mu^n\Omega^n)^{-1}[J^n]^{Tr}[M - T(P^n)]
\] (7.6)

Here, \( n \) is the iteration step, \( \mu^n \) is the damping factor and \( \Omega^n \) is a diagonal matrix where \( \Omega^n = \text{diag}([J^n]^{Tr}J^n) \) [302]. The main reason to include the term \( \mu^n\Omega^n \) in eqn. (7.6), as proposed in the Levenberg – Marquardt method, is to damp the oscillation and instabilities due to the ill-conditioned nature of \( (J^n)^{Tr}J^n \).

### 7.3.3 Determining the Sensitivity Coefficients

There are many different approaches described by Ozisik et al. [302] to determine the sensitivity coefficients. In this study, the boundary value problem approach was used to compute these coefficients. A boundary value problem can be developed by differentiating the original direct problem (Eqn. (7.1)) with respect to the unknown parameters (i.e. \( k \) and \( C_v \)) to construct the \( J_k \) and \( J_{C_v} \) vectors. The boundary value
problem of the sensitivity vector $J_k = \frac{\partial T}{\partial k}$ can be obtained by differentiating Eqn. (7.1) with respect to $k$, which is given by,

$$ k \frac{\partial^2 J_k}{\partial r^2} + \frac{k \partial J_k}{r \partial r} + \frac{\partial^2 T}{r \partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = C_v \frac{\partial J_k}{\partial t} $$

in $0 < r < R$ for $t > 0$

$J_k = 0$ for $t = 0$ in $0 \leq r \leq R$  \hspace{1cm} (7.7)

$J_k = 0$ at $r = R$ for $t > 0$

$\frac{\partial J_k}{\partial r} = 0$ at $r = 0$ for $t > 0$

Similarly for the sensitivity vector $J_c_v = \frac{\partial T}{\partial c_v}$, the boundary value problem can be written as,

$$ k \frac{\partial^2 J_{c_v}}{\partial r^2} + \frac{k \partial J_{c_v}}{r \partial r} = C_v \frac{\partial J_{c_v}}{\partial t} + \frac{\partial T}{\partial t} $$

in $0 < r < R$ for $t > 0$

$J_{c_v} = 0$ for $t = 0$ in $0 \leq r \leq R$  \hspace{1cm} (7.8)

$J_{c_v} = 0$ at $r = R$ for $t > 0$

$\frac{\partial J_{c_v}}{\partial r} = 0$ at $r = 0$ for $t > 0$

Now, solving Eqn. (7.7) and (7.8), the sensitivity matrix $J$ can be constructed from the eqn. (7.4).

### 7.3.4 Stopping Criteria

The standard deviation for the computed temperatures using the estimated properties can be written in terms of least square norm $S(P)$ as,

$$ \sigma_z = \sqrt{\frac{S(P)}{N - 1}} \text{ Where } N = \text{number of temperature data} \hspace{1cm} (7.9) $$

The stopping criteria of the algorithm can be written as,

$$ \sigma_z < \varepsilon \hspace{1cm} (7.10) $$

The $\varepsilon$ is a tolerance prescribed by the user. For this study the value of the $\varepsilon$ is chosen as 0.1 because the experimental data are accurate up to 0.1°C (Eqn. (7.9)). Also a maximum number of iteration $n_{max}$ is set to prevent the program run for infinite times.
7.4 The Computer Algorithm

The computer algorithm of Levenberg–Marquardt method is shown in Figure 7.4. The whole temperature range (20°C – 800°C) is divided into small segments of 5°C range. Then for each small ranges the program is run with its initial and boundary conditions to get a thermal property value (i.e. $k$ and $C_v$) for that range. This allows us to compute the different value of thermal properties for the different temperature ranges. Also this makes the program more stable compared to running for the whole range.

The program was used with temperature data at different radial positions. As it was explained earlier, the program takes the boundary conditions and estimates the thermal properties in a way that it would create a temperature response at a certain radial position similar to the experimental data for that position. For example, in the first case, the temperature data (from experiment) at the surface is used as boundary conditions and thermal properties were estimated by evaluating temperature response at $r = 40 \, mm$ similar to experimental data at that position (Figure 7.5).

Four computations were performed to estimate thermal properties by comparing temperature data at $r = 40 \, mm, 30 \, mm, 20 \, mm$ and $10 \, mm$. The computational simulations were named as sim-40, sim-30, sim-20 and sim-10 respectively depending upon the position where temperature results were compared.
Initialization
- Initial and Boundary conditions
- Iteration, $n = 1$
- Initial Guess for $P^n$ vector
- Initialize Damping parameter, $\mu^n$

Start

Solve the Eqn. (7.1) and Compute $T(P^n)$ using initial value of $P^n$

Calculate $S(P^n)$ from Eqn. (7.2)

Replace $n$ by $n+1$

Solve Eqn. (7.7) & Eqn. (7.8) and Calculate $P^{n+1}$ from the Eqn. (7.4)

Compute new estimation of vector, $P^{n+1}$ using the Eqn. (7.6)

Solve the Heat Eqn. (7.1) with new estimation $P^{n+1}$ and Compute the new set of temperatures $T(P^{n+1})$

Calculate $S(P^{n+1})$ from Eqn. (7.2) for new estimation of $P^{n+1}$

Replace $\mu^n$ by $10\mu^n$ Yes

Accept the new $P^{n+1}$ and replace $\mu^n$ by $0.1\mu^n$

Replace $n$ by $n+1$ No

Stopping Criteria Met?

Yes

Stop

No

$S(P^{n+1}) \geq S(P^n)$ ?

Yes

Stop

No

$r = 50$ mm

$r = 0$ mm

(center)

$*$

$r = 40$ mm

$*$

Figure 7.4 Computer algorithm for Levenberg – Marquardt method

Figure 7.5 Radial positions used for the first computational case
7.5 RESULTS AND DISCUSSION

The Figure 7.6 and Figure 7.7 shows the thermal conductivity ($k$) and heat capacity ($C_p$) of geopolymer respectively at different temperatures. These properties are plotted with the average temperature for each small temperature range. Both properties are plotted for four different set of computations, i.e. sim-40, sim-30, sim-20 and sim-10 which are related to different radial positions. An average profile for the thermal conductivity and the heat capacity were then constructed from the four computational results.

In the temperature range of 20°C – 100°C, different thermal conductivity values were found for different radial positions. Similar trends can be seen for heat capacity as well. This can be due to the presence of water in the geopolymer. The presence of water content can vary at different radial positions. Also, moisture movement can occur inside the specimen. These factors may cause different property values in this temperature range.

![Figure 7.6: Thermal conductivity with the corresponding temperature](image)

Figure 7.6: Thermal conductivity with the corresponding temperature
At temperatures just above 100°C, the thermal conductivity reduced drastically to around 0.2 W/m.K. On the other hand, the heat capacity sharply increased to $3.2 \times 10^6$ J/m$^3$.K – $3.5 \times 10^6$ J/m$^3$.K. This phenomenon indicates the phase change of the water inside the geopolymer. The water becomes vapour from the liquid which gives a peak in the heat capacity plot. This incident acts as a “heat sink” and holds the temperature (Figure 7.3). This also causes a slower temperature response towards the centre of the specimen. These indicate the reason of a lower thermal conductivity and a higher heat capacity in this temperature range.

Between 150°C – 250°C, the thermal conductivity did not change much. On the other hand, a second peak was appeared in the heat capacity plot of this temperature range. This can be due to the high-temperature geopolymerisation reaction. Pan et al. [273] and Rahier et al. [274] found that in the range of 200°C – 290°C geopolymerisation occurs inside the geopolymer. This geopolymerisation reaction may results a small peak in the heat capacity plot.

**Figure 7.7: Heat capacity with the corresponding temperature**
After 250°C onwards, the thermal conductivity increased gradually. The geopolymer undergoes dehydration and dehydroxylation process [288] during this temperature range till around 500°C. These are basically the process of releasing the free water and the chemically bonded water. Significant thermal shrinkage occurs due to the physical contraction of the geopolymer as the dehydration and dehydroxylation process continues [288]. This thermal shrinkage changes the micro-structure of the geopolymer which may increase the thermal conductivity during this temperature range. However, the heat capacity drops from the peak and becomes stable at the end as it reaches close to 500°C.

Another major shrinkage occurs in geopolymer between 500°C and 800°C, which results in densification due to the paste sintering and viscous flow into the voids of the material [221, 288]. So, through densification, voids are reduced which can lead to the higher thermal conductivity of the material. That is why the thermal conductivity of the geopolymer was found to increase continuously even after 500°C till it reached to 800°C. On the other hand, the heat capacity did not change much in this temperature range.

The temperature-dependent thermal conductivity and heat capacity estimated here can be different from the ones which were found from the steady state experiment (section 6.4). Because in this study, they are estimated from the transient temperature profile. And during the transient heating, there are many physical and chemical changes which occur dynamically with the temperature increase. These changes cannot be captured in the steady-state experiment. In this study, these changes found to be reflected in the thermal properties computed from the transient response.
Figure 7.8 Temperature distribution in geopolymer specimen at time $t = 9000$ sec

Figure 7.9 Comparison of temperature response between experimental data and COMSOL numerical simulations at different radial positions
A heat transfer modelling was carried out with a Multi-Physics Software COMSOL™ using the estimated thermal conductivity and heat capacity of geopolymer (Figure 7.8). The temperature dependent average profiles of the properties were loaded into the model. The geometry was chosen as same as the experimental cylinder used in this study. The boundary temperature profile was also assigned to the model. The goal of this modelling was to see whether the estimated properties can recreate similar temperature profiles as to the experimental one.

Figure 7.9 shows the comparison of the temperature profile between the experiment and the modelling. The numerical results establish a very good agreement with the experimental results. The average difference between the experimental and numerical results is around 3.5% with the standard deviation of 3.8%. Hence, the computed thermal properties are a good estimation for geopolymer material, especially during transient heating condition.

The experimental surface temperature (at r = 50 mm) were used as a boundary condition in the modelling. That’s why the numerical and experimental profiles can be seen very close for the surface temperature.

7.6 CONCLUSIONS

This thermal properties study of geopolymer from the transient temperature profile led us to the following conclusions:

a) The geopolymer material goes through physical and chemical changes with the increase of temperature. These can change the thermal properties of the material. The thermal properties estimated in this study reflect these physical and chemical changes of geopolymer at different temperatures.

b) The first part of the temperature range (20°C – 150°C), the changes of thermal properties were influenced by mainly moisture movement and phase change. Between 200°C – 800°C, the shrinkage and densification of geopolymer matrix were reflected through the change in thermal properties in this range.
c) The advantage of using the inverse method is that it makes possible to capture the complex thermal behaviour of geopolymer in the thermal properties. Other standard methods require material stability and long holding time at measuring temperature. These make impossible to capture the transient behaviour of geopolymer which is very important for certain cases e.g. transient heating during storage of thermal energy, etc. The thermal properties estimated in this study can be used to simulate and understand the transient heat transfer in the geopolymer material.
CHAPTER EIGHT

8 CONCLUSIONS AND FUTURE RECOMMENDATIONS

8.1 CONCLUSIONS

The effectiveness of PCM as a thermal storage in room temperature application was studied through experiments and numerical investigation. Also, feasibility of geopolymer as a high-temperature TES was studied through studying the thermal properties at high temperature. Following conclusions can be drawn from the current thesis:

1. The potential of PCM in reducing energy consumption is different for different Australian cities. It was found to have effectiveness in Australian cold temperature, mild temperate and warm temperate climate zones. The integration of PCM had a minor effect in hot and humid climate zone due to the smaller diurnal temperature fluctuation.

2. The optimum melting temperature of PCM in reducing the monthly energy consumption is far from unique for each month. PCM with different melting temperature was found to be effective at different times of the year.

3. The performance of PCM also depends on the location of PCM application in the buildings, the thickness of PCM layer and the surface area. The ceiling area was found to be the best place for PCM application due to the buoyancy effect of the warmer air in the thermal zone. The efficiency of PCM in reducing the energy consumption was found to increase with the decrease of the PCM layer thickness and the increase of the surface area for a same amount of PCM. This
is true up to an optimum level after which spreading PCM can actually increase energy consumption.

4. The effectiveness of PCM in reducing the energy consumption of HVAC operation is found to be different compared to temperature fluctuation reduction under free running condition. PCM with melting temperature outside the thermostat range does not provide efficient energy reduction, although it can yield larger reduction in temperature fluctuation under free running condition.

5. Experimental and numerical study of a 5-star energy rated real house showed that the improvement in the performance of PCM in reducing peak zone temperature and the thermal comfort depends on the occupants' behaviour. PCM was found to be more effective when the windows of the PCM zone were kept open for night purging, and internal doors were kept close all the time to prevent zone mixing.

6. The application of the PCM in a 5-star energy rated real house exhibited slight improvement in temperature fluctuation reduction and in the thermal comfort. Because the indoor temperature fluctuations of this type of house were already low, hence there is little room for improvements by PCM.

7. Experiment and simulation of PCM incorporation in the air duct (PCM-air duct) of the hollow core concrete slab system suggest that PCM effectiveness depends on the PCM configuration inside the air duct. The best configuration was found to be spreading the PCM to all the surrounding inner wall of the air duct which potentially increases the heat transfer for a given volume of air and PCM.

8. The increase of PCM amount by increasing its layer thickness in PCM-air duct was found to have no effect on improving the performance of PCM. Rather spreading the PCM along with the flowing path of air resulted in further reduction in diurnal temperature fluctuation. Because in the latter case the more heat transfer occurs due to the increase heat transfer area or area of interaction for a given volume of air. In a real summer weather, PCM-air duct
was found to have reduced the daytime maximum temperature more than 1°C for 47% of simulated days. The highest reduction was found to be 4.2°C.

9. For a given inlet temperature fluctuation, the combined effectiveness of PCM-air duct-hollow core slab system was not similar to the summation of the individual effectiveness of PCM-air duct and hollow core slab. There is some loss of efficiency when they are both applied in combination. The contribution of the PCM-air duct was found to be reduced by 50%-60% after the hollow core slab when the combination system was used.

10. The experimental study of the thermal properties of geopolymer as a potential high-temperature TES suggests that the thermal properties are highly dependent on geopolymers internal change at high temperatures. From room temperature to 200°C the thermal properties of the geopolymer is mainly driven by moisture presence. The thermal conductivity of geopolymer at temperatures up to 100°C was found to be linearly increasing from 1 W/m.K to 1.4 W/m.K. But above 100°C, the conductivity was mostly between 0.75 W/m.K to 1 W/m.K.

11. The thermal conductivity of geopolymer concrete was found to have a similar trend to geopolymer, but the value was higher than that of geopolymer. The peak value at 100°C was found to be 3.7 W/m.K where after 100°C it was around 1.5 W/m.K.

12. Subsequent heating and testing of geopolymer concrete indicated that the thermal conductivity becomes more stable. After two additional heating and testing, the thermal conductivity became almost constant (1.25 W/m.K) for the whole range of investigated temperature (20°C – 800°C) as the physical and chemical change inside the geopolymer concrete mitigates with the repeated heating.

13. The numerical study of the thermal properties of geopolymer using the transient temperature distribution yielded slightly different profile than the previous steady state experiment. The continuous change of physical and chemical structure with the increase of temperature are more dynamic in the transient case. Although irrespective of steady state or transient case the
material properties should be ideally the same, the dynamic changes of geopolymer with the continuous increase of temperature makes the thermal properties different for the transient case.

8.2 Future Recommendations

1. Future research needs to include more detailed analysis on how to utilize PCM more effectively in Australian buildings under different climate zones. Selection of proper PCM integration method is required to achieve higher PCM effectiveness in a similar 5-star energy rated residential building. Also, further research is recommended to investigate the relationship between house energy rating and PCM effectiveness.

2. The overall PCM-air duct-hollow core slab system can be tested through experimental works and energy savings can be to be estimated in an office building operation with heat gains (People, lights, etc.).

3. With the measured thermal properties, a model of high-temperature TES with geopolymer material can be numerically and experimentally investigated with sufficient thermal cycle to test its performance, strength, and structural integrity.
9 References


17. Pedersen, C.O. *Advanced zone simulation in energyplus: Incorporation of variable properties and phase change material (PCM) capability*. Proceedings in


63. Sari, A., Form-stable paraffin/high density polyethylene composites as solid-liquid phase change material for thermal energy storage; preparation and thermal


89. Shi, X., Memon, S.A., Tang, W., Cui, H., and Xing, F., *Experimental assessment of position of macro encapsulated phase change material in concrete*


243. ABCB, *Building improvements to raise house energy ratings from 5.0 stars.* 2009.


281. Grosskopf, B. and Kilian, B., *Table book with Ei(-x) and ΔV(2t)/ΔV(t) values.* 1980, FRG: Kubel-Druck, Wiesbaden.


(http://mathworld.wolfram.com/ExponentialIntegral.html)


