Sudan University of Science and Technology

College of Engineering

Mechanical Engineering

Department Power

An experimental study of concrete with phase change materials for cooling purposes.

دراسة عملية على الخرسانة بواسطة مواد متغيرة الطور لأغراض التبريد

Thesis submitted in partial fulfillment for the requirement of the Degree of B.E (HONORS) in mechanical engineering

Prepared by:

1- **Abdrhman Omer Ibrahim Mohammed**
2- **Awab Hassan Khalifa Suleman**
3- **Omer Ahmed Eltayeb Sirelkhatim Osman**

Supervised by:

Dr. A. A. A. Abuelnuor

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الآيــــة

بسم الله الرحمن الرحيم

اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ (١) خَلَقَ الْإِنسَانَ مِنْ
عَلَقٍ (٢) اقْرَأْ وَرَبُّكَ الْأَكْرَمُ (٣) الَّذِي عَلَّمَ
بِالْقَلَمِ (٤) عَلَّمَ الْإِنسَانَ مَا لَمْ يَعْلَمْ (٥)

صدق الله العظيم

سورة العلق– الآيات(1-5)

Dedication

Dedicated to the beloved Ummah

To the most precious persons in our life, our fathers, mothers and families.

ACKNOWLEDGEMENT

Thanks to ALLAH, the Most Gracious, the Most Merciful, the Most Bountiful who gave us the courage and patience to accomplish this research work. Without his help and mercy, this would not have come into reality.

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ABSTRACT

These days, with dramatic increases of the energy consumption in industrial and residential sector around the world, the deficiency of energy sources has become significantly important and a major issue. The buildings sector is responsible from the consumption of almost 40% of the entire available energy worldwide. Thermal energy storage by means of latent heat is an efficient way to reduce the temperature fluctuations inside buildings, leading to the improved thermal comfort of occupants. Phase Change Materials (PCMs) with high density for thermal energy storage can be efficiently employed for this purpose. This research proposes using Phase Change Materials (PCMs) in the building's roof. Two types of PCMs with different melting point were utilized, the first one was Calcium Chloride Hexahydrate and the second type is Polyethylene Glycol (PEG) 600. Two rooms with identical dimensions were constructed using concrete blocks, one with PCM and the other without PCM in the roof. The thermal performances of small-scale test rooms were measured. The temperature inside the PCM integrated room was demonstrated to be considerably lower than the room without PCM. For Calcium Chloride Hexahydrate the reduction was between 1-3℃ and the average was 2℃ , for Polyethylene Glycol (PEG) 600 the reduction was between 1-5℃ and the average was 2℃ . A fan was used to enhance indoor thermal comfort in the second type of PCM integrated room and the reduction was between 2-5 ℃ and the average was 3.5℃ .

المستخلص

في الحاضر و مع الزيادات المضطرة في استهلاك الطاقة في القطاع الصناعي و السكني حول العالم ؛ اصبحت قضية نقص مصادر الطاقة مهمة للغاية. قطاع المباني مسؤول عن 40% تقريباً من استهلاك الطاقة في العالم. يعتبر تخزين الطاقة الحرارية بواسطة الحرارة الكامنة طريقة فعالة لتخفيض تقلبات درجة الحرارة داخل المباني ، مما يؤدي لتحسين الراحة الحرارية للأفراد المواد متغيرة الطور ذات الكثافة العالية لخزن الطاقة الحرارية يمكن ان تستخدم بشكل فعال لهذا الغرض. يقترح هذا البحث استخدام مادة متغيرة الطور في سقف المبنى. و تم استخدام نوعين من المواد المتغيرة الطور بدرجة انصهار مختلفة، النوع الاول هو كلوريد الكالسيوم سداسي جزيئات الماء (ملح مائي)، و النوع الثاني بولي ايثيلين غليكول. اجريت التجارب بإثنين من الغرف ذات الابعاد المتماثلة بوجود و غياب المادة المتغيرة الطور، اظهرت النتائج بأن درجة حرارة الغرفة اقل الى حد كبير من الأخرى، في النوع الاول وجد التخفيض في حدود °C(3-1) و المتوسط 2°C، و في النوع الثاني وجد التخفيض في حدود °C(5-1) و المتوسط 2°C . استخدمت المروحة في النوع الثاني لتحسين الراحة الحرارية الداخلية في الغرفة التي تحتوي على المادة متغيرة الطور مما ادى الى زيادة التخفيض ليصبح في حدود °C (5-2) و المتوسط 3.5°C .

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List of abbreviation and terminologies

HVAC	Heating, Ventilation and Air Conditioning
PCM	Phase Change Material
SHS	Sensible Heat Storage
LHS	Latent Heat Storage
TES	Thermal Energy Storage
BioPCM	Biological Phase Change Material
APS	Arizona Public Service
STAR	Solar Testing and Research
PVC	Polyvinyl Chloride
EBS	Expanded Polystyrene
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers.
PCMOW	Phase Change Material Outer Wall.
PCMIW	Phase Change Material inner Wall.
PEG	Polyethylene Glycol
USA	United State of America.
$Q_{Sensible}$	Sensible heat storage.
Q_{Latent}	Quantity of heat stored.
Δh	Heat of fusion per unit mass or specific enthalpy.
ΔH	Heat of fusion or enthalpy
ΔT	Temperature difference
C_p	Constant pressure specific heat
m	Mass of heat storage medium.
k	Thermal conductivity.

CHAPTER

ONE

CHAPTER ONE

INTRODUCTION

1.1 Background

These days energy is becoming an important aspect for survival of mankind, with the rapid development of economy producing energy is a basic need for improving the living standards [1-3]. According to a report from the U.S. department of energy (DOE) in 2010, the buildings sector accounts for more than 40% of global primary energy consumption [4, 5], therefore, the demand of energy is growing fast. The highest energy consumption rate is belongs to the building sector which mainly attributed to the heating, ventilating and air conditioning system (HVAC) [6]. Currently, the electricity demand is mostly satisfied by using fossil fuels which increase the emission of greenhouse gases and consequently contribute in global warming. Besides the impacts of the energy production on the environment, there are huge costs associated with the energy production from these fossil fuel plants, therefore, there is a necessity to find means that substantially reduce energy consumption [7].

Using the renewable energy as a solution can contribute to increase the energy efficiency and decrease the usage of fossil fuel along with reduce the pollutant emissions into the atmosphere. There are various renewable energy sources such as solar energy which is becoming a crucial measure for promoting energy efficiency and buildings sustainability. In addition, the usage of renewable energy sources is a key factor to reduce the energy dependence of the buildings [8-10]. Thermal storage has been developed to overcome this building energy issue. Latent heat storage is a more promising type of heat storage compared with common sensible heat storage methods based on the heat capacity [11].

Phase Change Materials (PCMs) are widespread thermal storage material in the building applications due to their high heat capacity and non-toxic properties [12-14]. PCMs store energy in the form of latent heat by reversibly changing phase between solid and liquid states. As the result, adding PCMs to the building walls will reduce energy demand for heating and cooling in addition to time-shifts the maximum daily thermal load on the building [15].

1.2 Problem Statement

Increasing the energy demands at the present days is a major challenge that face the survival of mankind. Tropical countries like Sudan suffer from high temperature in daylight period; especially during summer season which increase indoor temperature in the buildings. Thus, using the air conditioning units to decrease the room temperature up to the human comfort level is inevitable, however, due to high temperature the air conditioning units have to work continuously for a long time and that consequently will increase the emissions of the green gases along with increasing energy costs and demands. Therefore, it is necessary to discover an alternative solution that can be considered a tradeoff between the energy demand, costs, environmental impacts and the human comfort temperature.

1.3 Objectives

This study aims to utilize phase change materials as a thermal storage energy in the building in order to reduce the energy cost, environmental impact, and demands along with promoting the human comfort temperature level in the buildings. This aim can be achieved by the following objectives:

1. To design and construct lab scale concrete model using PCMs as insulated material.

2. To evaluate the performance of the PCMs material in preserving the low room temperature for long time.

3. To compare the performance of the PCMs between the concrete model and the compressed wood model.

1.4 Scope

This study is limited to Calcium Chloride Hexahydrate and Polyethylene Glycol as phase change material, also, the obtained results are limited to the room’s wall built using concrete material only.

1.5 Significance of Research

Using PCMs prevents abrupt temperature changes inside the building room, and enhance the human thermal comfort by preserving the indoor low temperature for long period along with reducing the energy consumption and costs.

1.6 Research Methodology

The First step of this study is to establish an experiment of PCM system in buildings that use concrete wall. PCMs usage was adopted as a sort of thermal energy storage technology. In the Second step, PCMs was used in the roof of the building to investigate its effects on the overall human comfort level. In the final step, the performance of the PCMs usage as a thermal storage system in the building was investigated. Figure (1.1) shows the methodology flow chart of the present study.

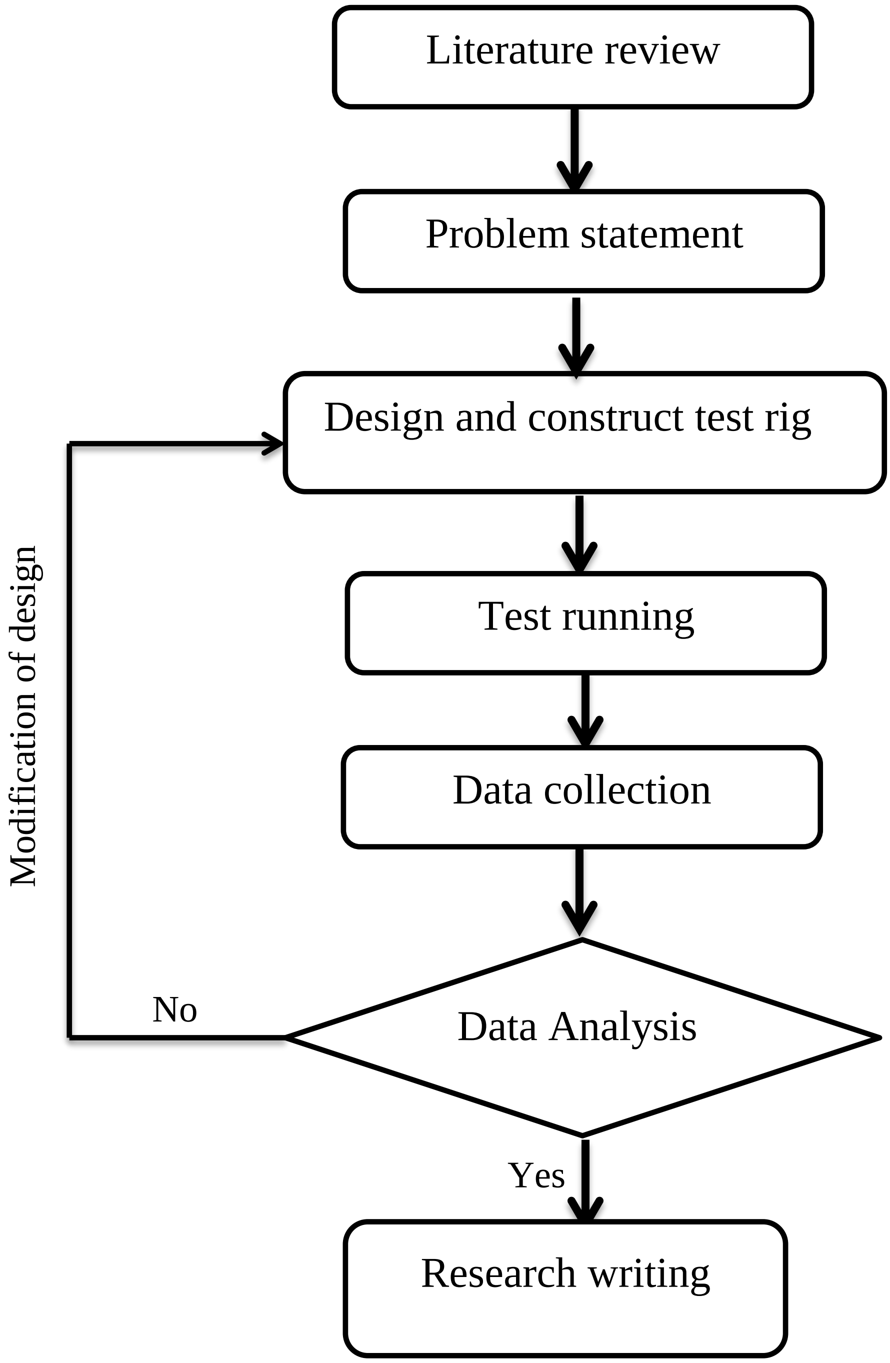

Figure (1.1): Methodology flow chart of test rig.

CHAPTER TWO

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Energy storage plays important roles in conserving available energy and improving its utilization, since many energy sources are intermittent in nature. Short term storage of only a few hours is essential in most applications, however, long term storage of a few months may be required in some applications [16, 17].

Thermal energy storage technology can provide a buffer against the temporal and spatial mismatches between the energy supply and demand processes. It can be stored under two physical methods (sensible and latent heat storage) . High-temperature sensible heat storage (SHS) using solid materials such as rocks, metals, concrete, sand, bricks, and oxide ceramics is one of the fundamental heat utilization technologies available for the current industrial processes .In order to further advance the SHS technology, tailored structures of the solid SHS materials such as grains, balls, checker bricks, and honeycombs have been fabricated to maximize heat transfer. However, innovative materials with high heat storage capacity have not been synthesized [18, 19]. In this context, latent heat storage (LHS) has received considerable attention as an alternative to SHS for high temperature thermal energy storage. LHS is based on the storage or release of latent heat when a phase change material (PCM) undergoes a solid-liquid phase transition.

LHS has the following three advantages over SHS. Firstly, the storage of thermal energy as latent heat yields remarkably high heat storage capacity compared to SHS. Secondly, the PCM can be a constant heat source at the phase change temperature during phase transitions, and thirdly, the reversible phase change process allows for repeated use of the PCM material [20]. For future high-temperature thermal energy storage, the presently used SHS materials need to be replaced with PCMs, which exhibit much higher heat capacity [21].

2.2 Thermal Energy Storage

Thermal Energy Storage (TES) allows heat and cold to be stored which can be used later. It can be stored under two methods: physical methods (sensible and latent heat storage) and chemical methods.

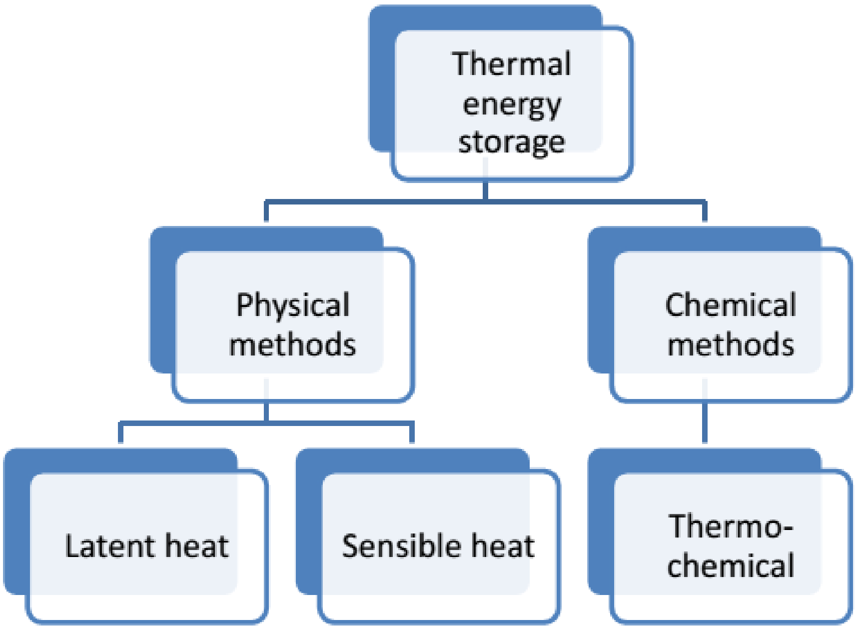

Figure (2.1): Classification of the thermal energy storage [22].

The most commonly observed thermal energy storage is by means of sensible heat. Sensible heat is the amount of heat released or absorbed by a substance during a change of temperature. It can be calculated as a product of mass, specific heat and temperature difference as

$$Q_{SENSIBLE} = m * c_p * \Delta T \qquad (2.1)$$

On the other hand, latent heat is the amount of heat released or stored by a substance during a change of state that occurs without much change in temperature. Figure (2.2) shows the difference between sensible and latent heat storage. Latent heat storage can occur as solid-liquid phase change, liquid-vapor phase change, and solid-solid phase change. For solid-liquid phase change material, the latent heat stored is equal to the enthalpy difference between the solid and the liquid phase [1] and due to the small volume change, the latent heat can approximately be written as

$$\Delta Q_{LATENT} = \Delta H = m * \Delta h \qquad (2.2)$$

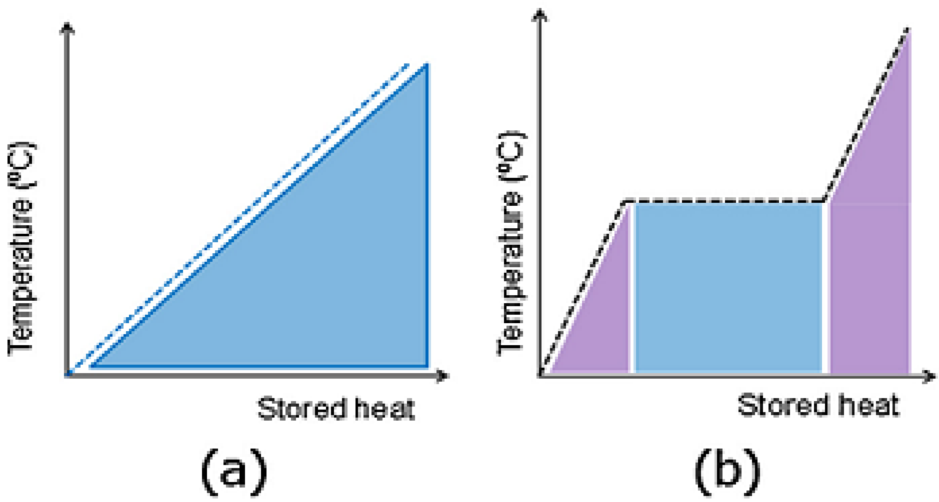

Figure (2.2): Methods of thermal energy storage for (a) Sensible heat ,(b) latent heat.

The storage media employing the solid-liquid phase are commonly known as latent heat storage material or phase change material (PCM). As seen from the latent curve in Fig. (2.2), PCM can be used to store or extract heat without substantial change in temperature. Hence it can be used for temperature stabilization in an application. The main advantage of PCM is that it can store about 3 to 4 times more heat per volume than sensible heat in solids and liquids at an approximate temperature of 20 °C.

2.3 Phase Change Materials

Phase change materials are substances that undergo phase change during the absorption/release of energy from/to the surroundings. The temperature of the material remains constant until the phase changing process is complete, thus a large amount of energy is stored Furthermore, during the solidification process, the stored energy is released. This process of absorbing and releasing of heat energy during melting and solidification is called latent heat of fusion[23, 24] . Latent heat storage can be made possible through solid-solid [25] , solid-liquid, liquid-solid, solid-gas, and liquid-gas phase changing transitions [24, 26] Among these transitions, the solid-liquid phase change is commonly used because it occupies smaller volumes during the transition and besides, it increases energy density. However, the use of other types of transitions is limited due to their low heat transformation and large storage volume requirement [27, 28].

2.4 Classification of PCMs

A large number of phase change materials are available in any required temperature range. A classification of PCMs is given as organic, inorganic and eutectic PCMs. There are a large number of organic and inorganic chemical materials, which can be identified as PCM from the point of view melting temperature and latent heat of fusion. As no single material can have all the required properties for an ideal thermal-storage media, one has to use the available materials to match system designs.

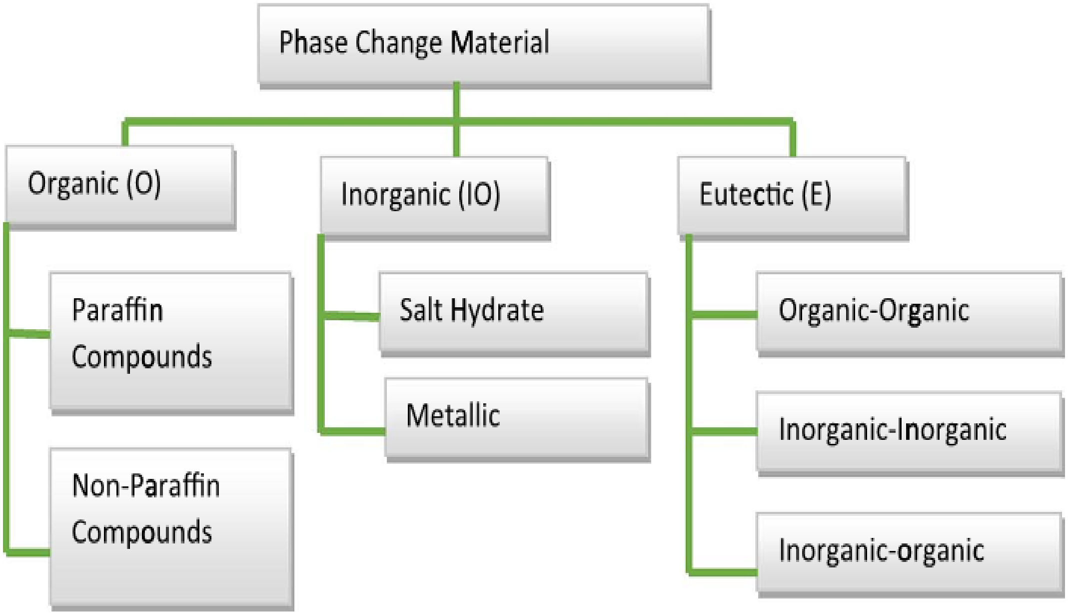

Figure (2.3) : Classification of PCMs [26, 29]

2.4.1 Organic phase change materials

Organic PCMs can be further described as paraffin and non-paraffin types [30]. Most of the organic PCMs are chemically stable, safe and non-reactive. Also, they have an ability to melt congruently without segregation and have self-nucleating properties that are compatible with traditional construction materials without posing any significant problems of super cooling [10].

Table (2.1): Latent heat and melting points of some organic PCMs are suitable for cooling in buildings[26, 31-35].

No	Material	Melting point (°C)	Latent heat (kJ/kg)
1	Glycerin	17.9	198.7
2	Paraffin C16	18.2	238
3	Butyl stearate	19	140
4	Propyl palmitate	19	186
5	Butyl stearate	19	140
6	Propyl palmitate	19	186
7	Emerest 2325	20	134
8	Emerest 2326	20	139
9	Lithium chloride ethanolate	21	188
10	Dimethyl sabacate	21	135
11	Paraffin C17	21.7	213
12	RT20	22	172
13	Polyglycol E600	22	127.2
14	D-Lattic acid	26	184
15	MICRONAL26	26	110
16	MICRONAL 5001	26	110
17	1-dodecanol	26	200
18	Octadecyl thioglyate	26	90
19	n-Octadecane	27	243.5
20	Paraffin C18	28	244
21	Methyl palmitate	29	215
22	Acid Methyl pentacosane	29	197
23	Methyl palmitate	29	205
24	Capric acid	29.62	139.8
25	ERMEST2325	17–20	138
26	Heptadecane	20.8–21.7	172
27	Polyethylene glycol 600	20–25	146
28	Paraffin C13–C24	22–24	189
29	RT27	26–28	179
30	Vinyl stearate	27–29	122

2.4.1.1 Paraffin

Paraffin wax consists of a mixture of mostly straight chain n alkanes $CH_3-(CH_2)-CH_3$. The crystallization of the (CH_3) −chain release a large amount of latent heat. Both the melting point and latent heat of fusion increase with chain length. Paraffin qualifies as heat of fusion storage materials due to their availability in a large temperature range. Due to cost consideration, however, only technical grade paraffins may be used as PCMs in latent heat storage systems Paraffins is safe, reliable, predictable, less expensive and non-corrosive. They are chemically inert, show little volume changes on melting and have low vapor pressure in the melt form. For these properties of the paraffins, system-using paraffins usually have very long freeze–melt cycle.

2.4.1.2 Non-paraffins

The non-paraffin organic are the most numerous of the phase change materials with highly varied properties. Each of these materials will have its own properties unlike the paraffin's, which have very similar properties. This is the largest category of candidate's materials for phase change storage. These organic materials are further subgroups as fatty acids and other non-paraffin organic. These materials are flammable and should not be exposed to excessively high temperature, flames or oxidizing agents. Some of the features of these organic materials are as follows :(i) high heat of fusion, (ii) inflammability ,(iii) low thermal conductivity, (iv) low flash points, (v (varying level of toxicity, and (vi) instability at high temperatures. Fatty acids have high heat of fusion values comparable to that of paraffin's. Fatty acids also show reproducible melting and freezing behavior and freeze with no super cooling The general formula describing all the fatty acid is given by $CH_3(CH_2)_{2n} - COOH$ and hence, qualify as good PCMs. Their major drawback, however ,is their cost, which are (2–2.5) times greater than that of technical grade paraffin's. They are also mild corrosive.

2.4.2 Inorganic phase change materials

Comparing to organic PCMs, inorganic PCMs have higher heat of fusion per unit mass with lower cost and flammability usually [36]. Inorganic materials are further classified as salt hydrate and metallic. These phase change materials do not supercool appreciably and their heats of fusion do not degrade with cycling.

2.4.2.1 Salt hydrates

Salt hydrates may be regarded as alloys of inorganic salts and water forming a typical crystalline solid of general formula $AB.nH_2O$. The solid–liquid transformation of salt hydrates is actually a dehydration of hydration of the salt, although this process resembles melting or freezing thermodynamically. A salt hydrates usually melts to either to a salt hydrate with fewer moles of water, i.e.

$$AB\ .\ n\ H2O \rightarrow AB.\ m\ H2O + (n - m)\ H2O$$

Or to its anhydrous form

$$AB\ .\ n\ H2O \rightarrow AB + n\ H2O$$

At the melting point the hydrate crystals breakup into anhydrous salt and water, or into a lower hydrate and water. One problem with most salt hydrates is that of incongruent melting caused by the fact that the released water of crystallization is not sufficient to dissolve all the solid phase present. Due to density difference, the lower hydrate (or anhydrous salt) settles down at the bottom of the container. Most salt hydrates also have poor nucleating properties resulting in super cooling of the liquid before crystallization beings. One solution to this problem is to add a nucleating agent .Salt hydrates are the most important group of PCMs, which have been extensively studied for their use in latent heat thermal energy storage systems. The most attractive properties of salt hydrates are: (i) high latent heat of fusion per unit volume, (ii) relatively high thermal conductivity (almost double of the paraffin's ,(and (iii) small volume changes on melting. They are not very corrosive, compatible with plastics and only slightly toxic. Many salt hydrates are sufficiently inexpensive for the use in storage [37].

Table (2.2): Latent heat and melting points of some salt hydrates [32-34, 36].

No	Material	Melting point (°C)	Latent heat (kJ/kg)
1	$KF \cdot 4H_2O$	18.5	231
2	$K_2HPO_4 \cdot 4H_2O$	18.5	231
3	$FeBr_3 \cdot 6H_2O$	21	105
4	$Mn(NO_3)_2 \cdot 6H_2O$	25.5	148
5	$LiBO_2 \cdot 8H_2O$	25.7	289
7	$FeBr_3 \cdot 6H_2O$	27	105
8	$CaCl_2 \cdot 6H_2O$	29	191
10	$CaCl_2 \cdot 12H_2O$	29.8	174
12	$LiNO_3 \cdot 2H_2O$	30	296
13	$LiNO_3 \cdot 3H_2O$	30	189

2.4.3 Eutectics

Eutectic PCMs consist of a combination of at least two other PCMs .During the freezing process they form a blend crystal [38] .This mixture can consist of inorganic with inorganic, organic with inorganic and organic with organic [39] .Comparison of organic, inorganic and eutectic PCMs [34].

Table (2.3): Latent heat and melting points of a selection of eutectic PCMs [26, 32-34, 36]

No	Material	Melting point (°C)	Latent heat (kJ/kg)
1	Capric + lauric acid	21	143
2	Capric + myrstic	21.4	152
3	Capric + palmitate	22.1	153
4	Methyl stearate + cetyl stearate	22.2	180
5	Capric acid + myristic acid	22.6	154.8
6	Methyl stearate + methyl palmitate	23.9	220
7	$C_{14}H_{28}O_2 + C_{10}H_{20}O_2$	24	147.7
8	$Na_2S_4 + MgSO_4 + H_2O$	24	n.a.
9	$C_{14}H_{28}O_2 + C_{10}H_{20}O_2$	24	147.7
10	Tetradodecanol + lauric acid	24.5	90
11	Capric acid + stearic acid	24.7	178.6
12	$CaCl_2 + MgCl_2 \cdot 6H_2O$	25	95
13	$CaCl_2 \cdot 6H_2O$ + Nucleat + $MgCl_2 \cdot 6H_2O$	25	127
14	Capric + stearate	26.8	160
15	$CH_3CONH_2 + NH_2CONH_2$	27	163
16	Methyl stearate + cetyl palmitate	28.2	189
17	Triethylolethane + urea	29.8	218
18	$Ca(NO_3) \cdot 4H_2O + Mg(NO_3)_3 \cdot 6H_2O$	30	136
19	$CH_3COONa \cdot 3H_2O + NH_2CONH_2$	30	200.5
20	$CaCl_2 + NaCl + KCl + H_2O$	26–28	188

Table (2.4): Comparison of organic, inorganic and eutectic PCMs [34]

	Organic	**Nonorganic**	**Eutectic**
Advantages	1. No corrosives 2. Low or none subcooling 3.Chemical and thermal stability 4.Compatibility with conventional construction materials	1. Greater phase change enthalpy 2. High thermal conductivity 3. Inexpensive	1. Sharp melting temperature 2. High volumetric thermal storage density (slightly higher above organic
Disadvantages	1.Low phase change enthalpy 2. Low thermal conductivity 3. Flammability	1.Supercooling 2.Corrosion 3.Phase segregation 4.Lack of thermal stability	1.Limited tested data available due to thermo physical properties

2.5 Selection Criteria for PCMs in Buildings

PCMs can reduce the energy needs of cooling systems and indoor temperature fluctuations, however, for PCMs to be effectively implemented for cooling in the building envelope, several selection criteria must be considered. From a physical point of view, the melting point of the PCM should be in the range of 10°C to 30°C to provide thermal comfort for occupants. This temperature should be selected with respect to average day 06 and night temperatures and other climatic conditions of the building site [40, 41].

Thermodynamically, the PCM should have high latent heat per volume unit, which is an important factor in building applications because it means that with lower volume, the PCM can absorb/ release higher amounts of energy leading to a lighter building envelope [42]. Moreover, it should also have a large specific heat capacity (C_p) [43].

Another significant thermodynamic factor is its heat transfer ability (conductivity). Higher conductivity results in faster thermal responses. Even though the thermodynamic properties are the main selection criteria for the use of a PCM, other important properties are related to its chemical aspects, including chemical stability, low volume expansion and low/no super cooling during freezing; it is also important for PCMs to be non-toxic, noncorrosive, nonflammable and non-explosive [41, 42, 44] . Furthermore, a PCM is suitable for applications if it is stable after a number of repeated melting/freezing cycles which called long-term stability [36].

Final qualification, which overshadows all other aspects, is economics. A PCM needs to have a reasonable price and availability on the market [26, 45, 46].

In summary, the physical requirements for a PCM are to have a suitable phase change temperature, a completely reversible freeze/melt cycle, a large change in enthalpy (Δh), a large specific heat capacity (C_p), a large thermal conductivity (k) and little sub -cooling. The chemical requirements are small volume, low vapor pressure, chemical stability, physical stability, non-toxicity and good compatibility with other materials. The economic requirements are low price and being recyclable and abundant.

2.6 Current Studies on PCM

Several researchers have proposed the incorporation of PCMs into different compartments of buildings, e.g. wallboards, walls, floors and ceilings, and shutters. They used different incorporation methods for PCM including traditional methods such as direct incorporation, immersion, macro-encapsulation, shape-stabilization, and microencapsulation.

2.6.1 PCM in roofs

In this research [47], experimental evaluation of organic-based BioPCM in the building envelope is discussed and compared with traditional building construction without it . The experimental work was carried out at the Arizona Public Service (APS) Solar Testing and Research (STAR) center in Tempe, Arizona (in the Phoenix metropolitan area) The data were collected for the entire 2008 calendar year .The set up consists of two nominally identical sheds as shown in Fig 2.4, named as the "North" and "South" sheds with length, width and height as 4.876 m x 3.657 m x 2.43 6m (16'' x 12'' x 8'') and with a 4/12 pitch roof.

Figure (2.4) Experimental Setup of South (non BioPCM) Shed and North (BioPCM) shed.

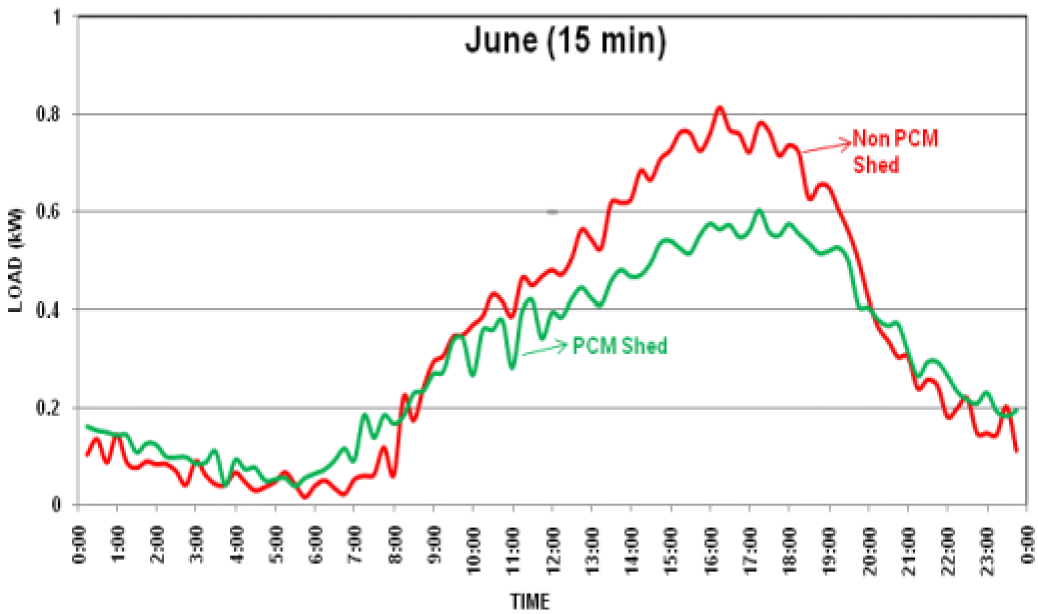

Figure (2.5) Experimental Peak Curve for June (15 min).

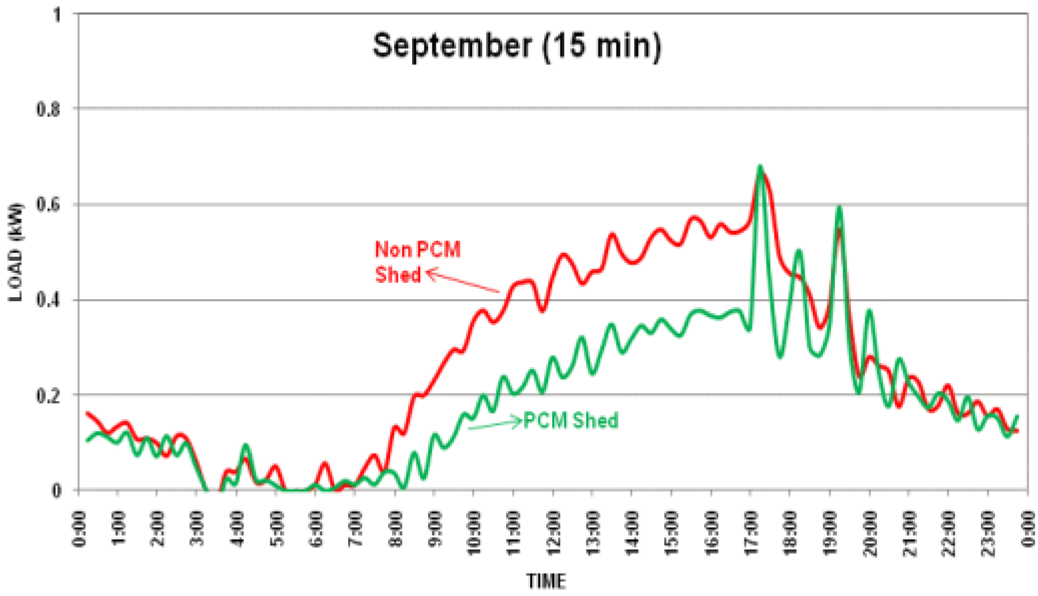

Figure (2.6) Experimental Peak Curve for September (15 min).

The PCM temperature variation yielded good results for the range of 23 to 27° C with huge energy savings and maximum peak load time shift.

A PCM cool roof system was created using PCM doped tiles as shown in Figure (2.7) [48] .The results indicate that the PCM doped tiles had a significant effect on reducing building surface temperatures and chamber temperatures. PCM doped tiles demonstrated the lowest diurnal variation with 7.2 °C. Figure (2.8) shows the concept of PCM Cool Roof System.

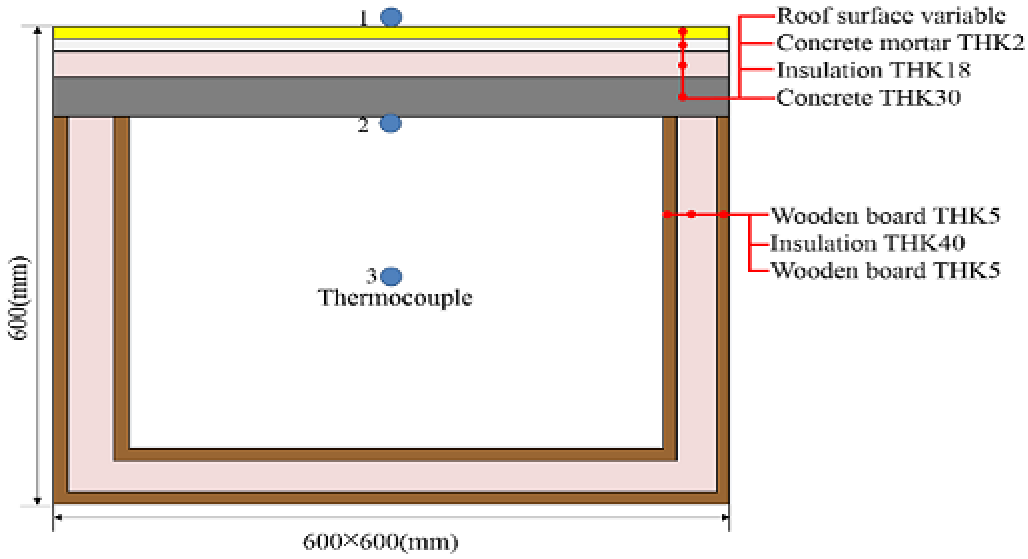

Figure (2.7): The scale model and thermocouples location [48].

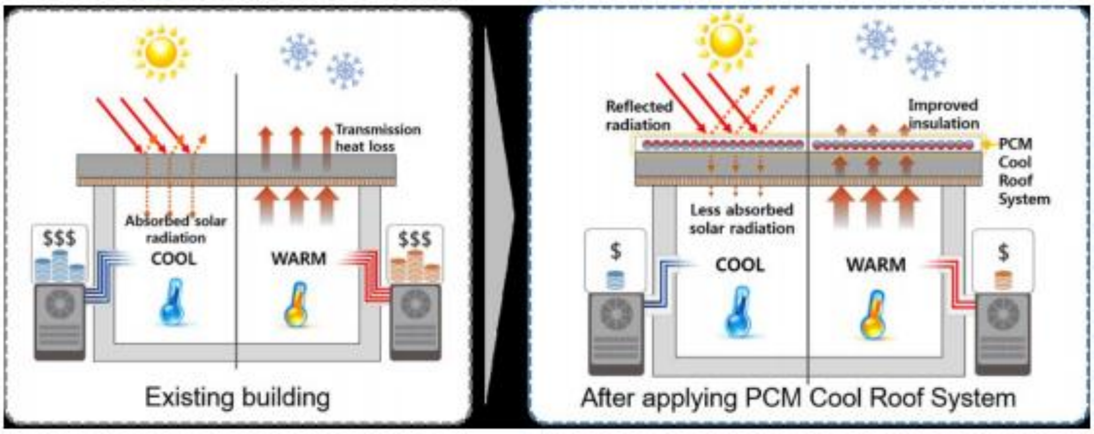

Figure (2.8): Concept of PCM Cool Roof System [48].

An array of identical wood-framed test huts was built on the Tamaki Campus, University of Auckland, New Zealand [49, 50]. As shown in Figure (2.9), the test huts were elevated from the ground. Gypsum boards were impregnated with 27 wt % of PCM with a melting range of (18–23) ℃ and a latent heat of fusion of 134kJ/kg. One of the observations was that the additional thermal mass of the PCM can reduce the daily indoor space temperature fluctuation by up to 4 °C on a typical summer day.

Figure (2.9): Wood-framed test huts built for PCM testing on the Tamaki Campus , University of Auckland, New Zealand [49, 50].

A full-scale experimental test was conducted with two rooms of identical internal dimensions in the presence and absence of PCM. Figure (2.10). The implementation of the PCM in the building [51] structures reduced the room temperature peak load by 5 °C for the same time period .This lowering in the peak temperature inside the room and the creation of thermal comfort is attributed to the effect of the heat storage capacity of the PCM on the temperature variation.

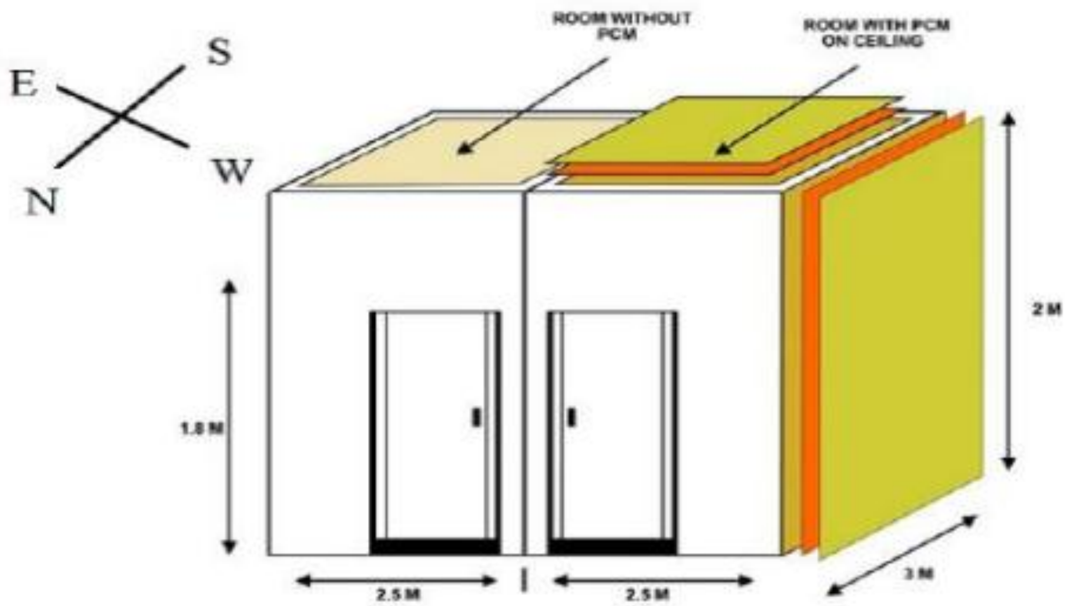

Figure (2.10): Geometry of the constructed test rooms, reference room (REF) (left, without PCM) and PCM2 (right).

2.6.2 PCM in concrete mix

In a research that used PCM in concrete mix [52] The purpose of the research is to determine the impact of PCM (Phase Change Materials) to reduce thermal gradients within the concrete mix in the initial phase of maturing Phase change material used in the research is BASF granules (Micron ®). Polymer balls are filled with organic PCM material. This material has the ability to absorb heat when the temperature of the mixture exceeds 26°C, and release the heat when the temperature goes down below 25°C.

For the research purposes, concrete mix with the addition of PCM materials in amount of 3.5% and sample size (50x0.50x 0.15) m^3 has been prepared. There are three sensors in this sample: on the bottom, in the middle and on the surface of the sample. The fourth sensor measures the temperature in the climatic chamber. For comparison, the same was executed in parallel sample of the same size, with the addition of PCM materials, and retarders. Third of the sample has the same dimensions, but without any additives. The temperature of the output of all the slabs was about 30 °C. The thickness of all slabs was the same of: 0.2 m, all of the samples were placed in a climatic chamber. The following graphs show temperatures progress in the three samples.

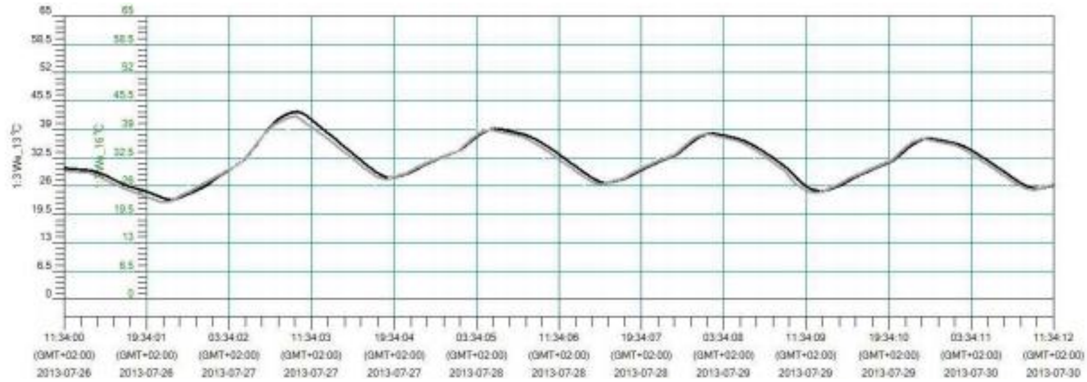

Fig. (2.11) Temperature progress in concrete with 3,5% PCM.

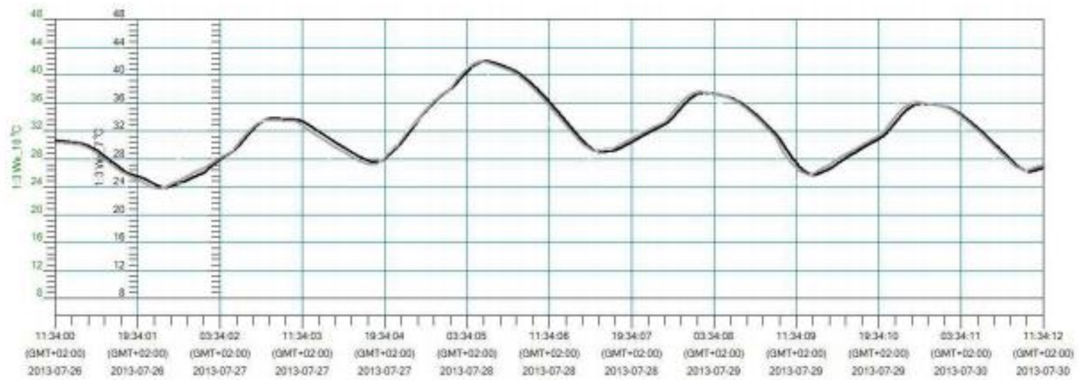

Fig. (2.12) Temperature progress in concrete with 3,5% PCM and retarder.

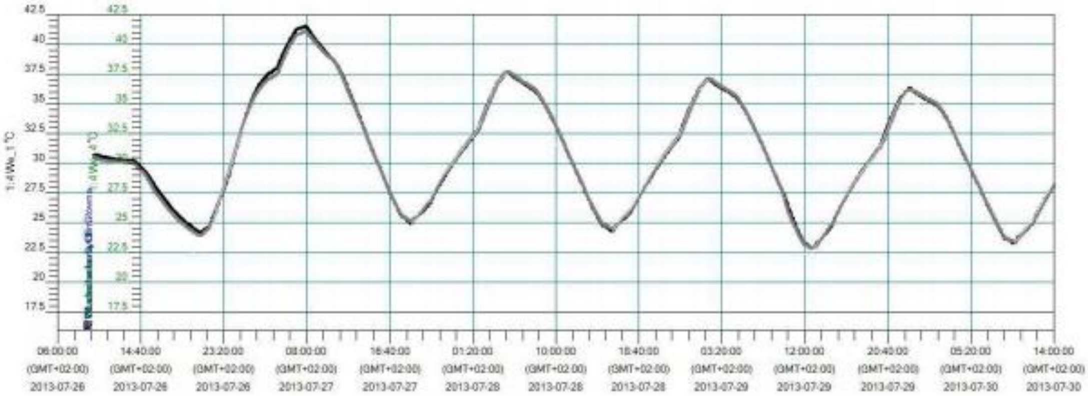

Fig. (2.13) Temperature progress in concrete without additives.

The use of PCM materials reduces thermal gradients and unifies the temperature inside the concrete mix. Through the use of PCM material, it is possible to concrete during high temperatures in dry, hot climates. The use of PCM material provides the right temperature of the concrete mix in the initial phase of maturation. Phase change type materials improve the heat exchange with the environment.

This research [53] investigates a new type of concrete blocks which integrates a form-stable PEG/SiO_2 composite PCM with the melting temperature of 28 C and the latent heat of 113.6 kJ/kg.

The thermal performance of the PEG/SiO_2 composite PCM concrete for indoor thermal management in passive solar buildings was investigated using a test chamber, the walls of which were made of the composite PCM concrete. For comparison, another identical chamber with conventional concrete walls was built as well .Figure (2.14) shows the schematic diagram of the test chamber, which has the dimensions of (60 cm x 60 cm x 60 cm). The chamber has a glazing window, three side walls, one floor and one roof.

In order to collect the maximum solar radiation throughout the year, the lazing window is 30 south by west oriented. Each of the three side walls is constituted by a polyvinyl chloride (PVC) panel of 3 mm thickness, an expanded polystyrene (EPS) panel of 8 mm thickness and a 20 mm thick concrete wall panel with or without PCM. For the roof and floor, the same PVC and EPS panels were used, but no concrete wall panels were placed.

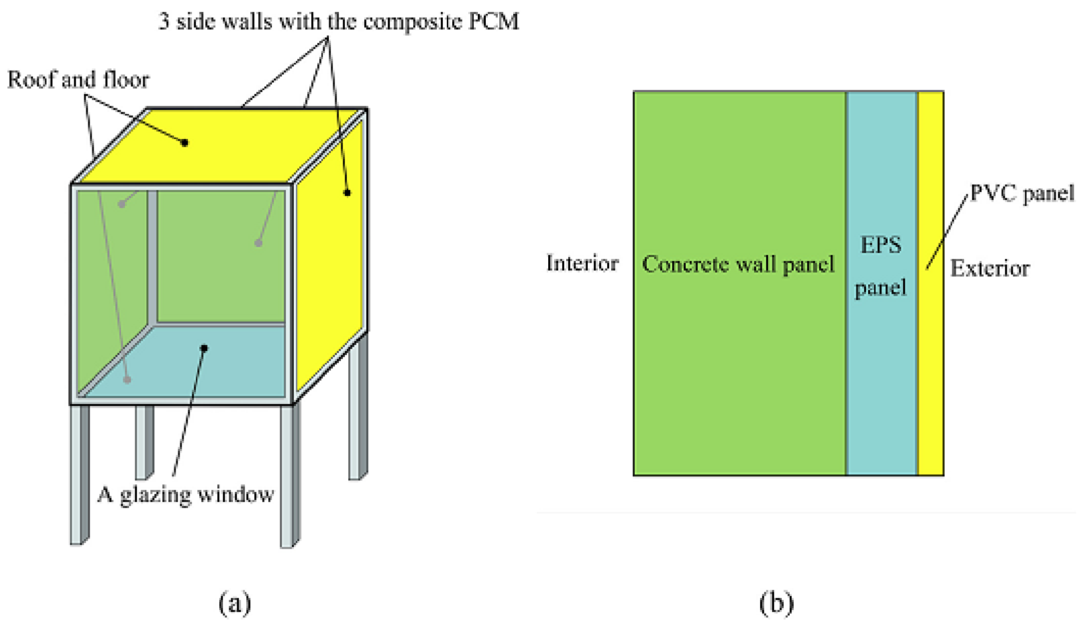

Fig. (2.14) Schematic diagram of the test chamber: (a) configuration of the chamber, (b) constitution of the side walls

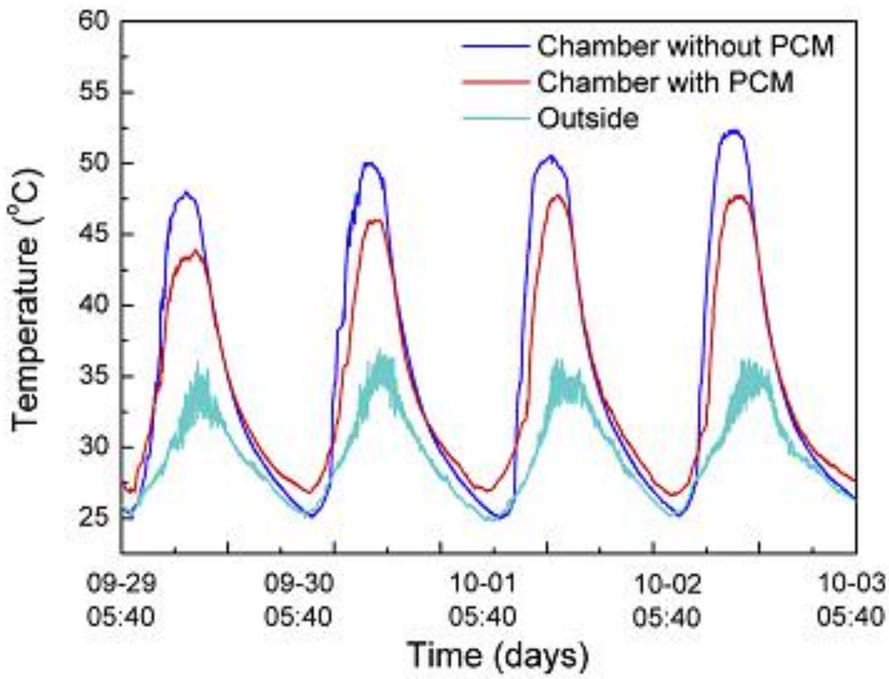

Fig (2.15) Temperature profiles of the test chambers (with and without PCM)

Thermal performance of passive solar chamber could be markedly improved by using the PCM concrete. Compared with the reference case, the chamber with PCMs represented a gentle fluctuation of temperature, reducing the maximum temperatures by (2.8-4.6) ℃ and improving the minimum temperatures by (1.4-1.8) ℃.

2.6.3 PCM in walls

The thermal performance was investigated for two new PCM systems incorporated into building envelopes using full - scale experiments method [54]. In the experimental study, panels containing Caprice acid (PCMOW) as well as Caprice acid and 1-dodecanol (PCMIW) were installed on the outside and inside surfaces of the walls and roofs, as shown in Figure (2.16).

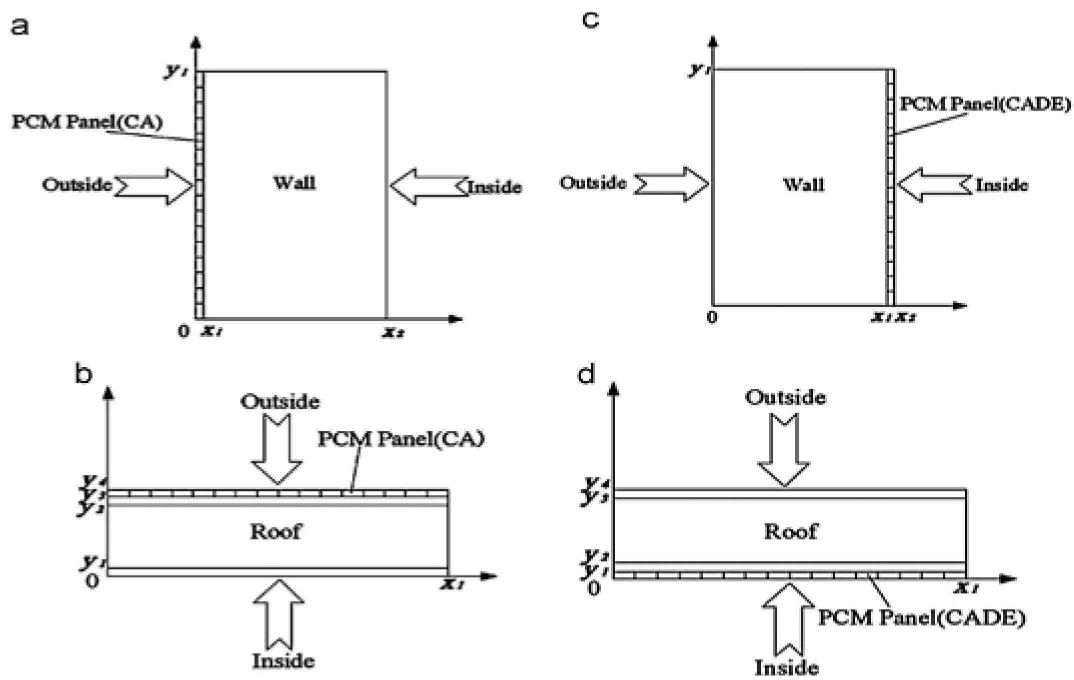

Figure (2.16): Structure of the building envelope for (a , b) the PCMOW and for (c , d) the PCMIW [54].

Experimentally the performance of shaped-stabilized PCM was evaluated [55].As shown in Figure (2.17), they used two similar rooms (experiment unit and control room) to analyze the PCMs effectiveness in reducing the indoor temperature fluctuations. The results showed that the thermal performance of PCMIW was better than PCMOW, particularly for the condition of opening the window and door at night Figure (2.18).

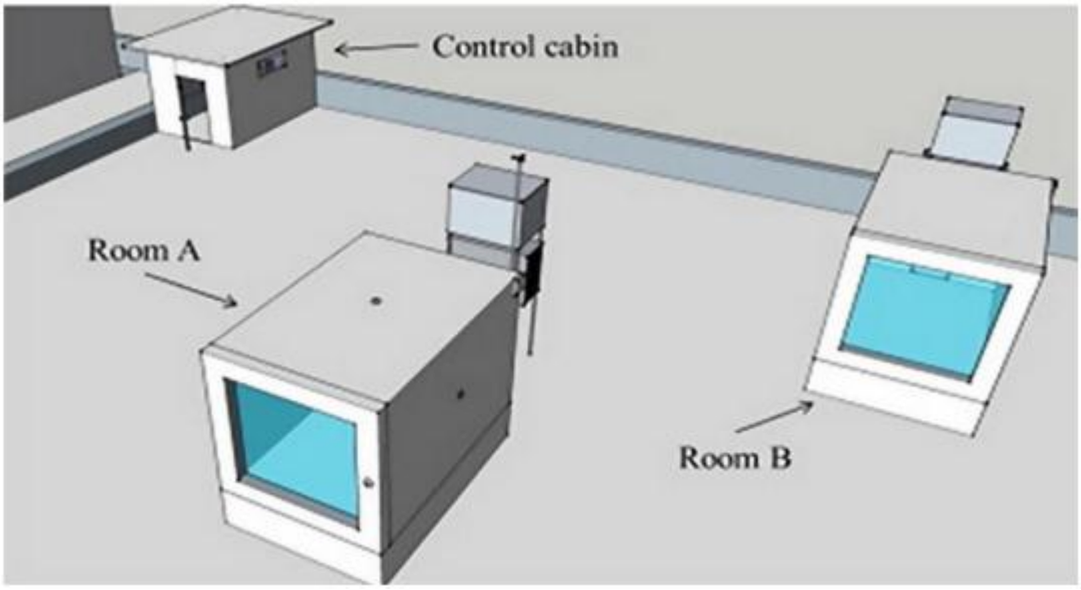

Figure (2.17): Schematic diagram of the experiment units and the control room [55].

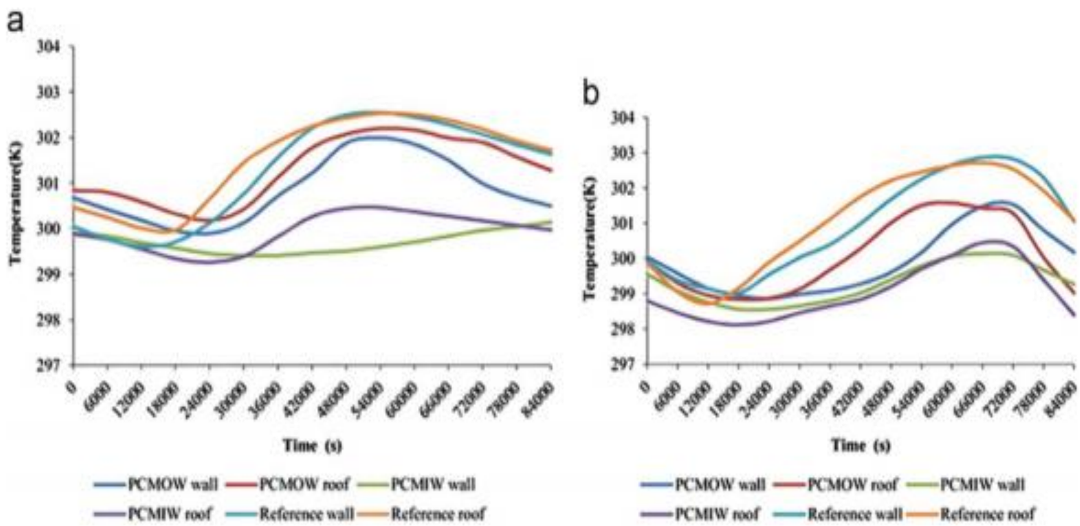

Figure (2.18): Temperature variations of the wall and roof for PCMOW, PCMIW and reference rooms for the condition of free cooling (left) and for the condition of opening the window and door at night (right) [56].

A full-scale experimental test was conducted for a Nano-PCM enhanced interior wallboard in a natural exposure test facility in the hot and humid climate of the USA [57]. Figure (2.19) depicts the test wall of the NET facility with PCM-enhanced wallboards. The results indicate that at a 22°C room temperature set point, the highest heat gain reduction per year was observed for the south- oriented wall.

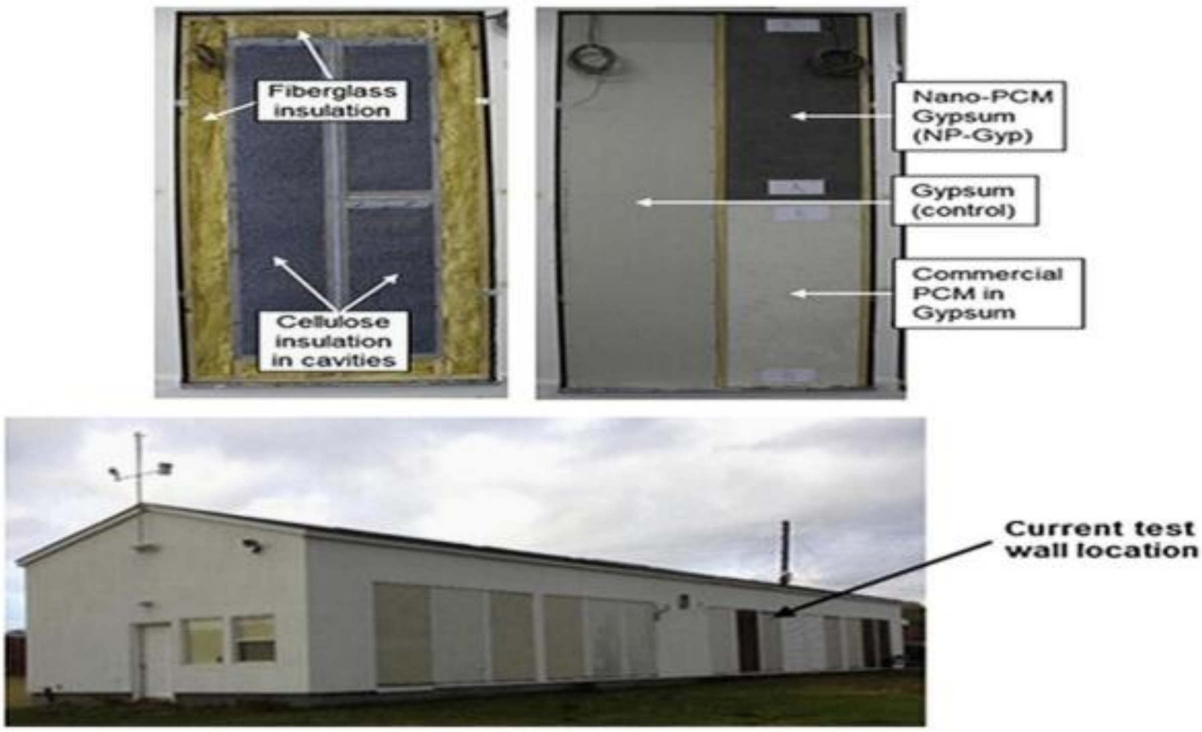

Figure (2.19): Test wall with the PCM-improved wall boards (upper panel), the location of the test wall on the south east façade of the building (lower panel) [57].

In this research [58] The performance of a bio-based phase change material (PCM) was experimentally investigated in two identical full scale test huts exposed to the exterior environment. A layer of PCM enclosed in protective lightweight plywood sheets were added on the inside of 50% of the walls (excluding floor and ceiling) in one of the test huts. Five months of data were recorded in 2013, from the end of

February y to the end of July. Several scenarios were tested for heating and cooling applications and clear differences were observed between both huts.

The selected material is a bio-based PCM (biodegradable and composed of soybean and palm oils) with a phase change temperature of 23 °C. It is mixed with a gelling agent the installation of the PCM in the test huts was conducted as presented in Figure (2.20).

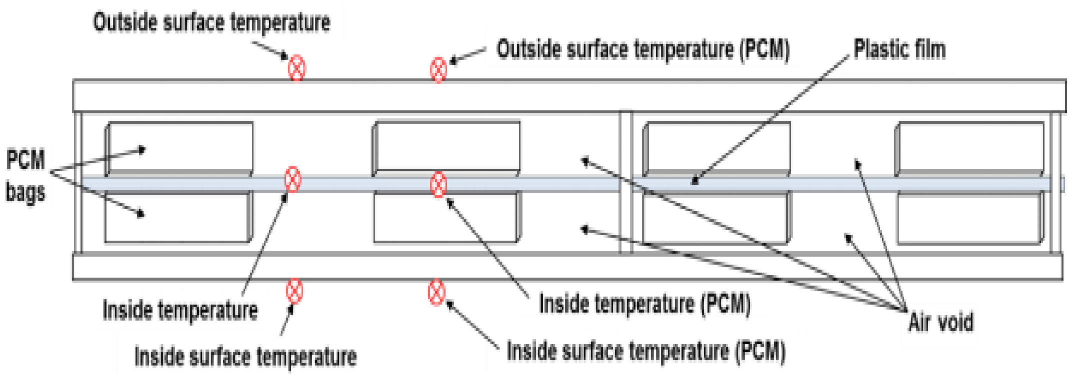

Figure (2.20): PCM-equipped panel (test hut with PCM)

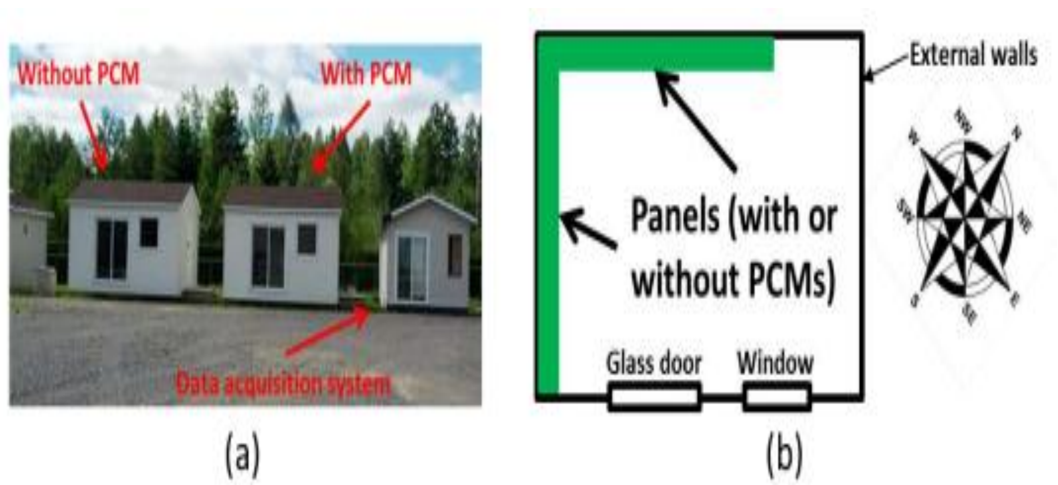

Figure (2.21): (a) Photo of the test bench and (b) top view of a test hut with its orientation

Table 2.5: dimensions of the test hut

Measures	Unit	Value
Length	m	5.49
Width	m	3.66
Height	m	2.44
Glazed door surface	m^2	3.91
Window surface	m^2	1.19

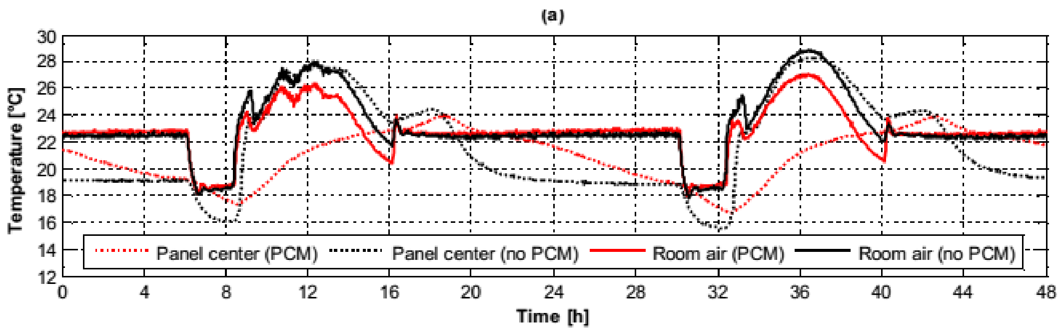

Figure (2.22): (a) Evolution of temperatures inside the test huts and in the center of the panels (with and without PCMs) during residential workday scenario

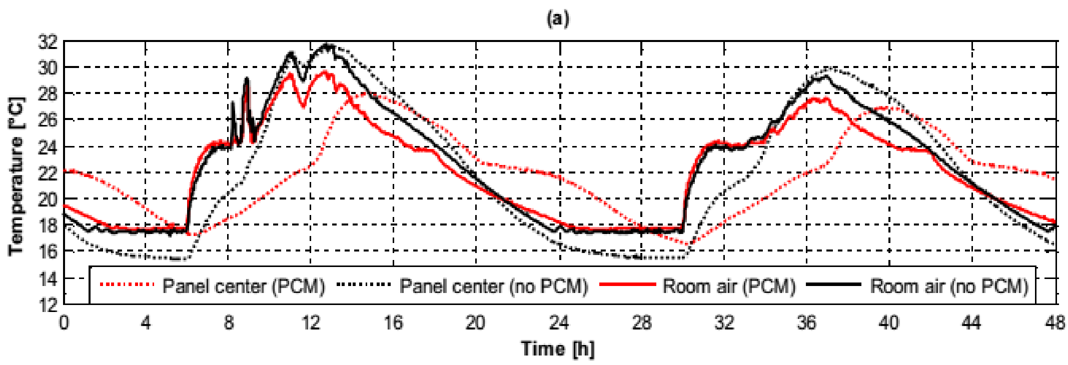

Figure (2.23): (a) Evolution of temperatures inside the test huts and in the center of the panels (with and without PCMs) during CI scenario

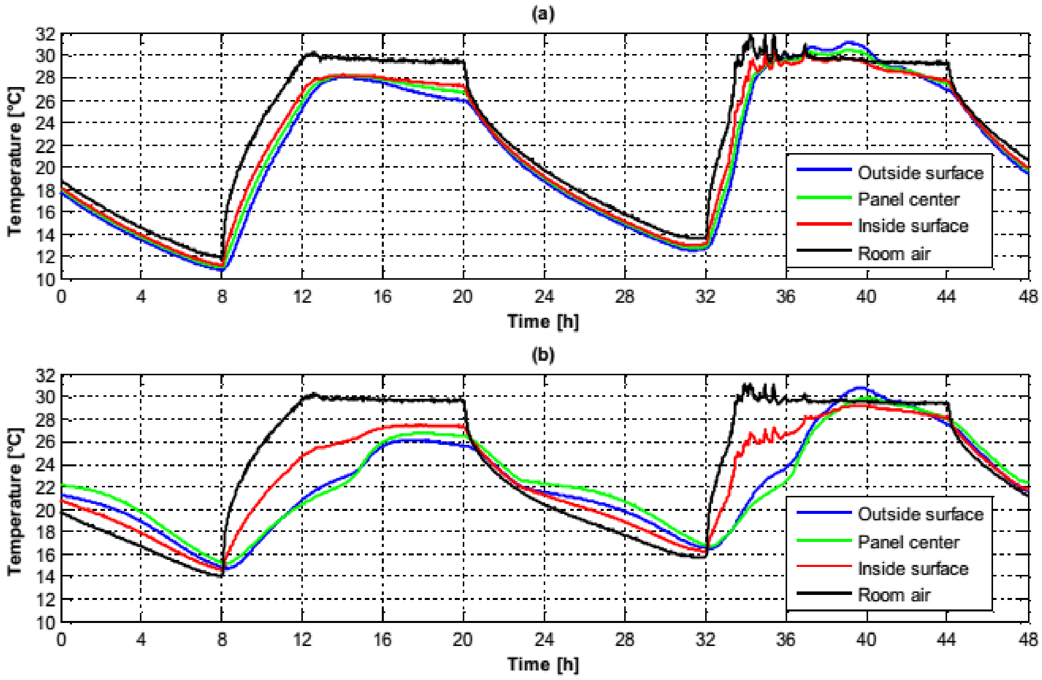

Figure 2.24: Evolution of the temperature gradient in the panel without (a) and with (b) PCM during the extreme set-back scenario (13-04 and 14-04).

Scenario	Date	Set-point			
Constant set-point	28-02 → 11-03	23 °C			
Residential workday set-point	11-03 → 22-03	6:00 AM		4:00 PM	
		↓ 19 °C		↑ 23 °C	
Commercial and institutional (CI) set-point	25-03 → 28-03	6:00 AM		6:00 PM	
		↑ 24 °C		↓ 18 °C	
Early morning preheating set-point	28-03 → 05-04	3:00 AM	6:00 AM	9:00 AM	8:00 PM
		↑ 25 °C	↓ 20 °C	↑ 22 °C	↓ 18 °C
Extreme set-back	08-04 → 30-04	8:00 AM		8:00 PM	
		↑ 30 °C		↓ 5 °C	

Table 2.6: Tested scenarios

Measured data have shown a significant increase of the thermal mass which allows some attenuation and time shifting of the temperature extremes. In terms of peak heating demand, results have shown that PCMs offer an advantage when the set-point during the day is higher than during the night. The combined effect of the solar radiation and a higher set-point allows storing more energy in walls during the day, which delays and decreases the heating demand during the night. This effect also affects positively the heating consumption.

2.6.4 PCM in the floor

A small-scale experiment was conducted to evaluate the thermal performance of a hollow concrete floor panel filled with PCM [59]. The main purpose of the PCM floor was to enhance the internal comfort without using an air conditioning system, which can be achieved through the melting and solidification processes during the day time and night time. The concrete hollow floor slab used in the study is shown in Figure (2.25). The PCM was able to completely store 70% of the heat energy and shifting heat gains to the evening.

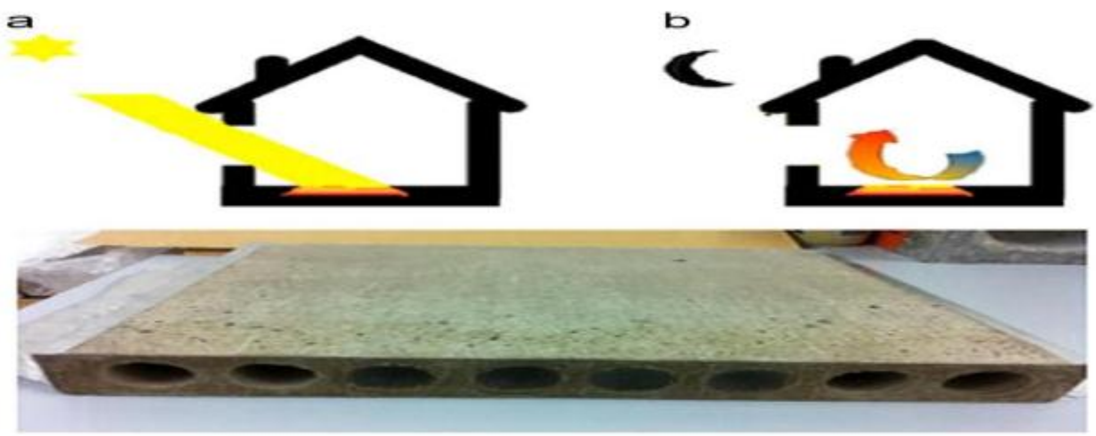

Figure (2.25): Diagram of the use of an internal thermal mass in the PCM floor panel during (a) the day time and (b) the night time and the concrete hollow floor slab.

PCM-enhanced floor systems were tested and analyzed in four plastic containers with dimensions approaching (1.0 × 1.0 × 0.5) m these sizes made the test boxes approximate a scale of 1 to 5, compared to the reference Dutch residential city buildings as shown in Figure (2.26). Two out of the four test containers had the floors containing microencapsulated paraffinic PCM, of melting temperature around 23°C. The experiment has shown that indoor peak space temperatures can be reduced with up to 4.0 and 3.7 °C in the test containers using PCM-enhanced floors, for heavy and light insulated envelope configurations, respectively [60, 61].

Figure (2.26): University of Twente test boxes for PCM floor testing [60, 61].

CHAPTER THREE

CHAPTER THREE

METHODOLOGY

3.1 Introduction

In this research the methodology was used to evaluate the performance of the PCM systems in the buildings using concrete as a basic material . The test room with PCM was constructed to determine its effect on the roof for thermal management of a residential building.

3.2 Location

The experimental work was carried out at Khartoum according to the record from the meteorological administration (Figure (3.1)).

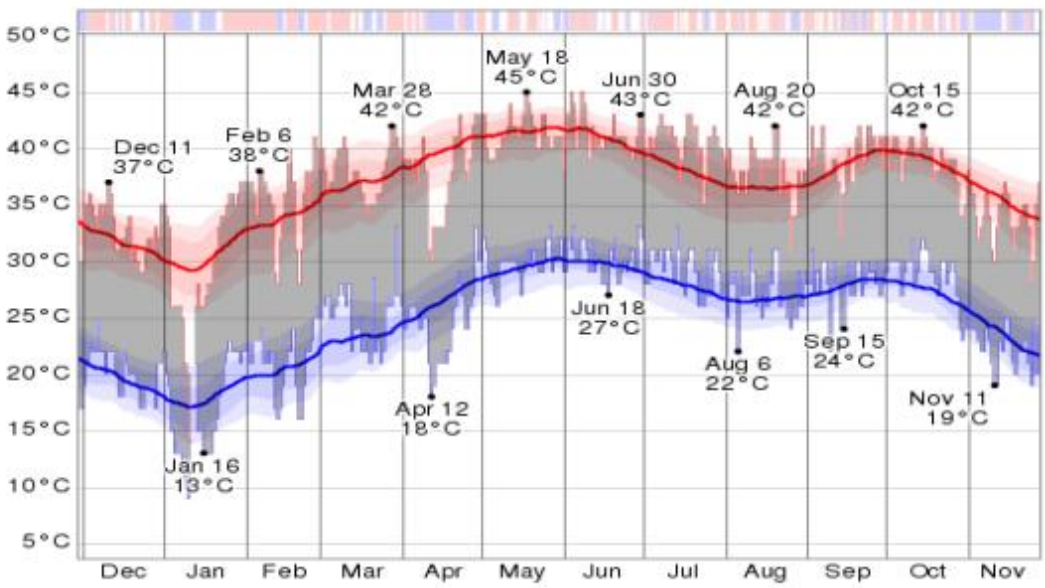

Figure (3.1): The distribution of the temperature on Khartoum in 2015.

3.3 Design

The concrete with thermal properties are [62]: a density of 2350 kg/m^3, heat capacity of 1000 J/kg.K, a thermal conductivity of 1.5 W/m.K, an emissivity of 0.90, and a solar absorptivity of 0.65 was used as construction material in the two models shown in Figure (3.2). The thickness of concrete block is 20cm and the dimensions of the two models are (60 cm x 60 cm x 60 cm).

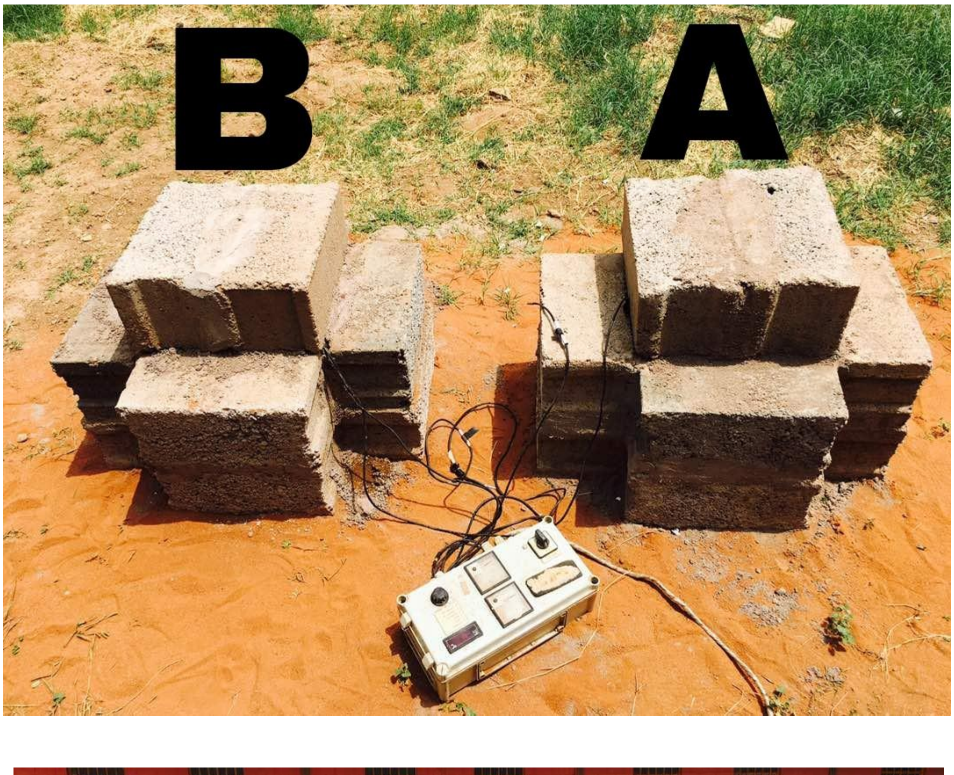

Figure (3.2): Two small-models, model (A) without PCM and model (B) with PCM

3.4 Experimental Setup

The roof is the main source of thermal loss in the building envelope. The reflective roof is good for increase cooling load and also reducing heating load. This research proposes a roof material containing Phase Change Material (PCM) to assess the feasibility of a PCM cool roof system. In this research direct incorporation was used to implement the PCM into the roof. This experiment was used two models, one model without PCM (model A) and another one with PCM (model B).

3.5 Experimental Parameters

Experimental parameter is an element of a system that is useful to measure any characteristic and define the system, which can help to achieve the experimental setup.

3.4.2 Phase Change Material

The PCM was selected based of the melting temperature recommended by the ASHRAE guidelines. For comparison purposes we use two types of PCM with different melting point the first one was Calcium Chloride Hexahydrate ($CaCl_2.6H_2O$) (shown in Figure (3.3)) whose latent heat is 187.8 kJ/kg.K and the melting point is 30 ℃. The thermal conductivity of the material is 0.538 W/m.K and the density is 1760 Kg/m³ at solid form and 1910 Kg/m³ at liquid form [62], The available mass of PCM is 1 Kg.

Figure (3.3): Calcium Chloride Hexahydrate (as PCM).

The second type of PCM was Polyethylene Glycol (PEG) 600 ($H(OCH_2CH_2)_nOH$) whose latent heat is 147 kJ/kg.K and the melting point is 20 ℃, the density is 1120 Kg/m³ at liquid form , The available mass of PCM is 1.3 Kg .

Figure (3.4): Polyethylene Glycol (PEG) 600 (as PCM).

3.4.3 Thermocouple

The thermocouple type K was used (shown in Figure (3.5)) which measures at temperature range (200 - 1260)°C. The thermocouple has four sensors to measure the temperature inside and outside the two models. The sensors No (1) measures the temperature of the PCM and (2) measure the temperature inside the models with PCM. The sensor No (3) measures the temperature inside the models without PCM. The sensor No (5) measures the ambient temperature.

Figure (3.5): Thermocouple type K.

3.4.4 Zinc vessel

The zinc vessel was used as a container for PCM as shown in Figure (3.6). A cover made from tin was used to protect PCM from impurities. The zinc has density 7130 kg/m^3 and thermal conductivity of 117 W/m.K [56]with thickness 0.3 mm. The tin has thermal conductivity of 240 W/m.K [56].

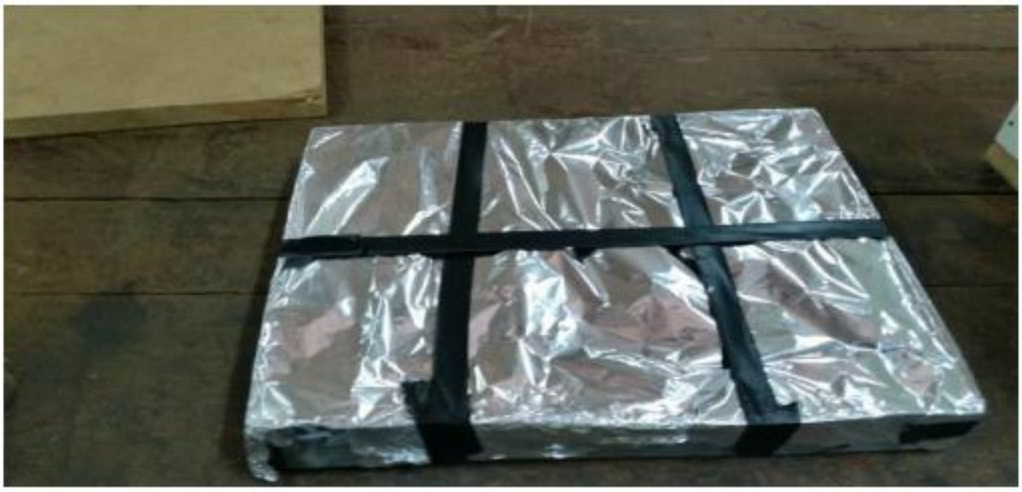

Figure (3.6): Zinc vessel with tin cover.

3.4.5 Fan

A fan (Figure (3.7)) was used as active system to increase the rate of heat transfer from indoor air to the PCM. The fan was connected to an electrical source to make it at work mode.

Figure (3.7): A fan using for increasing the rate of heat transfer

3.5 Experimental Procedures

Figure (3.8) shows the main test part in this experiment. The zinc vessel was carefully filled with a molten Calcium Chloride Hexahydrate $(CaCl_2.6H_2O)$ as PCM. Once completed this process, the Calcium Chloride Hexahydrate was cooled down at cooling conditions. Then, the vessel was put in the model A. K-type thermocouples are used to measure the temperature. Four thermocouples are attached to the indoor air temperature inside model A and B, the PCM sheet, and the ambient temperature as shown in Figure (3.8). The recordings were taken every 5 minutes.

The experiment was repeated several times and the average value was calculated. The same procedures carried out with molten Polyethylene Glycol (PEG) 600 $(H(OCH_2CH_2)_nOH)$ as PCM. Also fan has been used on other experiment for increasing the rate of heat transfer.

Figure (3.8): Experimental setup of two small-scale models.

CHAPTER FOUR

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained in the experimental setup. All data presented in these studies were an average value taken from several experiments at the same conditions.

4.2 Experimental result and discussion

The design and construction for test rig of concrete model was completed as shown in Chapter three section (3.3) Figure (3.2) The experiment was conducted and repeated several times and the average value was calculated. Two types of PCMs (Calcium Chloride Hex hydrate - Polyethylene Glycol 600) were used for comparison purposes.

4.2.1 Results of Calcium Chloride Hex hydrate

Figure (4.1) below shows the result of Calcium Chloride Hex hydrate as PCM in concrete model.

From figure (4.1) below the X- axis shows the time period and the Y- axis shows temperature. As shown in Figure (4.1) the temperature of the room with PCM was found to be less than the one without. The temperature of the room with PCM was found to increase for 30 minutes and increased after this period, however still less than the room temperature without PCM due to the heat absorbed by the room roof exposed to the sun, which caused an inner increase of the temperature.

The temperature difference in this period of the room temperature with PCM compared to the room temperature without PCM was found nearly between (1 to 3) ℃ and The mean reduction was 2 ℃.

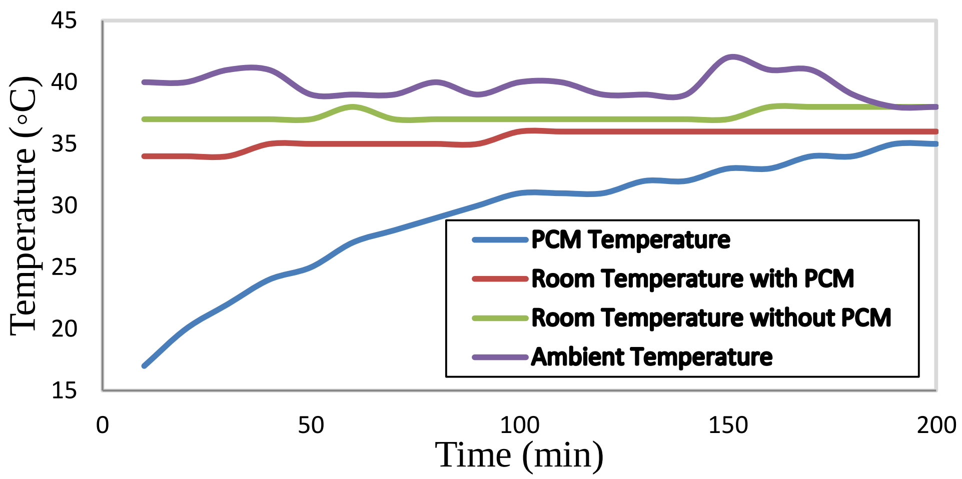

Figure (4.1): The temperatures average variation over time period.

Figure (4.2) shows the result of Calcium Chloride Hex hydrate as PCM in wood model [63]. the PCM in the building structure using wood reduced the room temperature peak load by (3 -4) ℃.

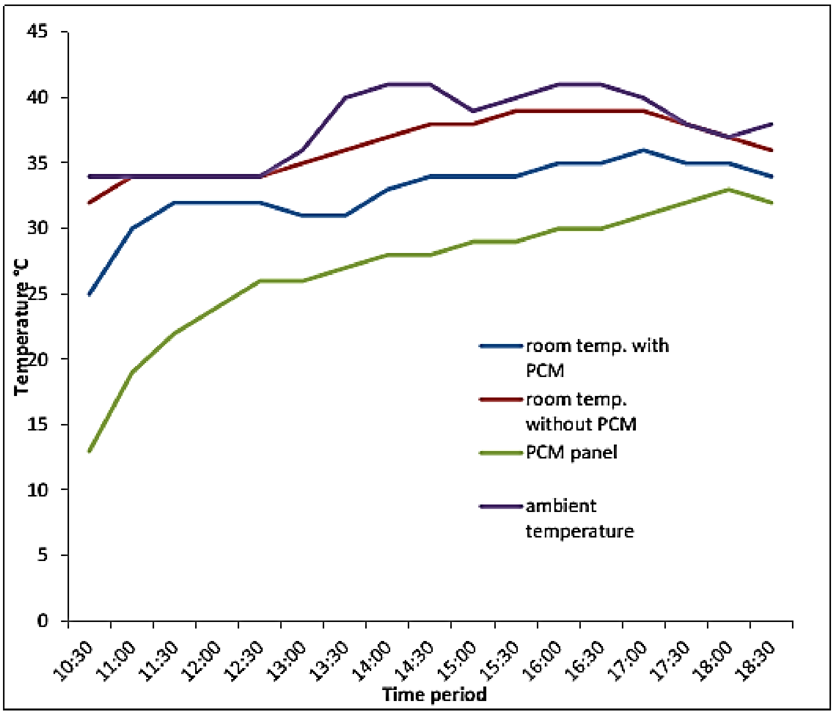

Figure (4.2): The temperatures average variation over period (10:30 - 18:30)[63].

Comparing the results between the Calcium Chloride Hex hydrate in the two model (concrete and wood) shows that the temperature decreased in the wood model more than the concrete model due to the high heat absorbing in concrete.

4.2.2 Results of Polyethylene Glycol 600

Two methods were used for conducting the experiment. In the first scenario the air flow inside the room, the air flows inside the room naturally and the second scenario the air forced inside the room using air fan.

4.2.2.1 Results of Polyethylene Glycol 600 without fan

Another type of PCM was used in this study, the result of using Polyethylene Glycol 600 was demonstrated in the figure below. From figure (4.3) the X- axis shows the time period and the Y- axis shows temperature. As shown in the figure the temperature of the room with

PCM was found to be less than the one without PCM. The PCM temperature increased according to the sensible heat. It reached to the melting point after 45 minutes and crossed over the melting point.

The temperature difference in this period of the room temperature with PCM compared to the room temperature without PCM was found nearly between (1 to 5) °C and The mean reduction was 2 °C.

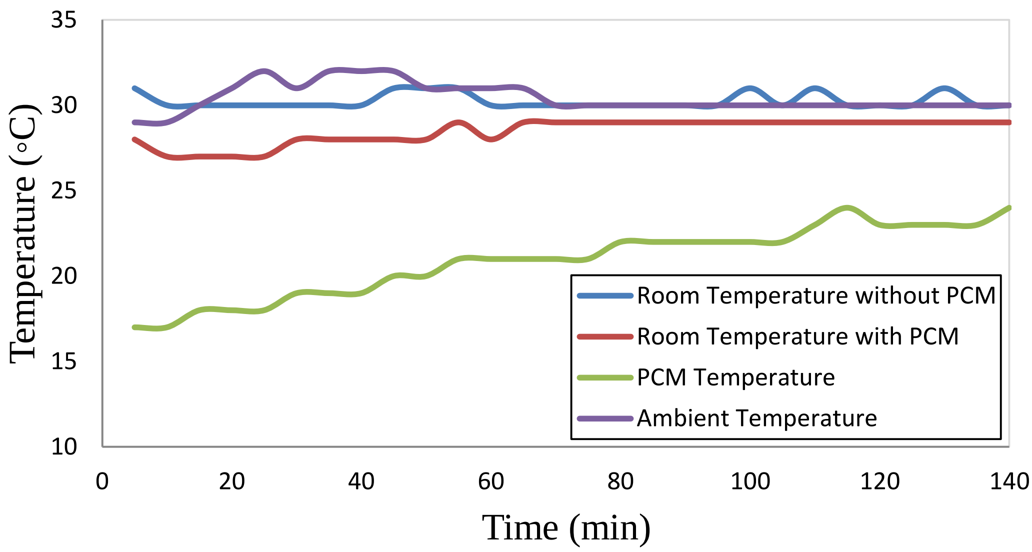

Figure (4.3): The temperatures average variation over time period.

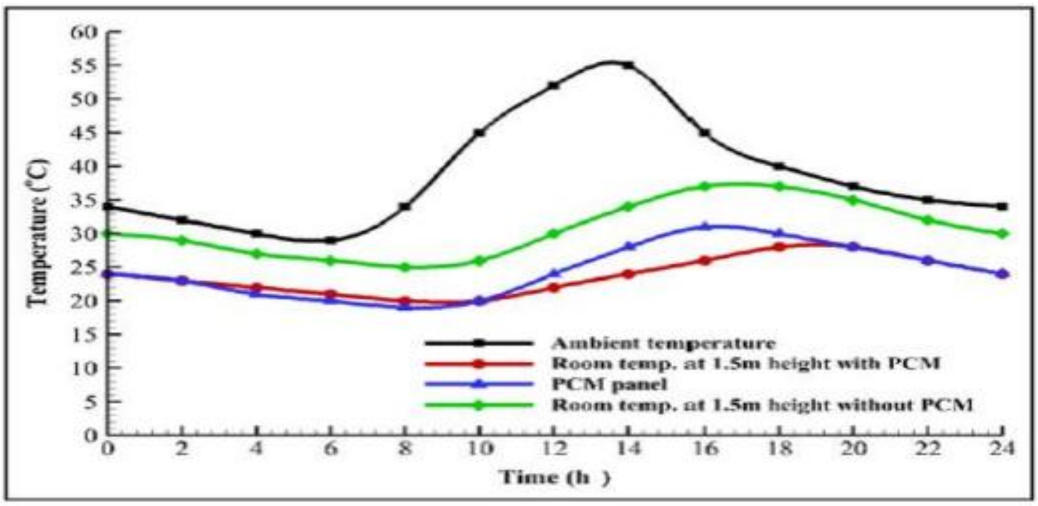

Figure (4.4): The temperatures average variation over time period [51].

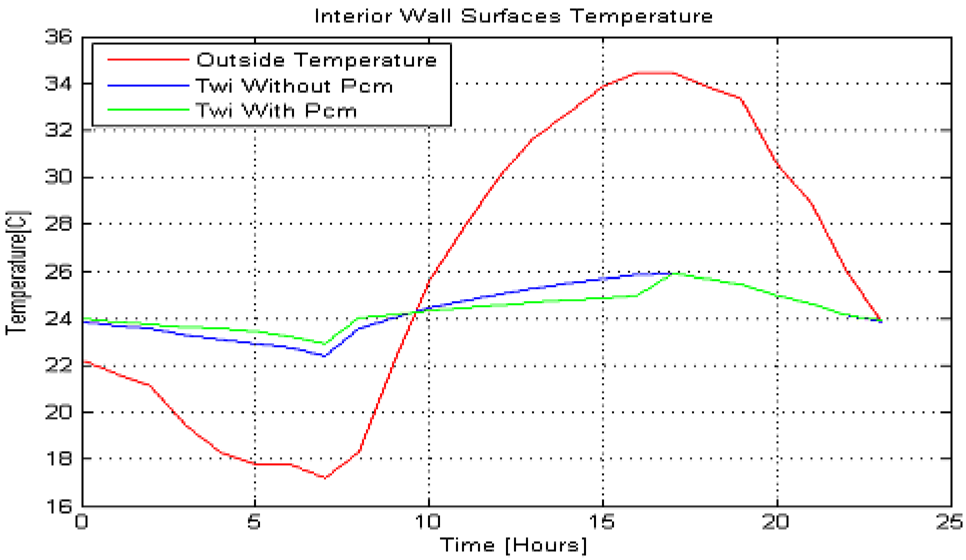

Figure (4.5): The temperatures average variation over time period [64].

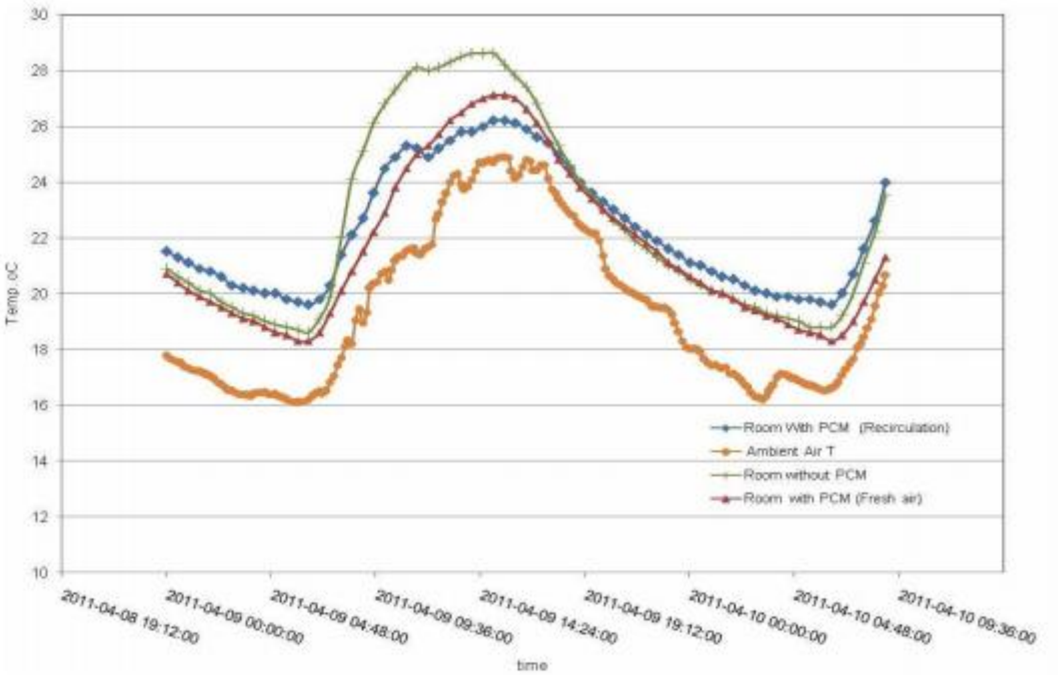

Figure (4.6): The temperatures average variation over time period [65].

4.2.2.2 Results of Polyethylene Glycol 600 without fan

Several experiment was done by using a fan to enhance indoor temperature by increasing the rate of heat transfer. The fan was put in the PCM integrated room and connected to electrical source. The recordings were taken every 10 minutes. The experiment was repeated several times and the average values were taken.

From figure (4.7) below the X- axis shows the time period and the Y- axis shows temperature. As shown in figure (4.7) the temperatures of the room with and without PCM were found to increase as a result of increasing in ambient temperature. However the room temperature with PCM was less than the room temperature without PCM due to the heat absorbed by the room roof exposed to the sun, which caused an inner increase of the temperature. The PCM temperature increased according to the sensible heat. It reached to the melting point after 30 minutes and crossed over the melting point.

The temperature difference in this period of the room temperature with PCM compared to the room temperature without PCM was found nearly between (2 to 5) ℃ and The mean reduction was 3.5 ℃.

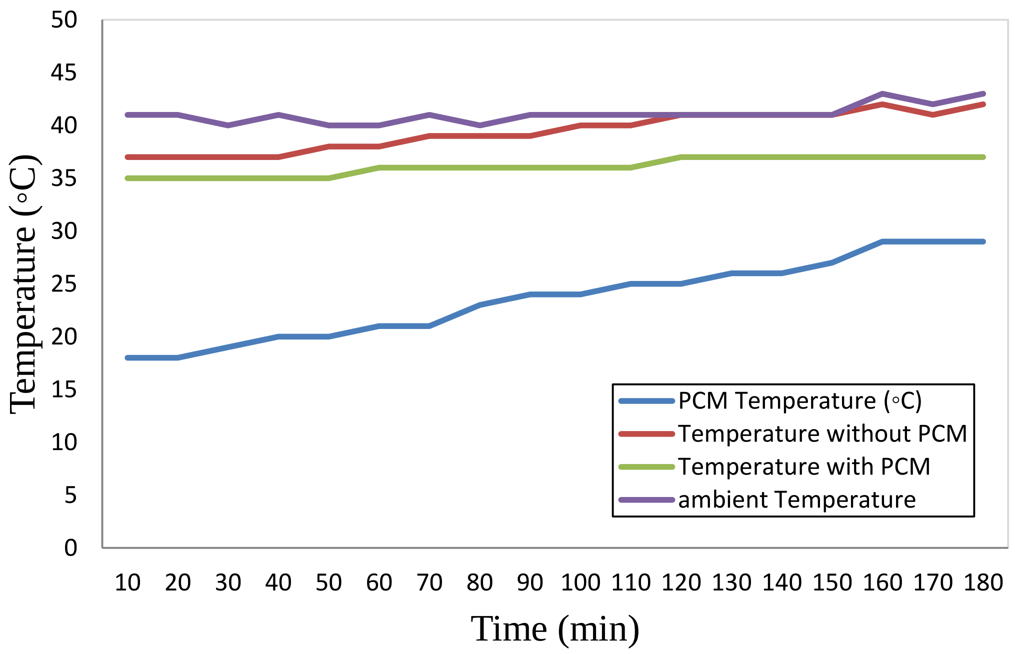

Figure (4.7): The temperatures average variation over time period.

CHAPTER FIVE

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Two rooms of identical internal dimensions were constructed using concrete blocks, one with PCM and the other without PCM in the roof. Thermal management of PCM incorporated building structures in the specific climatic condition of Sudan was reported. Experiments investigations were made to examine the temperature reduction inside a residential building using such PCMs. Two types of PCM with different melting point the first one was Calcium Chloride Hexahydrate and the second type of PCM was Polyethylene Glycol (PEG) 600. The thermal performances of small-scale test rooms were evaluated. The temperature inside the PCM integrated room was demonstrated to be considerably lower than the one without PCM. For Calcium Chloride Hexahydrate the temperature difference was found nearly between (1 to 3) ℃ and The mean reduction was 2 ℃, for Polyethylene Glycol (PEG) 600 the temperature difference was found nearly between (1 to 5) ℃ and The mean reduction was 2 ℃. A fan was used to enhance indoor thermal comfort in the second type of PCM integrated room and the temperature difference was found nearly between (2 to 5) ℃ and the mean reduction was 3.5 ℃.

Comparing the results between the Calcium Chloride Hex hydrate in the two model (concrete and wood) shows that the temperature decreased in the wood model more than the concrete one due to the high heat absorbing in concrete.

From research it was found that PCM is a powerful alternative, which employs the latent heat storage concept, can act as a smart material to control the indoor environment of a building.

The thermal storage effects of PCMs have positive effects on building thermal and energy performance and can help enhance indoor thermal comfort.

5.2 Recommendations

The followings are the conclusive remarks and recommendations for the future studies in this direction.

1- The research should be conducted in summer season in order to investigate the effect of the maximum heat on the utilized material.
2- Researches on enhancing the heat transfer performance of PCM and/or developing heat transfer enhancement materials are needed.
3- The room's wall should be built using zinc material instead of concrete and wood also traditional roof can be used for evaluating the performance of PCM.
4- The experimental prototype use to perform this investigation should be transfer to a real physical model in order to obtain a clear insight about the efficiency of the utilized material in this research.

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