

**INNOVATIVE APPROACH TOWARDS SUSTAINABLE
EXTERNAL WALL SYSTEM: STATE OF THE ART
REVIEW ON PCM**

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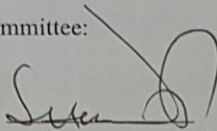
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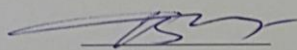
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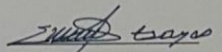
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ABSTRACT

One of the crucial concerns in Ethiopia is creating sustainable development. The number of public and private construction projects in Ethiopia is increasing rapidly. Thus, the various activities and materials involved in the structural engineering aspect of constructed deliverables from material selection through its lifecycle utilization and eventual disposal play a significant role the overall process of sustainable development. A material is only considered a renewable or sustainable resource if it can be replaced at a rate that meets or exceeds the rate of its consumption. Traditionally, cost consideration is the main reason for choosing construction materials; but the integrated environmental and economic sustainability aspects should also be considered. One of such materials that contribute to sustainability is the use of Phase Changing Materials (PCM) as storage medium for both cooling and heating applications which substantially reduces the energy demands of building sectors. This thesis is concerned with the material composition and geometric aspects of non-structural walls as related to their environmental effects.

The data sources for this study include primary and secondary sources. Primary data was obtained from National Metrology Agency (NME). It includes Ten Years of monthly average maximum and minimum temperatures for the two most populated cities in Ethiopia, Addis Ababa and Dire Dawa and represented by the total of five stations. Whereas secondary resources have been various literature related to the study.

Finally, thermal analysis was done for three procedures containing a total of seventy-nine cases. The results of the analysis indicate that Heat Flux decrease as the thickness of the wall increases and as the temperature decrease. Average thickness of 25cm is recommended for concrete wall to create a thermal comfort. However, as the temperature increases, latent heat storage system should be provided for additional heat storage capacity. Furthermore, greater Heat Flux can be obtained for wall containing PCM rather than the one without PCM and also the drop of temperature is gradual throughout thickness for wall containing PCM. Finally, it is recommended that, PCM should be integrated in construction materials to maintain temperature fluctuations.

Key Words and phrases: Phase Change material (PCM), Sustainable Materials, Non-Structural Walls, Heat Transfer

DECLARATION

I, the Undersigned, declare that this thesis is my original work and has not been presented in any other university, and that all sources of the materials used for the thesis have been appropriately acknowledged.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Air conditioning	
ASCE	American society of civil engineers	
CO ₂ eqv	Carbon dioxide equivalent	
GHG	Greenhouse gas	
IPCC	Intergovernmental panel on climate change	
Max	Maximum	
NME	National metrology agency	
PCM	Phase changing materials	
RC	Reinforced concrete	
TES	Thermal energy storage systems	
ΔT	Temperature difference	[°k]
NT	Nodal Temperature	[°k]
HFL, q''_x	Heat Flux	[W,J/s]
$\rho (\theta)$	Density as a function of temperature	[kg/m ³]
λ, K	Conductivity	[W/m.k]

1. INTRODUCTION

1.1 Background

Structural engineers are faced with a major challenge of addressing the effect of global environmental issues in a design to create a high performance, green and sustainable structure. The total environmental impacts of buildings are both the life cycle impacts of building materials and the nature of energy consumption during operational period. Therefore, the proper understanding on thermal energy storage systems, Nanotechnological advancements on materials that would help the system to consume less energy will enable to decrease the effect of global warming.

Nowadays buildings are being constructed with low thermal mass to reduce the cost of construction. This study mainly concentrates on the thermal property enhancement of such thin concrete walls principally on the thermal property enhancement of building wall consisting of microencapsulated phase Changing materials(PCM), Concrete, Gypsum Board materials. In this thesis, a finite element software system (Abaqus) is used for analysis together with analytical verification method.

1.2 Statement of the Problem

The initial problem that will be addressed in this thesis is filling the knowledge gap between Structural and Thermal aspects regarding thermal energy storage systems and construction materials. Thus, this will be done first by creating the state of the art understanding on green and sustainable materials and new Nanotechnological advancements on phase changing materials. The other problem to be answered is the effect of PCM integration on the thermal property of wall. Initially, the effective concrete wall thickness for thermal mass generation will be identified. Then phase changing materials will be selected and detailed thermal analysis will be done for densely populated cities of Addis Ababa and Dire Dawa, by using thickness of wall which does not satisfy thermal comfort.

1.3 Objectives

1.3.1 General Objective

The main objective of this study is finding the thickness of concrete which generates thermal mass, creating indoor thermal comfort and identification of the thermal changes that occur in a multilayered plane wall through integration of phase changing materials.

1.3.2 Specific Objectives

Some of the specific objectives of the study are:

- Creating a basic understanding on the requirements from building materials to be sustainable and key necessities from structural engineers to create Sustainable buildings.
- Creating a basic understanding latent heat storage systems and active and passive thermal energy storage systems.
- Creating State of the art understanding on PCM, incorporation process of PCM into construction materials and elements, Building applications of PCMs and last of all, the requirements on the proper Selection of PCM for thermal energy storage application.
- Identification of the thickness of concrete wall for thermal mass storage
- Identification of appropriate phase changing materials for Addis Ababa and Dire Dawa for thermal capacity enhancement.
- Comparison of the Heat Flux and Nodal Temperature values for wall with and without PCM.

1.4 Significance of the Study

The most important significance of the study is forming a better understanding on green and sustainable materials and phase changing materials. The study will also attempt to

identify the thickness of the concrete wall that will create a thermal comfort without any additional heating systems. Furthermore, the thermal improvement due to the integration of PCMs together with the conventional wall materials will also be perceived. Finally, the understanding on these concepts will aid on the selection of materials to prevent the effect of climate change and green house problem.

1.5 Scope and Limitations of the Study

The basic concepts on the scope and the limitations of the study are listed below.

- The study is limited to one dimensional, steady state conduction in a plane wall with no heat generation where the Heat Flux is constant independent of the thickness.
- The transverse wall area is assumed to have a 2m by 2m dimension. Even if the model is three dimensional, conduction problem is one dimensional analysis.
- A temperature range between 7°C to 34°C has been considered in this study. Such wide temperature range was necessary to capture the details of the thermal comfort level and phase transformation process in various cities.
- External wall is considered for this study because of the reason that temperature variation impacts mainly external walls rather than internal partitions.
- The effects of the color of the wall, building orientation¹, building area² and type of the building were ignored due to the fact that these parameters are considered while designing a building from AC perspective. This study mainly concentrates on the effect of thermal load due to temperature change and the response of the wall materials for this change.
- Steady state consideration is taken for the analysis where heat transfer is instantaneous with no distributed source or sink of energy within the wall. This is due to the reason that that enthalpy is not influenced by the selection of the temperature step size, enthalpy is a state function [1].

¹ For Addis Ababa; the North-East orientation has the lowest cooling load, followed by South-East then North orientation. while for Dire-Dawa, East orientation has lower cooling load, followed by South-East orientation [25].

² Cooling load decreases as the room area increases [25].

- Solar radiation is negligible.
- The type of wall materials used for the study are limited to Hardened concrete and gypsum board.
- The concrete and all the other materials are assumed to have homogenous thermal properties throughout the thickness.
- Phase changing materials selection is based on the thermal compatibility with the temperature distribution of various stations. The type of the phase changing materials will be changed whenever the study area changes. However, the data used for this study somewhat represent the temperature distribution in most parts of Ethiopia.

1.6 Organization of the Study

The research is organized into the total of Seven Chapters. The First Chapter is a general introductory part on the basic concepts of the study. This Chapter consists of the background, statement of the problem, the objectives and the scope and limitations of the study. The Second Chapter is more or less concerned on Green and Sustainable Materials and role of temperature and moisture in concrete. The Third Chapter is concerned with creating a detailed understanding on phase changing materials, their application in buildings and the important issues to be considered when choosing these materials. The subsequent Fourth Chapter emphasize on materials and methods for this study. The methodology processes and the thermal properties of the materials and temperature selection step will be discussed. The basic reason for the choice of the seventy-nine Cases for the thermal analysis will be elaborated. The Fifth Chapter is concerned on the modeling and analysis. The basic inputs and the required outputs from the analysis on Abaqus will be discussed. Chapter Six will concentrate on the results and discussion aspects of the research. This Chapter also consists of the verifications or validation segment of the research. Analytical comparison method will be deliberated. Finally, Chapter Seven will focus on conclusion of the thesis and recommendations for the future researches.

2. STATE OF THE ART REVIEW ON GREEN AND SUSTAINABLE MATERIALS

2.1 Introduction

Construction industry is a growing sector in both developed and developing countries for which it is drawing attention towards improving social, economic and environmental indicators of sustainable development. This sector environmentally is responsible for high energy consumption, waste generation, global greenhouse gases emissions, pollution and resource depletion. It has been recognized that a major reduction in environmental issues is not achievable without a significant effort in contributions from the building and construction sector. Thus, Green and sustainable materials will substantially impact the energy consumption and volume of emissions.

A material is only considered a renewable or sustainable resource if it can be replaced at a rate that meets or exceeds the rate of its consumption. The building industry consumes about 40 percent of the extracted materials and is responsible for 35 percent of CO₂ emissions [2]. The building sector has the largest potential for the reduction of GHG emissions. Thus, significant reduction can occur by using green and sustainable materials. These materials incorporate multiple sustainability measures across a range of categories including energy efficiency, water efficiency, resource efficiency, responsible site management and improved indoor air quality.

2.2 Sustainability

The Intergovernmental Panel on Climate Change (IPCC) reports that building related GHG emissions are estimated as 8.6 billion metric tons CO₂eqv in 2004, and that figure can almost double by 2030 to reach 15.6 billion metric tons CO₂eqv [3]. Significant potential for energy efficiency improvements and greenhouse gas (GHG) emission reduction from buildings is common among developed and developing countries. The large increase of people and economic activities in city's have strengthened the relations between cities, health and the environment. Cities are not only responsible for

environmental and health problems but also, they hold the key for a greener economy and a sustainable future.

There are different definitions for sustainable development the first one is meeting the needs of the present without compromising the ability of future generations to meet their own needs [4]. The other definition of sustainable development established by American Society of Civil Engineers (ASCE) in the 2001 Policy Statement is “sustainable development is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development”. Some of the greatest threats to the sustainable development on earth are; population growth and urbanization, energy use and global warming, excessive waste generation and the subsequent pollution of soil, air, and water, transportation in cities, and limited supply of resources. The effects of the above problems are interrelated. As Engineers provide the bridge between science and technology, they are expected to participate in interdisciplinary teams with ecologists, economists, sociologists and professionals from other disciplines, for environmentally sustainable strategies and solutions [4].

2.2.1 Sustainable Materials

Traditionally, cost is the main factor considered when choosing construction materials but the integrated environmental and economic aspects should also be considered when choosing construction materials. Consequently, life cycle assessment provides information about the resources, emissions and other impacts resulting from the life cycle of material use. Thus, one must consider the impact of the material from extraction to disposal. The evaluation of environmental impact of construction materials at each stage allows for a cost-benefit analysis over the lifetime of a structure, rather than simply an accounting of initial construction costs. The impacts the solution and the challenges of the future will enable structural engineers to integrate their knowledge with the trending new technologies. The selection of materials using life cycle design is based on three basic phases: Pre-Building, Building, and Post-Building [5]. These three groups of

criteria which are based on the material life cycle can be used in evaluating the environmental sustainability of building materials.

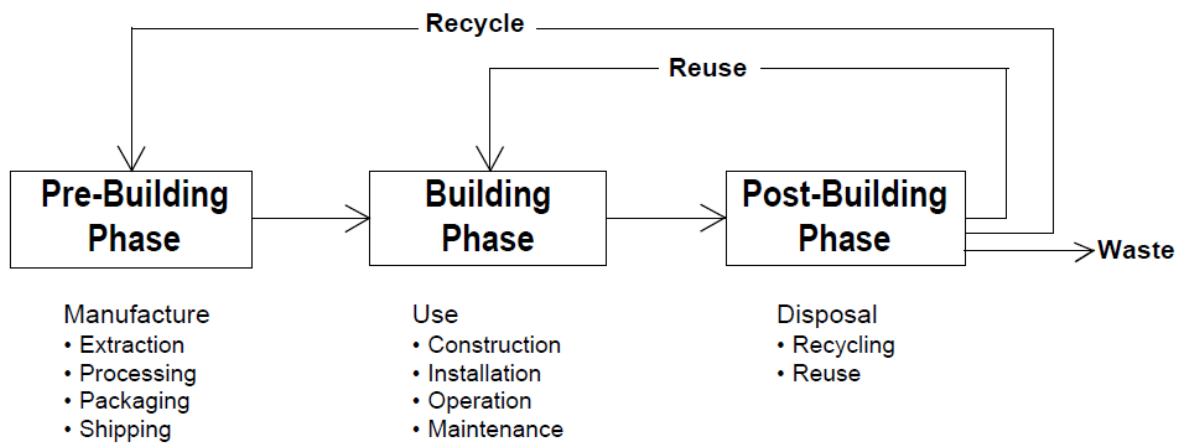


Figure 2.1 Three phases of building material lifecycle

2.2.2 Sustainability Requirement from Structural Engineers

The selection of construction materials for a high performance green and sustainable structure is really tough and challenging task for any design team. High performance concept focus more on reducing the operational energy and resource consumption. Construction materials provide the structural engineer with real opportunities to contribute to a project's sustainability. Generally, structural engineers use traditional criteria's such as structural capacity and economy for material selection thus it is required further to consider efficiency, availability, recycled content, reuse, and impact a material has on the environment [5]. There should be a balance between environmental, economic and social aspects to create sustainable development. [6]. These relation is described in Figure 2.2 below.

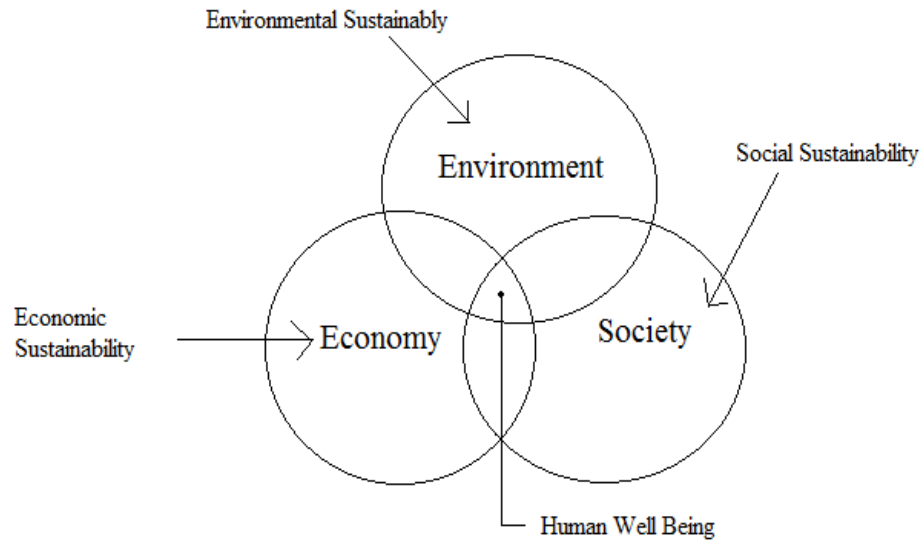


Figure 2.2 The three aspects of sustainability: economic, social and environmental

Sustainable design has to consider three major aspects of sustainability, namely, social, economic and environmental. A proper understanding on Life cycle 'cradle to grave' thinking focus on various aspects associated with an improved material performance over its entire life cycle. Each step of the manufacturing process, from gathering raw materials, manufacturing, distribution, and installation, to ultimate reuse or disposal, is examined for its environmental impact. Pollution prevention measures taken during the manufacturing process can contribute significantly to environmental sustainability.

The increasing production of cement and other materials requires more conscientious process from gathering of raw materials to manufacturing. Wastewater from cement production is also problematic when it is released directly into streams, it might contain toxic substances [5]. By becoming aware of which manufacturers use environmentally sustainable manufacturing methods and avoiding goods produced through highly polluting methods, architects and engineers can encourage the marketing of sustainable building materials.

2.3 Green Materials

Green materials are materials which incorporates multiple sustainability measures across a range of categories including energy efficiency, water efficiency, resource efficiency,

responsible site management and improved indoor air quality. Green materials also required to satisfy standards of a green building certification program, such as the United States Green Building Council's (USGBC) and Leadership in Energy and Environmental Design (LEED) or Green Globes. Material selection is integral component in the design process of green building [7].

2.4 Requirements from Construction Material to be Green and Sustainable

Construction materials provide the structural engineer with real opportunities to contribute to a project's sustainability. Generally, structural engineers use traditional criteria's such as structural capacity and economy for material selection thus it is required further to consider efficiency, availability, recycled content, reuse, and impact a material has on the environment [5].

When choosing materials there should be proper understanding on their environmental impact, their durability and their end of life purpose. Some of the factors that should be considered while selecting materials are listed below:

- Least energy consumption for manufacturing
- Durability
- Less Transportation distance between manufacturing supply and demand sites
- The environmental effect of the raw and finished material
- The recycling and disposal methods

Generally concrete is the most widely used building material in the world. It's mostly made locally which decrease transportation cost. Concrete consists of cement paste binder, aggregate and sometimes admixtures. While concrete is an essential and structural material, the cement production is large contributor to total emission. Each ton of cement is responsible for approximately one ton of CO₂ emissions. Consequently, Reducing the amount of cement in concrete will in return reduce carbon dioxide emissions. The amount of cement in concrete can be reduced by substituting fly ash or ground granulated blast furnace (Slag) instead of cement to some extent. Recently recycling of concrete is trending. Also by combining cement with fly ash the carbon footprint of concrete can be minimized.

The vast scale growing demand of concrete for various constructions in Ethiopia requires the need for understanding on the contributions of this material to greenhouse emissions. Unfortunately, concrete require tremendous amounts of energy to produce and responsible for very high carbon emissions. Thus, as it continues to be dominant construction material additional or replacement materials should be explored to mitigate the greenhouse gas problem.

3. STATE OF THE ART REVIEW ON PHASE CHANGING MATERIALS (PCM)

3.1 Introduction

Many modern buildings have a low thermal mass for architectural and cost reasons. One of the disadvantage of light weight buildings having low thermal mass is, they tend to have high temperature fluctuations which result in high heating and cooling loads. The usage of PCMs in such buildings can smooth out these temperature variations. PCMs can be encapsulated in building materials such as concrete, gypsum wallboard, in the ceiling or floor to increase its thermal storage capacity [8].

If inside temperature of a space rises above 25°C then air conditioning will probably be necessary to create comfort. PCM can provide high latent heat thermal energy storage density over the narrow range of temperatures typically encountered in buildings. The necessary layer thickness of concrete wall to store as much heat as 1cm thick layer of PCM is 24cm [9]. Based on research done here in Ethiopia, 25cm optimum wall thickness is required for a favorable indoor temperature of 298°k/25°C [10]. As for wood and gypsum board, used for lightweight buildings, a wall thickness in the range of 30cm to 50cm would be necessary. Therefore, adding even small amounts of PCM to the building structure can significantly enhance the thermal mass of the building and make a lightweight building perform like a massive building with respect to thermal comfort [9].

PCMs have found applications in a wide array of areas such as in thermal energy storage, building energy efficiency, cooling of food products, spacecraft thermal systems, solar power plants, microelectronics thermal protection, waste heat recovery etc. This chapter reviews previous works on PCM as latent heat storage and provides an insight to the state of art understanding on PCMs.

3.1.1 Theoretical Background

The investigation of PCM for applications for heating and cooling in building mass has a long History. In 1930s, M.Telkes investigated the use of PCM to store solar heat and use

it for space heating. However, the applications were not economical. In the past decade, the situation has started to change because of rising energy prices. The energy demand to ensure indoor thermal comfort has increased worldwide, especially the demand for cooling and air conditioning [9].

In buildings, PCM impregnated components have been demonstrated to maintain and regulate the interior temperature, resulting in improved energy performance of the building. In particular, PCM impregnated gypsum boards, are one of the most popular PCM applications, and have been tested for over four decades. Preceding research studies conducted on building components containing a phase change material (PCM) have shown a great potential for direct and indirect energy and cost savings in the building envelopes. In the USA, these technologies have been mostly implemented in wall and roof applications. In early 1990s, the oak ridge national laboratory conducted theoretical and experimental studies that showed that wallboard can be successfully impregnated with PCM as high as 30%. The PCM enhanced wallboard was analyzed for passive solar applications and was found to save 7–20% reductions in the cooling loads for southern USA locations, with a potential payback time period of five years. In 2006, Kissock and Limas investigated the application of a paraffinic PCM in walls and roofs for reducing the peak diurnal cooling and heating loads transmitted through the envelope [1]. The combined numerical and experimental study was focused at quantifying the effectiveness of the PCM in reducing the thermal loads through the building component. The PCM studied was paraffin octadecane having an average melting temperature of 25.6°C. When compared to a conventional wall, cooling load savings of approximately 16% were obtained. Several numerical and experimental studies have shown that application of PCM enhanced building component can significantly improve the energy performance of a building [1]. There has been significant research conducted on PCMs for space heating and cooling in buildings. By embedding PCMs in gypsum board, plaster, or other wallcovering materials, the building structure acquires latent storage properties [8].

3.2 Thermal Energy Storage Systems (TES)

The external wall on a structure acts as boundary between outside and inside temperature variation. Its primary function is to protect the building against wind precipitation and solar radiation. The heat capacity of the of the wall material is an important parameter for controlling the indoor temperature and reducing the temperature swings during the day.

Energy can be stored in material both in the form of latent and/or sensible heat both of which are types of energy released or absorbed in the atmosphere. As heat energy is added to a solid, two processes happen. First, the temperature of the solid goes up. The heat added that causes the temperature change is called “sensible heat.” Then, as the temperature of the solid reaches the melting point, the solid undergoes a phase change to a liquid. During the phase change, heat is added to the material, but the temperature remains constant. The heat needed for the phase change is referred to as “latent heat.” The same process is repeated if heat continues to be added to the material. Latent heat is released during phase changes from a gas to a liquid, and from a liquid to a solid, and sensible heat is released as the temperature of the substance drops between phase changes [11]. This process is shown on the Figure 3.1 below.

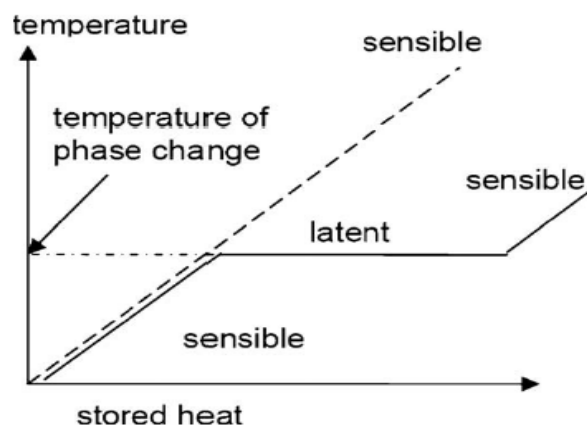


Figure 3.1 Sensible and Latent Heat storing processes

The main advantage of latent heat storage systems is to reduce the nonrenewable energy demand for thermal heating and cooling. The other advantage is they enable to shift

heating and cooling demand from peak to off peak hours. The general purpose of thermal energy storage is to keep the indoor temperature within specified comfort limits.

TES in buildings can be divided into two major categories, passive and active storage. For a passive storage, the driving force for charging and discharging is by storing of temperature difference between the TES and the surroundings. In the case of an active storage, the charging and discharging occurs with active help from pumps or fans. Most of the techniques used for TES in buildings are active. However only one passive energy storage technique will be discussed, latent heat storage using PCM in the building walls.

3.2.1 Active Systems

Active thermal storage systems are distinct from passive thermal storage systems in that they are designed to be charged and discharged at specific times and/or at the command of a control system. Additionally, active systems use mechanical systems (such as a pump or fan) to facilitate their charge and discharge [12].

3.2.2 Passive Systems

Passive system uses temperature difference in the building for storing and releasing of heat. Using the latent energy of a phase change in a material means that the energy can be stored in a smaller temperature interval around the melting point of the PCM. Temperature variations are still necessary, but the same amount of energy can potentially be stored within a smaller temperature range if PCM is used. It is, however, important to make sure that the temperature variation is large enough so that the PCM can actually melt and solidify again. For PCM the corresponding important parameter is the heat of fusion which tells how much energy can be stored in the phase change of the material. Schematic picture for building wall illustrating the difference between a light, heavy and PCM wall is shown in the Figure 3.2 below [12].

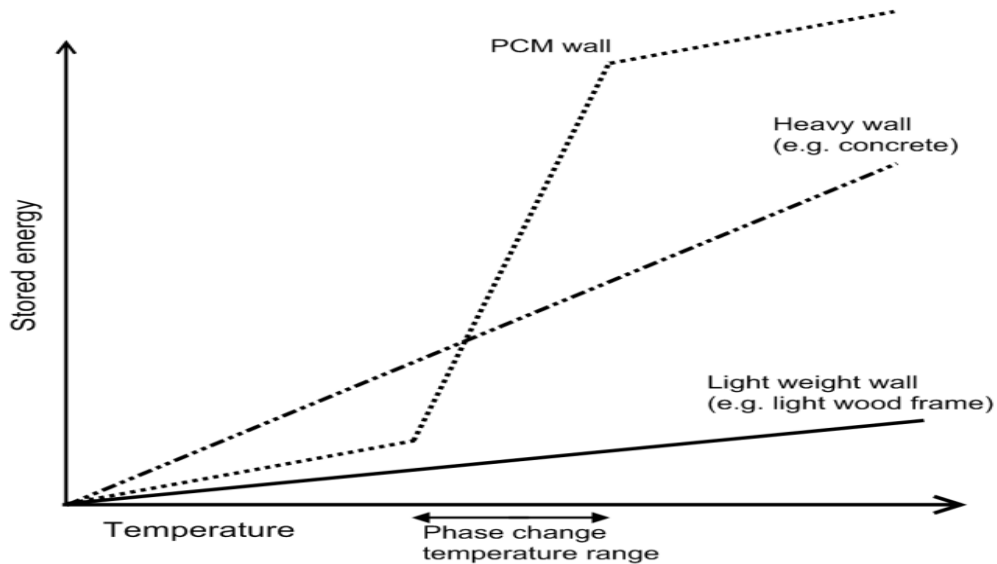


Figure 3.2 Diagram showing Heat storage variation between different walls

A large number of PCM are known to melt with a heat of fusion in any range of interest and are compatible for various range of temperatures. However, for their employment these materials must exhibit certain desirable thermodynamic, kinetic and chemical properties.

3.3 Classification of PCMs

Over the last 40 years' different classes of materials, including hydrated salts, paraffin waxes, fatty Acids, the eutectics of organic and non-organic compounds and polymers have been considered as potential PCMs [9]. PCMs can be divided into three main groups based on the temperature ranges over which the TES phase transition occurs:

- (i) Low temperature PCMs – with phase transition temperatures below 15°C, usually used in air conditioning applications and the food industry.
- (ii) Mid temperature PCMs, the most popular – with phase transition temperatures in the range 15°C - 90°C with solar, medical, textile, electronic and energy saving applications in building design.
- (iii) High temperature PCMs with a phase transition above 90°C developed mainly for industrial and aerospace applications.

PCMs can also be classified by their mode of phase transition: gas–liquid, solid–gas, solid–liquid and solid–solid systems. The applications of PCMs with a solid–gas or liquid–gas phase transition is limited in TES systems because of the large volume changes associated with the transition. Significantly smaller volume changes occur, usually 10% or less, with solid–solid and solid–liquid transformations. This makes them economically and practically attractive as materials for TES systems. Generally, the heat of phase transition for solid–solid PCMs is lower than that of solid–liquid PCMs. However, PCM leakage is significant technical problem with solid–liquid PCMs [13].

Currently, mainly solid–liquid PCMs are being used in energy storage applications because the solid–solid PCMs generally show smaller latent heat of phase transition. However, the solid–solid PCMs have the major advantages of a smaller volume change during the phase change than solid–liquid PCMs and have no leakage [13]. The classification of PCMs is shown in the Figure 3.3 below.

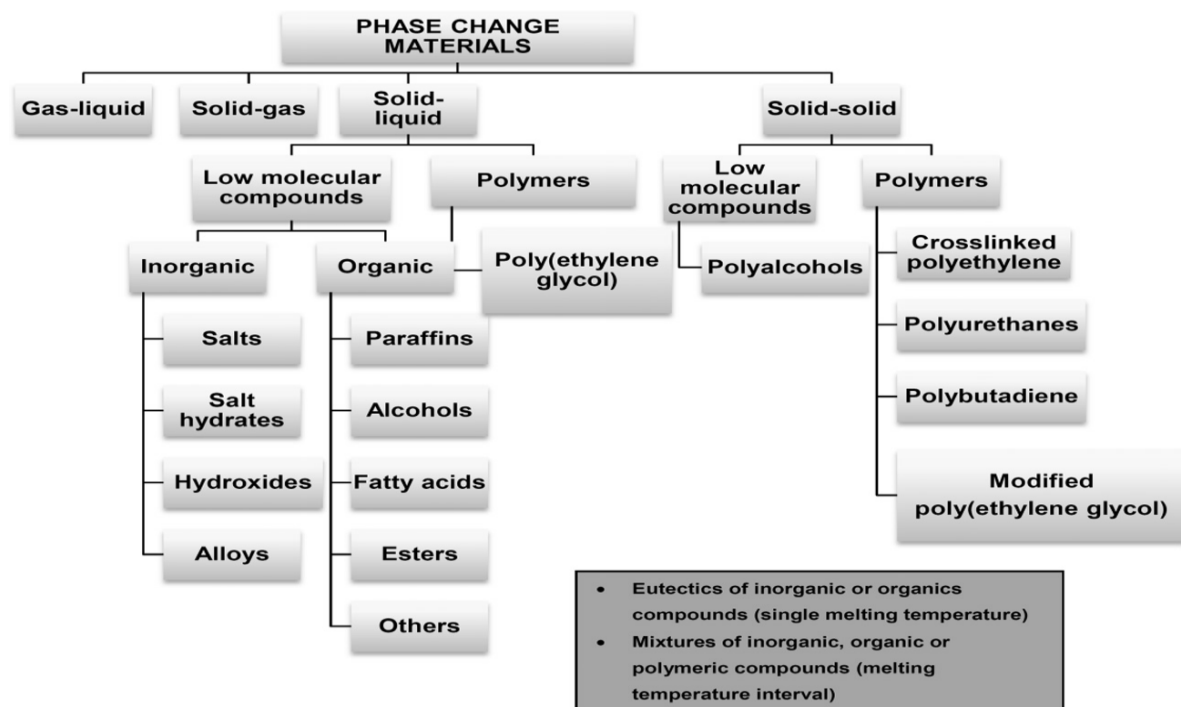


Figure 3.3 Classification of energy storage materials

3.4 Desirable Properties, Advantages and Disadvantages of PCM

The PCM to be used in the design of thermal storage systems should accomplish desirable thermo-physical, kinetics and chemical and economic requirements. These

requirements are listed below. It is worth mentioning here that no PCM can have all the desirable properties.

Thermal

- Melting point in the desired operating temperature range
- High latent heat of fusion per unit volume so that smaller size of container can be used
- High thermal conductivity to assist in charging and discharging of PCM within the limited time frame.
- High specific heat so that additional energy in the form of sensible heat is available to the thermal energy storage system.
- Small volume change during phase transition to avoid the containment problem
- Thermally reliable (i.e. Cycling stability) so that PCM is stable in terms of phase change temperature and latent heat of fusion and can be used in long run

Kinetic

- No super-cooling, No sub-cooling
- No phase segregation

Chemical

- Chemically stable over a number of freeze and throw cycles
- Corrosion resistant to construction/ encapsulated materials
- Non-toxic, non-flammable and non-explosive so as to assure safety
- Chemically compatible with construction /encapsulated materials

Physical

- Small phase transition volume change
- High density

Economic

- Low price

- Large scale availability
- Good recyclability for environmental and economic reason

3.4.1 Advantage and Disadvantages

Organic and inorganic compounds are the two most common groups of PCMs. The basic advantage and disadvantages of PCMs are summarized in Table 3.1 below [13].

Table 3.1 Advantages and Disadvantages of organic and inorganic PCM

	Advantages	Disadvantages
Organic materials	Safe and non-reactive	Low thermal conductivity in
	High heat of fusion	Lower latent heat density
	Chemically stable	Often broad melting range
	No segregation	Can be combustible
	Compatibility with conventional material of construction	Volumetric latent heat storage capacity can be low
	Self-nucleating properties	More expensive
	Ability to melt congruently	
	Freeze without much	
	Recyclable	
Inorganic materials	Generally, cheap	Change of volume is very high
	High volumetric latent heat	Needs additive to stabilize
	Higher thermal conductivity	Prone to supercooling
	Well defined phase change	Can be corrosive to metals
	Temperature	
	Non-flammable	
	Biodegradable and recyclable	

3.5 Incorporation of PCM into Construction Materials and Elements

PCM can be incorporated in construction materials and elements by direct incorporation, immersion, encapsulation, techniques. The most advanced and ideal method, encapsulation is discussed below.

3.5.1 Encapsulation

In this technique, PCM has to be encapsulated before being used into construction elements. It has been pointed out by Regin et al. that PCM encapsulation

- Should meet the requirement of strength, durability and thermal stability and reliability
- Should protect the PCM, by acting as a barrier, from destructive interactions with the surrounding environment
- Should have sufficient surface area for efficient heat transfer
- Should be structurally stable and provide ease in handling.

Encapsulations are usually classified by their size into macro- and microencapsulation.

Micro-encapsulation

Micro-encapsulation is by far the most widely used type of encapsulation. Micro-encapsulation is the encapsulation of solid or liquid particles of 1 μm to 1000 μm diameter are enclosed in a thin solid shell usually made from natural and synthetic polymers [9]. Microencapsulated PCMs are also produced on the industrial scale.

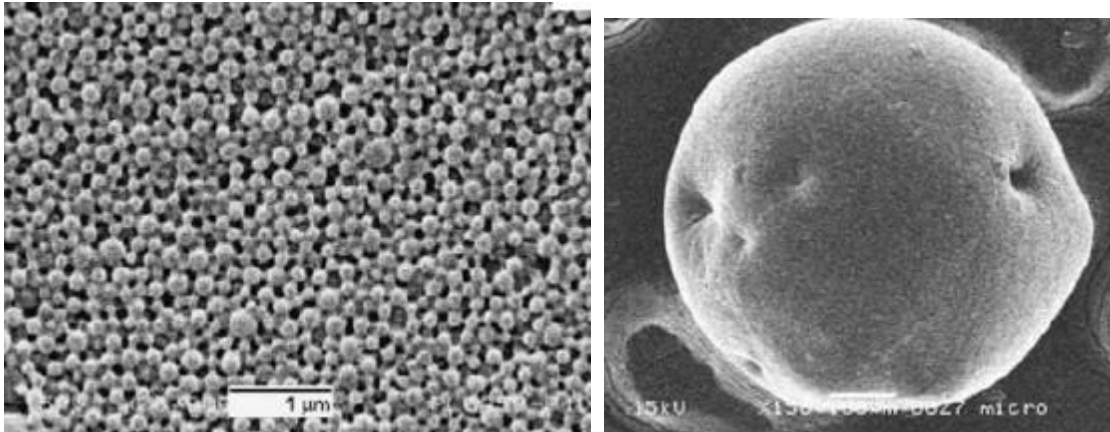


Figure 3.4 Microencapsulated PCM profile

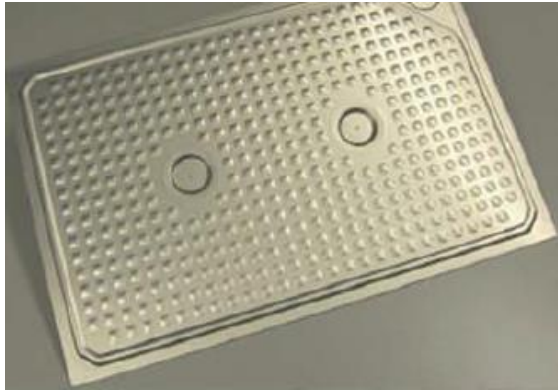
Macro-encapsulation

Macro-encapsulation means filling the PCM in a macroscopic containment. These are often containers and bags made of metal or plastic. Macro-encapsulation is very common because such containers or polymer are available in a large variety already from other applications. If the container is rigid enough, the encapsulation can also add mechanical stability to a system. When encapsulating PCM, several aspects should be taken into account. The first one is, the material of the container wall must be compatible with the PCM [9]. Macro encapsulation is available in various configurations like flat plate, cylinder, shell, tube and spherical forms. These forms are shown in Figure 3.5 below [14].



(a) Spherical PCM balls

(b) Metal ball encapsulate



(c) PCM in aluminum panels

Figure 3.5 Different encapsulated PCM forms

To encapsulate salt hydrates, usually plastic containers are selected because of material compatibility. Plastics are not corroded by salt hydrates. Plastic encapsulations can also be used for organic PCM, but the combination of PCM and encapsulation material has to be chosen very carefully because organic materials may soften plastics. If good heat transfer is important, the low thermal conductivity of container walls made of plastic can be a problem. An option is to choose containers with metal walls. Metal walls also have the advantage of higher mechanical stability. It is however necessary to select a suitable metal which is not corroded by the PCM [9].

3.6 Commercial Phase Change Materials

Many substances have been studied as potential PCMs, but only a few of them have been commercialized as so. Often a potential PCM cannot be sold as pure PCM, because handling of the pure material is critical. In most Case, materials are sold in an encapsulated form. The number of commercial PCM, PCM composite materials and encapsulated PCM is growing from year to year, it is therefore impossible to give a complete description of all the available commercial products. Currently, more than 50 PCMs are commercially available with a wide range of phase change temperature. Most commercial PCMs are based on materials from the material classes of the salt hydrates, paraffins and eutectic water-salt solutions [9].

3.7 Desirable Temperature and PCM for Thermal Analysis

PCM melting temperature should be related to the climate specific optimal temperature to achieve maximum performance of the storage. A nonoptimal melting temperature significantly reduces the latent heat of the storage capacity. A 3°C difference from the optimal temperature causes a 50% loss of latent heat storage capacity. There are a large number of PCMs, which can be identified as PCMs from the point of view melting temperature and latent heat of fusion. However, except for the melting point in the operating range, a majority of PCMs do not satisfy the criteria required for an adequate storage media [9].

PCMs that have a melting point near room temperature can replace thermal mass without the bulk of large structures. This can lead to a significant reduction of the building energy consumption, as well as reduction of conventional structure materials. This energy storing building materials can reduce peaks in demand by creating a more even load time characteristic.

3.8 Building Applications of Phase Change Materials

During the last two decades, integration of PCM in wallboards and concrete has gained interest. The performance of gypsum wall boards impregnated with PCM was investigated by Hawes et al. They used direct incorporation and immersion techniques and successfully impregnated 25–30 wt.% PCM in gypsum wallboards. In comparison to conventional wallboards it was found that PCM wallboards have the following properties [14].

- Comparable flexural strength
- Excellent fire resistance than conventional board
- Good compatibility with paints and wallpaper
- More durable in moist environment

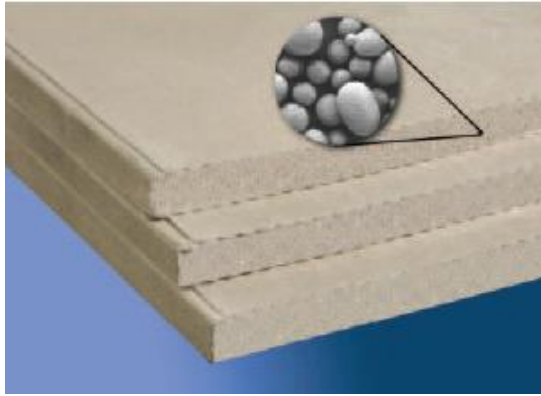


Figure 3.6 PCM smart board

4. MATERIALS AND METHODOLOGY

4.1 Materials

The key material used for the analysis is concrete this due to the reason that it has a high capacity for heat storage and moderate conductance that allows heat to be transferred deep into the material for storage. When sized properly, concrete is effective in managing diurnal energy. Nevertheless, the dimension of concrete should be decided based on the structural requirements. Additional solutions such as incorporation of PCM should be taken if the selected dimension doesn't satisfy the thermal requirements.

Although Steel has a potential for heat storage, due to its high emissivity property large majority of radiation is reflected rather than absorbed and stored, on the other hand its high conductivity indicates an ability to quickly transfer heat stored in the material's core to the surface for release to the environment, thus shortening the storage cycle to minutes rather than the hours needed. Furthermore, for steel the thickness required in order to act effectively as diurnal thermal mass is so large, heavy, and costly that it is not practical.

4.1.1 *Thermal Properties of Materials Used for this Study*

Density

Density refers to the mass per unit volume of a material and is measured in kg/m³. A high-density material maximizes the overall weight and creates a high thermal mass.

- For concrete, the variation of density with temperature is influenced by water loss and is defined as follows [15].

$$\rho(\theta) = \rho(20^{\circ}\text{C}) \text{ for } 20^{\circ}\text{C} \leq \theta \leq 115^{\circ}\text{C}$$

Thus, for concrete with a moisture content of 3% by weight the density is 2300 kg/m³.

- For gypsum board the fixed density (ρ) value obtained from various researches is 800 kg/m³.

- Whereas the density (ρ) of air is given as 1.205 kg/m³

Thermal conductivity

Thermal conductivity of a material can be defined as the rate of Heat transfer through a unit thickness of the material per unit area per unit Temperature difference. Thermal conductivity measures the ease with which heat can travel through a material by conduction.

- The thermal conductivity λ_c of concrete may be determined between lower and upper limit values.

The upper limit of thermal conductivity λ_c for normal weight concrete can be determined from:

$$\lambda_c = 2 - 0.2451 (\theta / 100) + 0.0107 (\theta / 100)^2 \text{ W/mk for } 20^\circ\text{C} \leq \theta \leq 1200^\circ\text{C} \quad 4.1$$

Where θ is the concrete temperature.

The lower limit of thermal conductivity λ_c for normal weight concrete may be determined from:

$$\lambda_c = 1.36 - 0.136 (\theta / 100) + 0.0057 (\theta / 100)^2 \text{ W/m K for } 20^\circ\text{C} \leq \theta \leq 1200^\circ\text{C} \quad 4.2$$

Where θ is the concrete temperature.

- Thermal conductivity of gypsum board is independent of temperature variation and is given as 0.17 W/m.k
- Finally, for air the thermal conductivity is a fixed value of 0.0257 W/m.k

4.1.2 Thermal Properties of PCM

As discussed previously in Section 3.7 the melting temperature of PCM should be related to the climate specific optimal temperature to achieve maximum storage capacity. Based on the climate specific average temperatures for the five stations the selected PCMs are shown on the Table 4.1 below [16] .

Table 4.1 Commercial PCM selected for analysis

Type	Supplier	Group	Form	Melting temperature, T _m °c/°k	Latent heat of fusion, L kj/kg	Density, ρ kg/m ³	Liquid Thermal conductivity, k W/m·K	Solid Thermal conductivity, k W/m·K	Specific heat, cp kj/kg·K
1	Insolcorp	Inorganic	Macro-encapsulated	18 °c /291.15 °k	200	1540	0.54	1.09	3.14
2	Insolcorp	Inorganic	Macro-encapsulated	23 °c /296.15 °k	200	1540	0.54	1.09	3.14
3	TEAP	Inorganic	Bulk	24 °c /297.15 °k	175	1490		1	2
4	Plusice	Organic	Bulk	26 °c /299.15 °k	150	790		0.21	2.22
5	Insolcorp	Inorganic	Macro-encapsulated	29 °c /302.15 °k	200	1540	0.54	1.09	3.14

The selection of PCM is based on station specific mean temperature values. These values are specified on Appendix A. Based on these average values, compatible PCM is selected. There are three stations which represent the overall temperature in Addis Ababa. These stations are Addis Ababa bole station, Akaki station and Intoto station. Type 2 PCM is selected for Addis Ababa bole station since the average mean temperature is 23.70°C/296.9°k. For Akaki station having 26.479°C/299.6°k mean temperature, Type 4 PCM is chosen. Type 1 PCM is chosen for Intoto station having 17.818°C/290.968°k mean temperature. Similarly, for Dire Dawa city two stations are provided to represent the overall temperature in the city. These stations are Dengego station and Dire Dawa station. Type 3 PCM is selected for Dengego station having mean temperature 24.372°C/297.522°k. Finally, for the Dire Dawa station having mean temperature of 32.986°C /306.136°k, Type 5 PCM is selected.

4.2 Methodology

4.2.1 Method for the Selection of Temperature Data

The critical input for the analysis portion of the thesis is gathering of thermal data. The weather data including monthly maximum and minimum temperature, for ten years, was collected from National Metrology Agency (NME). The data was gathered for two cities,

Addis Ababa and Dire Dawa. The choice of the city's is based on the number of population ranking [17] [18] [19]. Based on the choice of cities, five stations which are located around the perimeters were taken. Accordingly, three stations (Addis Ababa Bole, Akaki, and intoto) were selected to represent the temperature at Addis Ababa and two stations (Dire Dawa, Dengego) were selected to represent the temperature at Dire Dawa. The different station data's were considered separately as for the reason that, the structure built at one part of the city will be affected with different temperature distribution from other locations of the city. Subsequently the thermal data were collected and statistical analysis were done for each station separately. The reviewed temperature data for the five stations is provided on Appendix A.

The following step of the data analysis process consists of calculation of the Normal Distribution, Standard Deviation and computation for 95% Confidence Interval to eliminate the upper and lower extreme data's.

Normal Distribution

The normal distribution is a commonly occurring continuous probability distribution. The graph of the probability density $f(x)$ is known as the "bell curve", as it exhibits symmetry about the center with approximately 50% of the values less than the mean and 50% greater than the mean. The probability density function is given by [20]:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \text{ where } \mu \text{ is its Mean and } \sigma \text{ its Standard Deviation} \quad 4.3$$

For any distribution X , the Mean, denoted μ , is the expected value of X . The Variance, σ^2 , is the expected value of the square of the difference between the value of the X and its Mean. The square root of the Variance, σ , is called the Standard Deviation.

Confidence Interval

A confidence interval is a range of values that represent an estimate for an unknown population parameter. The endpoints can be determined [21]:

$$\text{Lower Endpoint} = \bar{X} - 1.96 \frac{\sigma}{\sqrt{n}} \quad 4.4$$

$$\text{Upper Endpoint} = \bar{X} + 1.96 \frac{\sigma}{\sqrt{n}} \quad 4.5$$

Generalizing, the mean confidence interval can be calculated in the following manner:

$P\left(\bar{X} - Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \leq \mu \leq \bar{X} + Z_{\alpha/2} \frac{\sigma}{\sqrt{n}}\right)$, where α is the significance level, σ is the Standard Deviation, n is the sample size, and μ is the mean.

4.2.2 Methodology for Case Selection

There are total of seventy-nine Cases carefully chosen for the thesis. The criteria for the Case selection process is described below:

Procedure 1: Sensitivity Procedure for Thermal Mass Achieving Thickness Determination

As discussed previously in Section 3.2, sensible heat storage is often common in solid materials, like stone, brick and concrete. Thus, the first eight Cases were selected to determine the sufficient concrete thickness to achieve thermal comfort (25°C/298°k) without any additional latent heat storage material like PCM. Various thicknesses ranging from 0.15m to 0.30m were considered to study the effect of the thickness variation on the Heat Flux and Nodal Temperature distribution in a concrete specimen. In addition to the various thicknesses, the analysis is done for 28°C and 34°C which are total max temperature for Addis Ababa and Dire Dawa city respectively. The Cases for this Procedure range from Case 1 to Case 8.

Table 4.2 Cases for Procedure one

Case numbers for Procedure 1 (concrete only)	Maximum Temperature (°C)	Concrete Thickness(m)	Remark
Case 1	Addis Ababa Max (28°C)	0.15	<ul style="list-style-type: none"> - Thermal analysis was done only for concrete wall - Done for various thickness - No adjacent layer - No PCM - Consists of (Case 1 - Case 8)
Case 2		0.2	
Case 3		0.25	
Case 4		0.3	
Case 5	Dire Dawa Max (34°C)	0.15	
Case 6		0.2	
Case 7		0.25	
Case 8		0.3	

Procedure 2: Control Cases for Comparison with Procedure 3

The second Procedure consists of two layered wall material, concrete and Gypsum wallboard. This process is done as a control parameter for the comparison purpose with the Third Procedure which is wall consisting of concrete and microencapsulated Gypsum wall board. The Cases on this Procedure cover all the temperatures that prevail both in Addis Ababa and Dire Dawa (7°C - 34°C). These Procedure ranges from Case 9 to Case 34. Primarily the parameters fixed in this Procedure are the thickness for the concrete wall as 20cm and the Gypsum wallboard thickness as 14cm.

Table 4.3 Cases for Procedure two

Case numbers for Procedure 2 (concrete +gypsum board)	Prevailing temperatures (°C)	Remark
Case 9	7	<ul style="list-style-type: none"> - Concrete wall of 20cm thickness and gypsum wall board of 14cm thickness. - NO PCM - It is done for all the temperatures both in Addis Ababa and Dire Dawa. - It is used as a control for the Cases with PCM. - Consists of (Case 9 - Case 34)
Case 10	8	
Case 11	9	
Case 12	10	
Case 13	11	
....	
Case 32	33	
Case 33	34	

Procedure 3: Investigation of the Effect of PCM Integration on Thermal Property Improvement

The third Procedure focus on the effect of integration of PCM on the overall improvement of thermal properties of a wall. The temperature distribution at each station is various. Thus, stations in Addis Ababa and Dire Dawa should be considered separately. For this procedure, the concrete layer thickness is fixed as 20cm and the micro-encapsulated gypsum wall board layer thickness is fixed as 14cm. The PCM selection for the various stations was described earlier in Section 4.1.2. Based on the diverse prevailing temperature distributions at various stations, the Cases are explained as follows.

Table 4.4 Cases for Addis Ababa Bole station

Case Numbers for (Concrete +PCM) Addis Ababa Bole	Prevailing Temperatures (°C)	Remark
Case 34	9	<ul style="list-style-type: none"> - Two wall layers - 20cm concrete wall ,14cm micro-encapsulated gypsum wall board. - The PCM used is Type 2 with properties shown in Table 4.1 - Consists of (Case 34 - Case 41)
Case 35	10	
Case 36	11	
Case 37	12	
Case 38	23	
Case 39	24	
Case 40	25	
Case 41	26	

Table 4.5 Cases for Akaki station

Case Numbers for (Concrete +PCM) Akaki	Prevailing Temperatures (°C)	Remark
Case 42	7	<ul style="list-style-type: none"> - Two wall layers - 20cm concrete wall, 14cm micro-encapsulated gypsum wall board. - The PCM used is Type 4 with properties shown in Table 4.1 - Consists of (Case 42 - Case 52)
Case 43	8	
Case 44	10	
Case 45	12	
Case 46	15	
Case 47	16	
Case 48	17	

Case Numbers for (Concrete +PCM) Akaki	Prevailing Temperatures (°C)	Remark
Case 49	25	
Case 50	26	
Case 51	27	
Case 52	28	

Table 4.6 Cases for Intoto station

Case Numbers for (Concrete +PCM) Intoto	Prevailing Temperatures (°C)	Remark
Case 53	8	<ul style="list-style-type: none"> - Two wall layers - 20cm concrete wall, 14cm micro-encapsulated gypsum wall board. - The PCM used is Type 1 with properties shown in Table 4.1 - Consists of (Case 53 - Case 60)
Case 54	9	
Case 55	10	
Case 56	16	
Case 57	17	
Case 58	18	
Case 59	19	
Case 60	20	

Table 4.7 Cases for Dengego station

Case Numbers for (Concrete +PCM) Dengego	Prevailing Temperatures (°C)	Remark
Case 61	11	<ul style="list-style-type: none"> - Two wall layers - 20cm concrete wall ,14cm micro-encapsulated gypsum wall board. - The PCM used is Type 3 with properties shown in Table 4.1 - Consists of (Case 61 - Case 71)
Case 62	12	
Case 63	13	
Case 64	14	
Case 65	15	
Case 66	16	
Case 67	23	
Case 68	24	
Case 69	25	
Case 70	26	
Case 71	27	

Table 4.8 Cases for Dire Dawa station

Case Numbers for (Concrete +PCM) Dire Dawa	Prevailing Temperatures (°C)	Remark
Case 72	18	<ul style="list-style-type: none">- Two wall layers- 20cm concrete wall ,14cm micro-encapsulated gypsum wall board.- The PCM used is Type 5 with properties shown in Table 4.1- Consists of (Case 72 - Case 79)
Case 73	19	
Case 74	20	
Case 75	21	
Case 76	31	
Case 77	32	
Case 78	33	
Case 79	34	

5. MODELING AND ANALYSIS

5.1 Introduction

The simulation process for steady state heat transfer analysis is done by using FEM software ABAQUS. The required output variables for one dimensional conduction problem are Nodal Point Temperature (NT) and Heat Flux (HFL). Heat Flux is the rate of heat energy transfer through a given surface per unit time. Since the temperature at the interface between consecutive layers is similar Tie constraint is used to equate the temperature at the matching points at the interface. DC3D8 an 8-node linear heat transfer element type is used for all the Cases in the analysis. The transverse wall area is taken as 2m by 2m.

5.2 Modeling

5.2.1 Basic Considerations for Modeling

There are two boundary conditions taken for every analysis. These boundary conditions are external surface temperature specified on Table 4.4 up to Table 4.8 and an internal temperature of a magnitude of 0°C applied on the interior part of a 50cm thickness wall modeled as air. The air is modeled to see the effect of the thermal drop and the consecutive falling of temperature in the room.

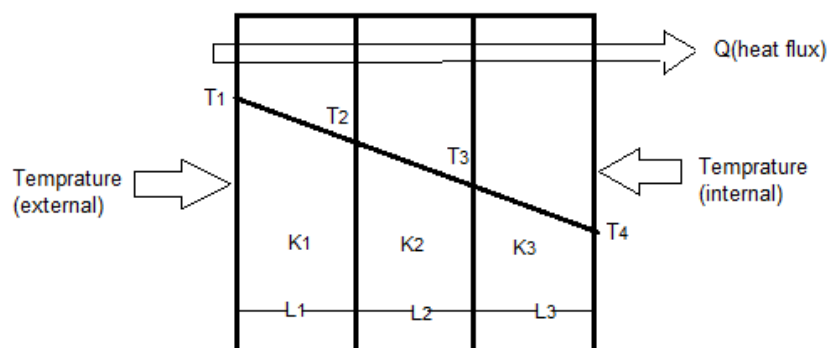


Figure 5.1 Temperature and Heat Flux distribution through multilayered wall

Where

Temperature external - the values vary for the three procedures and for the particular Cases. The values are specified in Section 4.2.2

Temperature internal - a magnitude of 0°C is specified for the internal boundary condition. Fixing the internal temperature in value other than zero will not allow to see the drop in the temperature variation.

K_1 , K_2 , K_3 - are the conductivity values for the three layers

For Procedure 1

L_1 - thickness of concrete layer (20cm)

L_2 - thickness for layer of air (50cm)

L_3 - NO THIRD LAYER AVILABLE

For Procedure 2

L_1 - thickness of concrete layer (20cm)

L_2 - thickness of gypsum board (14cm)

L_3 - thickness for layer of air (50cm)

For Procedure 3

L_1 - thickness of concrete layer (20cm)

L_2 - thickness of micro-encapsulated gypsum board (14cm)

L_3 - thickness for layer of air (50cm)

5.2.2 Stapes Taken for the Overall Modeling Process

The modelling procedures consists of at least eight steps. Each stage and the values considered are clarified below.

- i. Construction of parts (wall layers), the various wall layers are modeled according to the provided thicknesses

- ii. Introduction of the thermal properties for various materials including the layer of air.
- iii. The Assembly process, the sections are assembled to parts and linked to the material properties of the respective layer.
- iv. In this stage, the type of the analysis whether it is steady state or transient is chosen. For this study, steady state is considered.
- v. Creating an interaction, a Tie constraint is selected to equate the temperatures at the matching nodes in the interface.
- vi. Creating boundary conditions, the basic considerations for the values are clarified in Section 5.2.1.
- vii. Creating a mesh. The 2m by 2m lateral area is subdivided into a mesh of 0.1m square and the thickness is divided to 0.01m mesh to see the detailed temperature drop. The mesh distribution for three layered wall is shown in the Figure 5.2 below.
- viii. Creating a job and submit the model for Analysis.

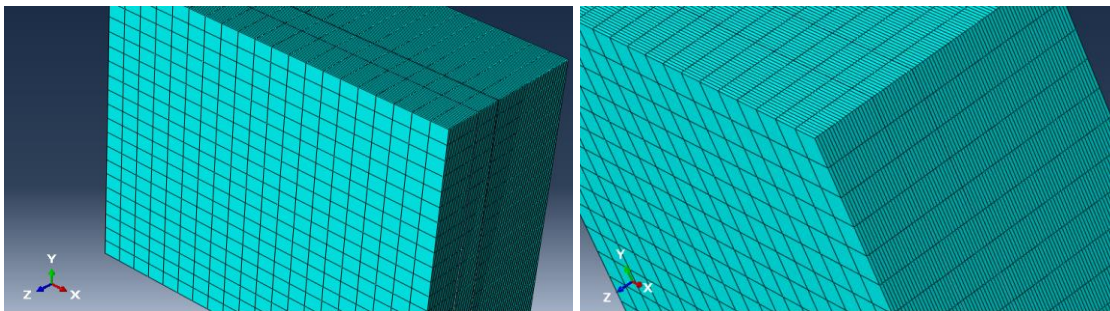


Figure 5.2 Meshing distribution for three layered wall model

5.3 Analysis

As the thickness of nonstructural infill wall increase, the temperature fluctuation will decrease since thermal mass carrying capacity of the wall increase. Thus, initial analysis will be done to obtain the optimum thickness to create thermal comfort and the following analyses will aid to create a visualization on thermal enhancement due to PCM integration.

6. SUMMARY OF RESULTS AND DISCUSSION

6.1 Sensitivity Procedure for Thermal Mass Achieving Thickness Determination

Maximum temperature of 28°C and 34°C for Addis Ababa and Dire Dawa respectively were used to obtain the optimum thickness of concrete to achieve thermal comfort (25°C/298°k) only by thermal mass without any additional latent heat storage system.

It can be realized from Figure 6.1 that, for all the temperatures considered in the analysis, the Heat Flux decrease in a linear manner throughout the various thicknesses. It can also be observed that, Heat Flux increases as the temperature increase. However, the Heat Flux variation is small for the values around thickness of 25cm.

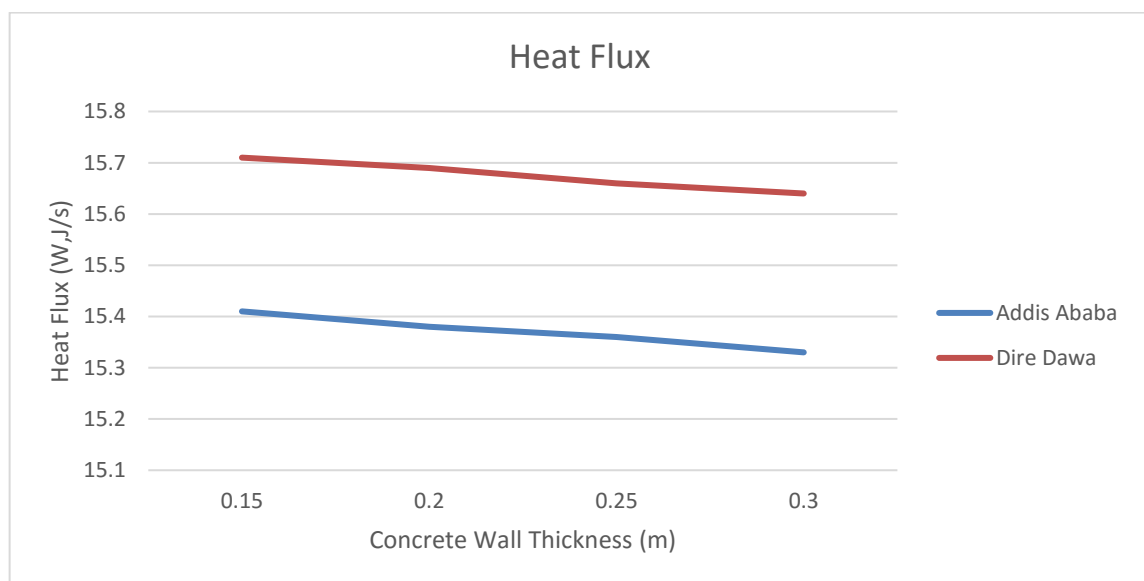


Figure 6.1 Heat Flux distribution throughout the thickness concrete wall

For the Case of Nodal Temperature distribution, the temperature decrease linearly for each Case until it achieves the thermal comfort level and then start to drop abruptly. From the data, it can be seen that for the temperature of 28°C (Addis Ababa Max), thermal comfort is achieved around 23cm thickness. As the temperature increase to 34°C (Dire Dawa Max), thermal comfort is reached at a thickness around 29cm.

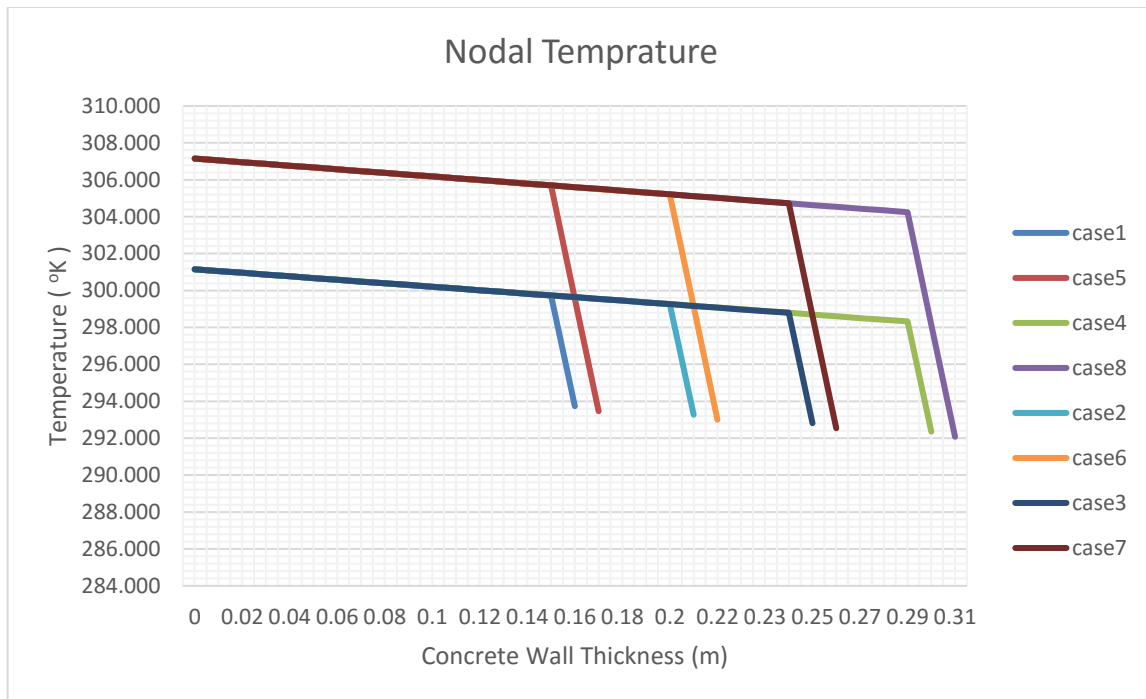


Figure 6.2 Nodal Temperature distribution throughout the thickness of concrete wall

Based on the above observations on Heat Flux and Nodal Temperature graphs the average thickness of 25cm is recommended for concrete wall to create a thermal comfort. However, as the temperature increases other thermal storage mechanisms should be considered.

6.2 Investigation of the effect of PCM Integration on Thermal Property Improvement

Based on the Results of Procedure 1, 25cm is recommended for concrete wall to achieve thermal comfort without any additional thermal storage systems. For the subsequent Cases, 20cm concrete wall is fixed to visualize change due to the incorporation of PCM.

Therefore, by fixing the concrete wall thickness parameter as 20cm the analysis is done for each station as follows.

6.2.1 Addis Ababa Bole Station

From the graph in Figure 6.3 the primary observation shows greater Heat Flux values for wall containing PCM rather than the one without PCM. This is due to the latent heat

storage capacity of PCM wall. Since the fusion temperature for Type 2 PCM is at 23°C, temperatures greater than the melting temperature of the PCM, maintains small Heat Flux variation.

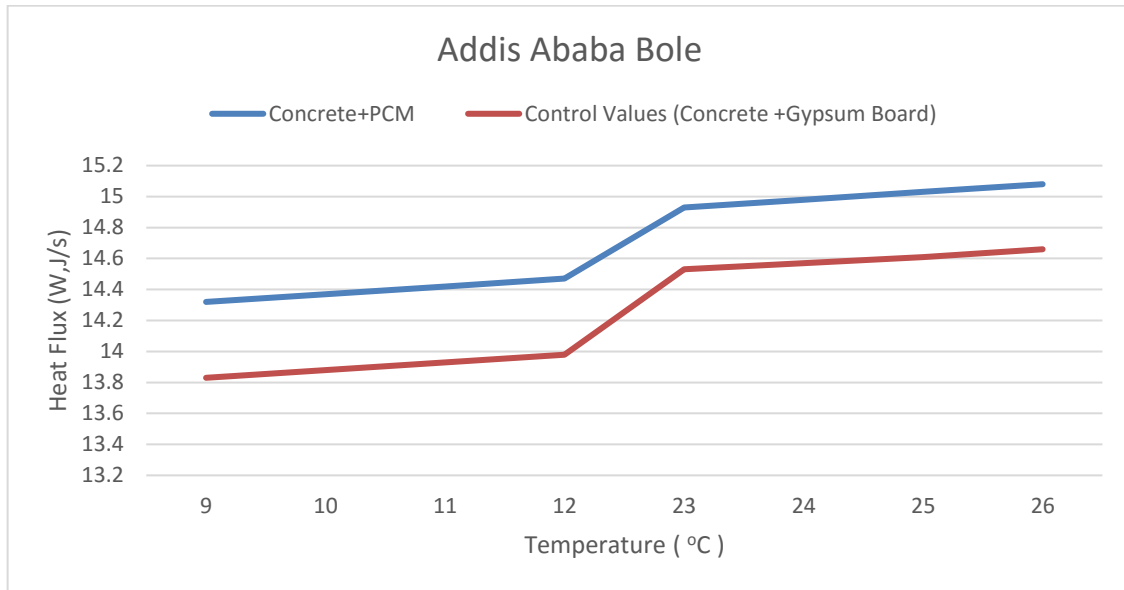


Figure 6.3 Comparison of Heat Flux distribution for Addis Ababa Bole station

6.2.2 Akaki Station

Based on the graph in Figure 6.4, the Heat Flux distribution of the model with PCM is analogous with the control model. This is due to the reason that latent heat of fusion and solid thermal conductivity from Table 4.1 for Type 2 PCM is low and there is no data provided for liquid thermal conductivity. Consequently, these factors affect the PCM to have less Heat Flux outcomes. The other observation indicates that the Heat Flux variation is small for the wall containing PCM when the temperature is higher than the fusion temperature.

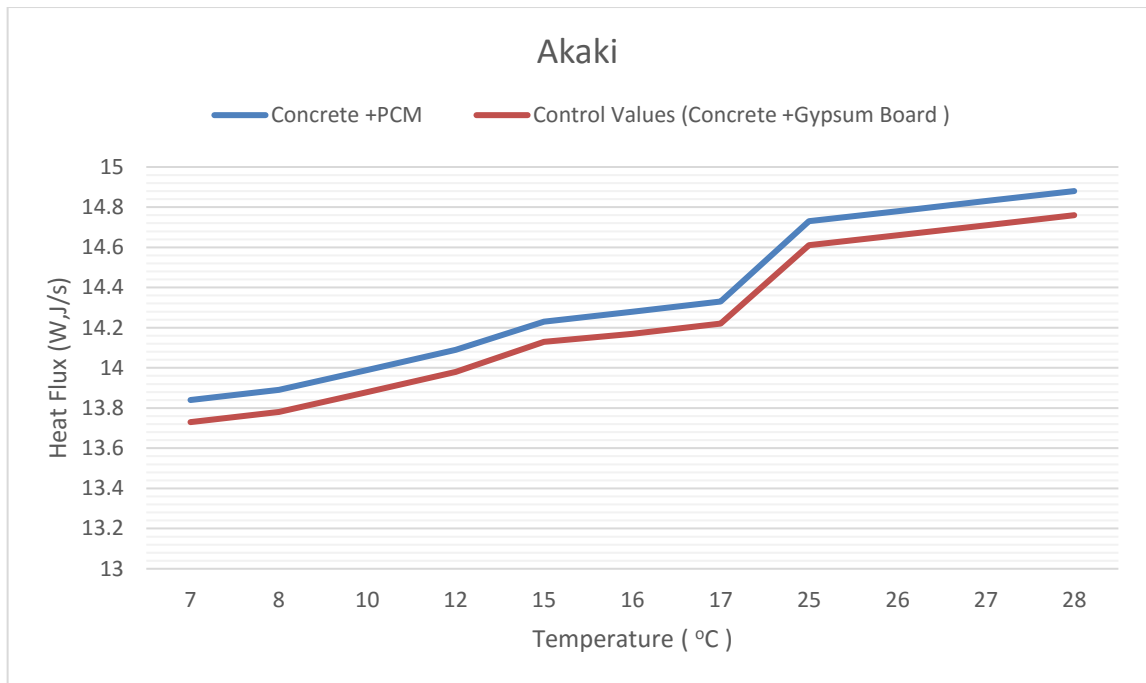


Figure 6.4 Comparison of Heat Flux distribution for Akaki station

6.2.3 Intoto Station

From the graph in Figure 6.5 it can be seen that the Heat Flux distribution is almost constant throughout the temperature range for the model containing PCM. In such cold reigns, lower melting temperature will maintain the Heat Flux constant. Although for the other stations most of the fusion temperatures observed has higher values. Consequently, it will create variation between solid state Heat Flux with the liquid state heat flux.

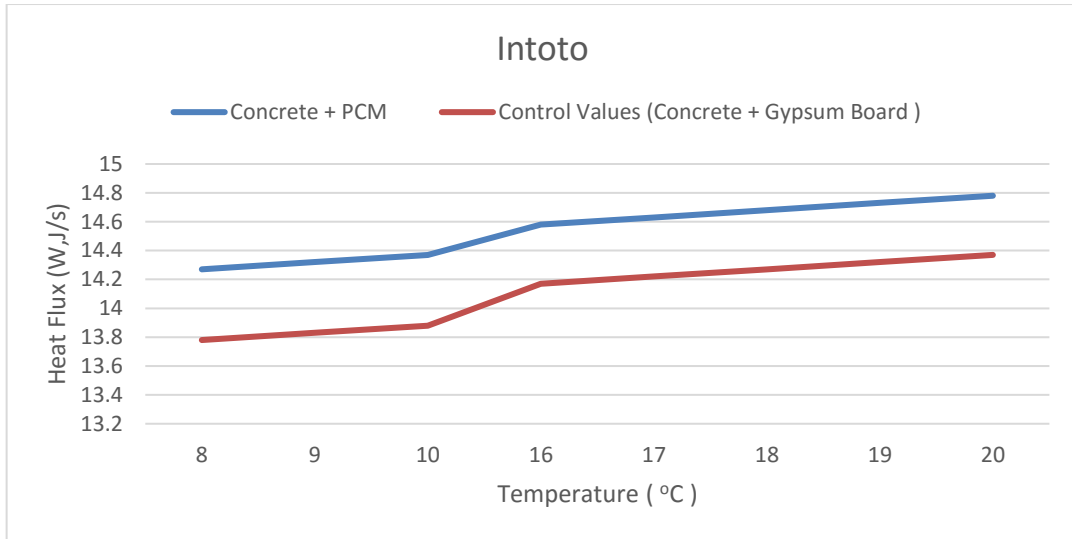


Figure 6.5 Comparison of Heat Flux distribution for Intoto station

6.2.4 Dengego Station

The higher thermal conductivity and the medium latent heat of fusion will create constant Heat Flux distribution throughout the various temperature ranges in this station.

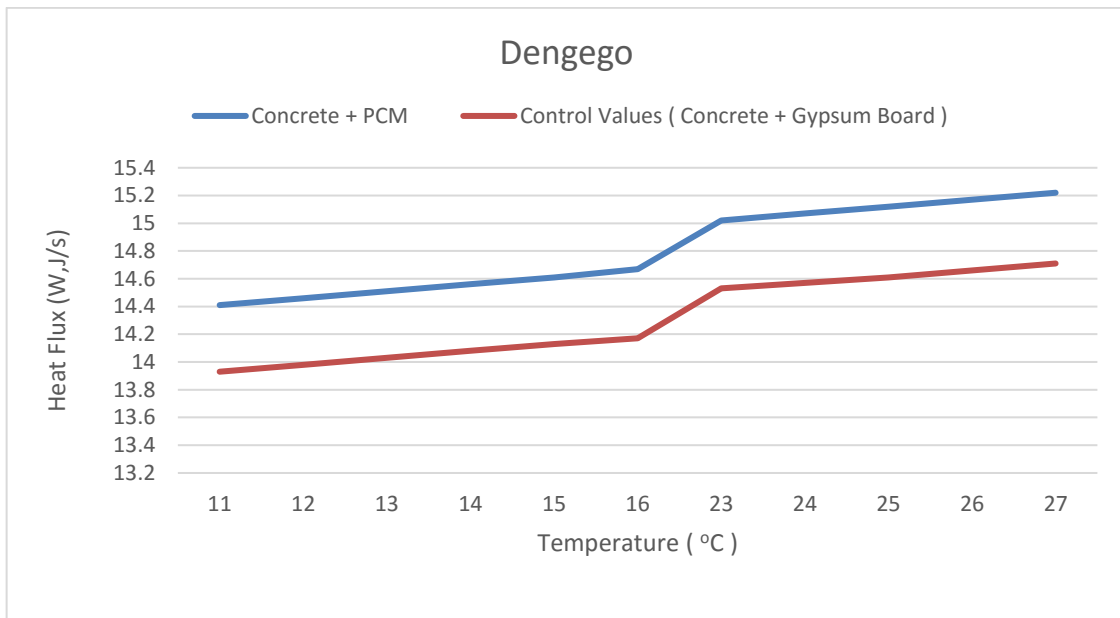


Figure 6.6 Comparison of Heat Flux distribution for Dengego station

6.2.5 Dire Dawa Station

From Figure 6.7 the elevated storage in PCM is ascribed to the high latent heat capacity and heat retaining susceptibility.

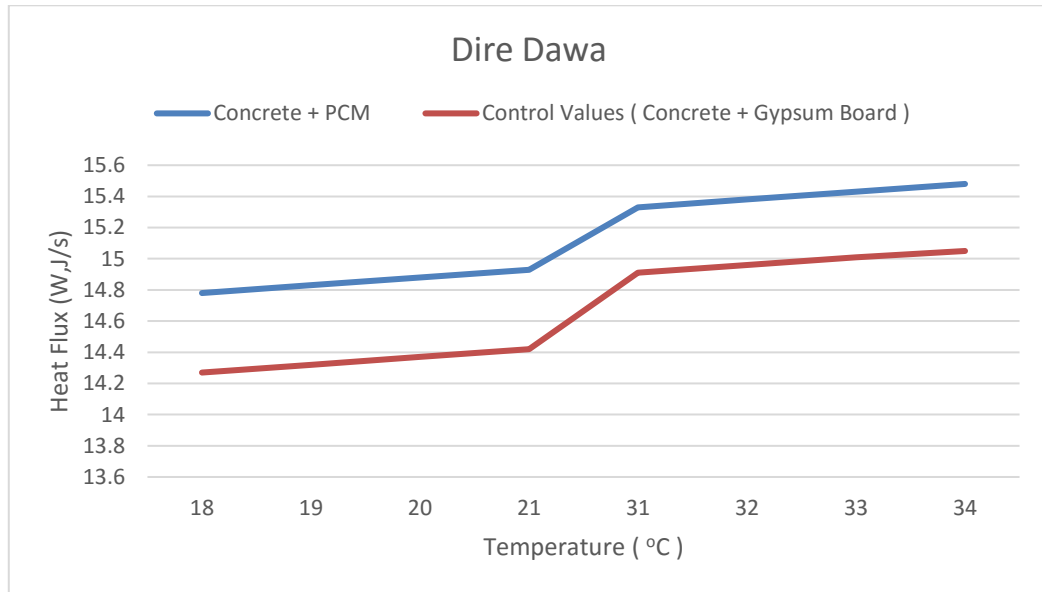


Figure 6.7 Comparison of Heat Flux distribution for Dire Dawa station

6.3 Comparison of wall without PCM (Procedure two) and wall containing PCM (Procedure three)

The Cases taken for comparison purpose are described below:

- From Procedure 2: Case29 for 28°C and Case33 for 34°C
- From Procedure 3: Case52 for 28°C and Case79 for 34°C

Visualization of the results from Figure 6.8 indicates almost similar Heat Flux values for temperature of 28°C. Whereas for temperature of 34°C the Heat Flux is higher for the model with PCM and lower for the model without PCM.

From the above observation, it can be suggested that for lower temperatures heat can be stored in thermal mass but for higher temperatures, latent heat storage system should be provided for additional heat storage capacity.

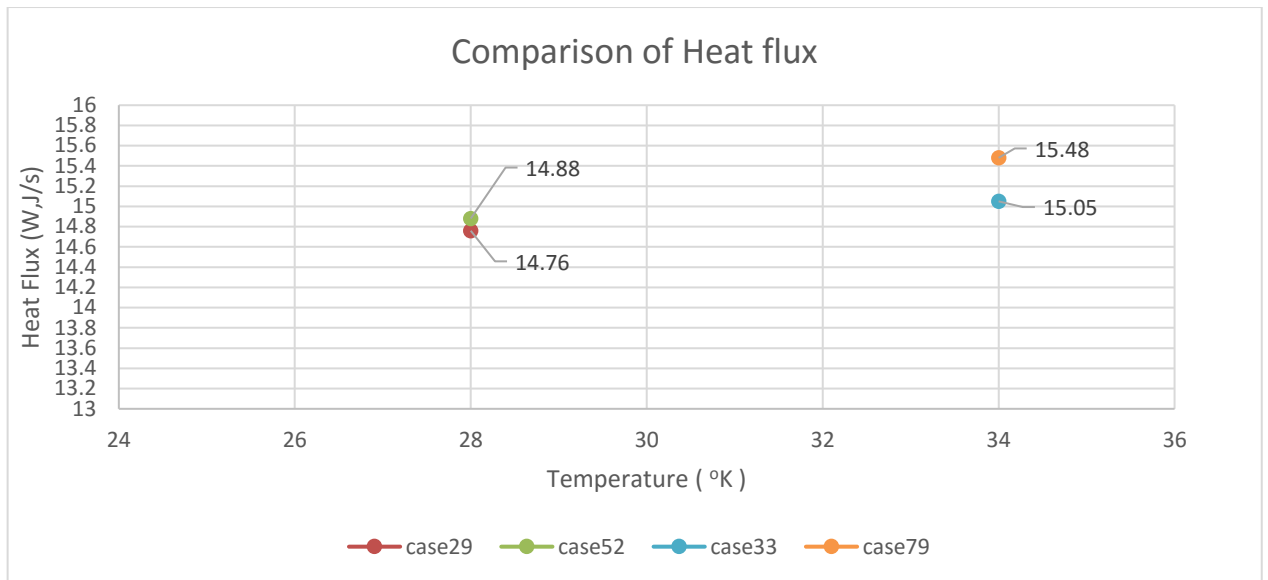


Figure 6.8 Comparison of Heat Flux

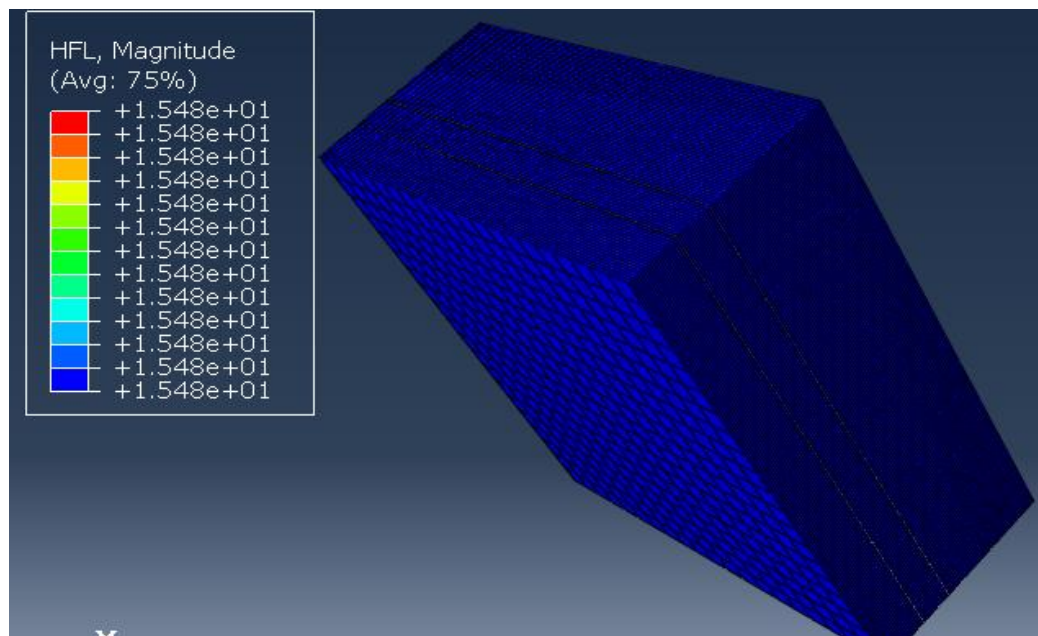


Figure 6.9 Abaqus model Heat Flux value for Case seventy-nine

Correspondingly, for the Case of Nodal Temperature (NT) values from Figure 6.10, the values drop very suddenly for the model without PCM. This is due to the small heat storage capacity of Gypsum board. However, for model containing PCM the latent heat storage capacity enables to hold heat throughout the Microencapsulated gypsum board thickness. Additionally, the drop of temperature is gradual throughout thickness.

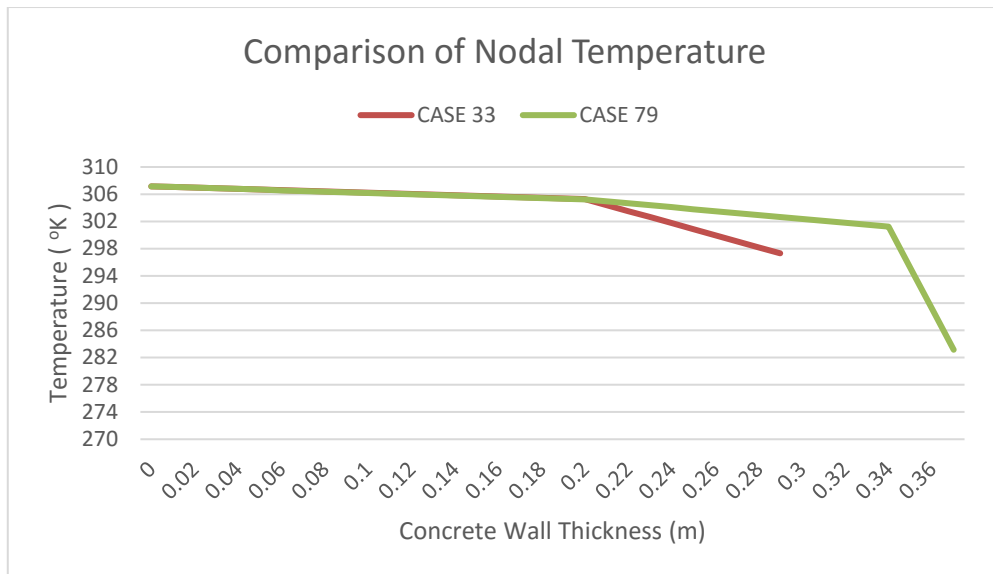


Figure 6.10 Comparison of Nodal Temperatures

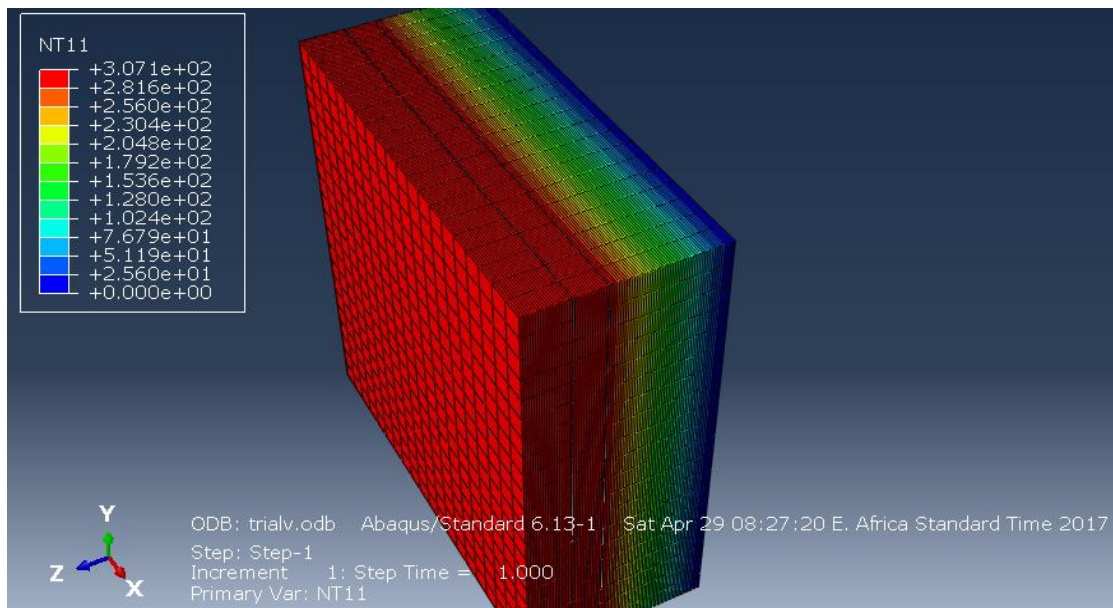


Figure 6.11 Abaqus model Nodal Temperature Values for Case seventy-nine

6.4 Comparison of Analytical Verification Vs Abaqus results

The formulation of equations for the Analytical verification method is based on the concepts explained on Appendix D. Thus, the Analytical and the Abaqus results are compared and the percent error is computed to check the variation between the results.

6.4.1 Heat Flux Comparison

Comparison of Heat Flux values is done for Cases ranging from 1 to 4 (sample Cases for Procedure 1) and Case ranging from 34 to 41 (sample Cases for Procedure 3). These comparisons are done based on Equation D.12.

From the results shown in Table 6.1 and Figure 6.13, it can be confirmed that the Abaqus and the analytical results are similar and the error is very small.

Example - For Case one

$$q''_x = \frac{1}{\left(\frac{0.15m}{1.62728888}\right) + \left(\frac{0.5m}{0.0257}\right)} * (301.15-0) = 15.40611672$$

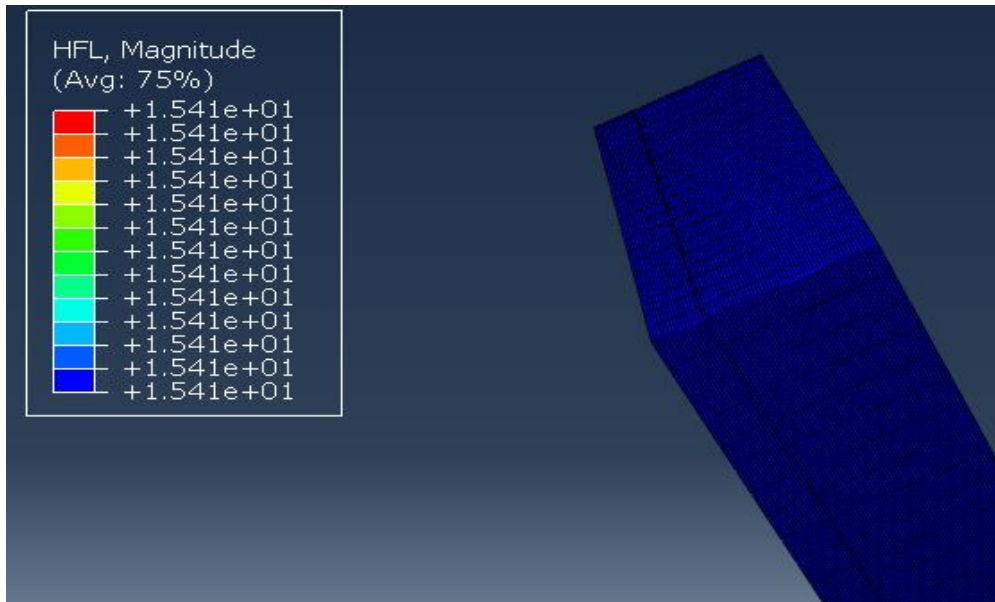


Figure 6.12 Abaqus model Heat Flux value for Case one

Table 6.1 Tabular Heat Flux comparison for Cases one to four

Heat Flux (W, J/s) for Procedure one			
Case No	Abaqus	Analytical	% error
Case1	15.41	15.40611672	0.02520612
Case2	15.38	15.38193836	0.012601544
Case3	15.36	15.35783578	0.01409196
Case4	15.33	15.33380861	0.02483802

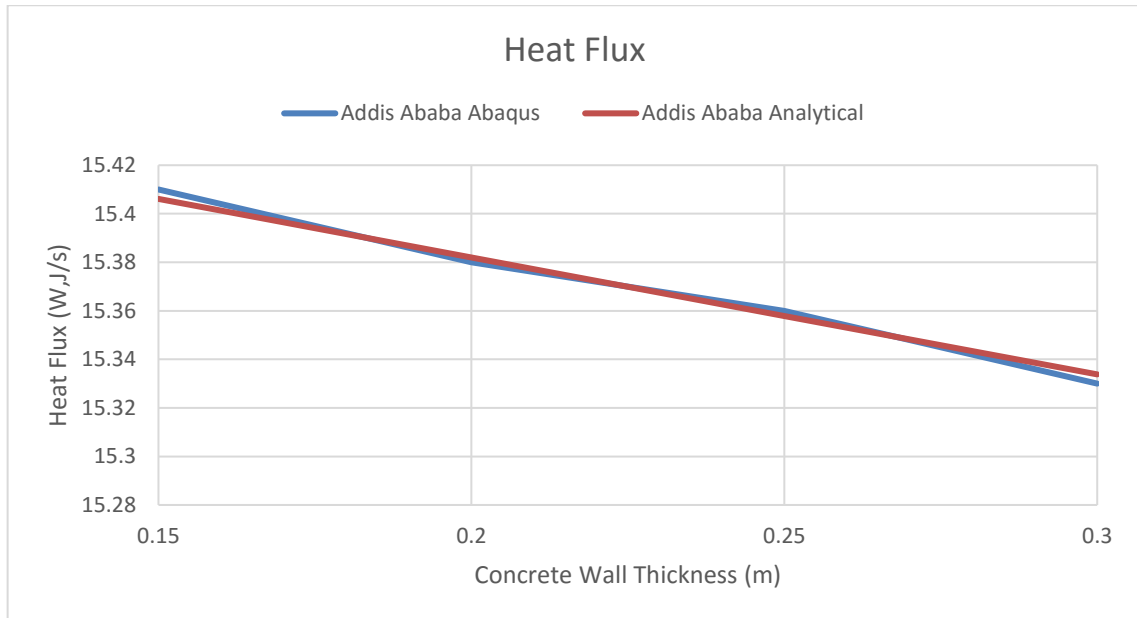


Figure 6.13 Graphical Heat Flux comparison for Cases one to four

As for Cases on Procedure 3 (concrete + microencapsulated PCM), from Table 6.2 and Figure 6.14 the maximum error obtained for the comparison of Analytical verses Abaqus results is 0.009712063%.

Example - For Case thirty-four

$$Q''_x = \frac{1}{\left(\frac{0.2m}{1.66291692}\right) + \left(\frac{0.14m}{1.09}\right) + \left(\frac{0.5m}{0.0257}\right)} * (282.15 - 0) = 14.31945378$$

Table 6.2 Tabular Heat Flux comparison for Addis Ababa Bole station

Heat Flux for Addis Ababa Bole			
Case No	Abaqus	Analytical	% error
Case34	14.32	14.31945378	0.003814532
Case35	14.37	14.37010519	0.000731999
Case36	14.42	14.42075575	0.005240735
Case37	14.47	14.47140547	0.009712063
Case38	14.93	14.92938634	0.004110394
Case39	14.98	14.97969252	0.002052634
Case40	15.03	15.02999784	1.43478E-05
Case41	15.08	15.08030231	0.00200465

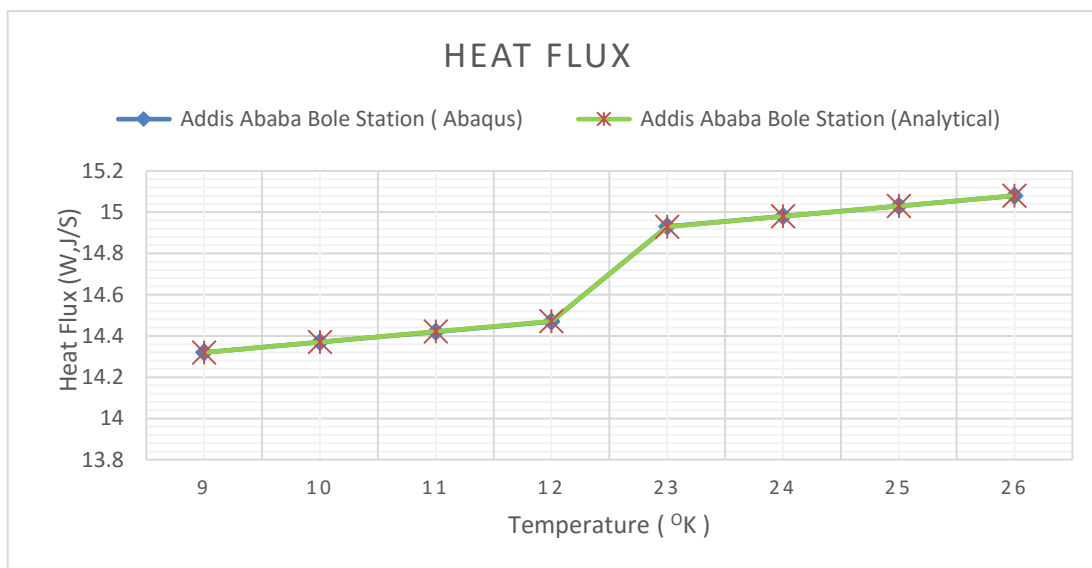


Figure 6.14 Graphical Heat Flux comparison for Addis Ababa Bole station

6.4.2 Nodal Temperature Comparison

For the verification of nodal temperature, a simplified model of concrete 2mX2mX0.2m cross section is taken. The temperature that is applied to the model is 34°C with the material values as specified in Section 4.1.1. The analytical results are calculated by using Equation D.10. As seen in Table 6.3, the Nodal Temperature results for the Abaqus and the Analytical outputs are the same. Likewise, From Figure 6.16 it can be observed that the results align.

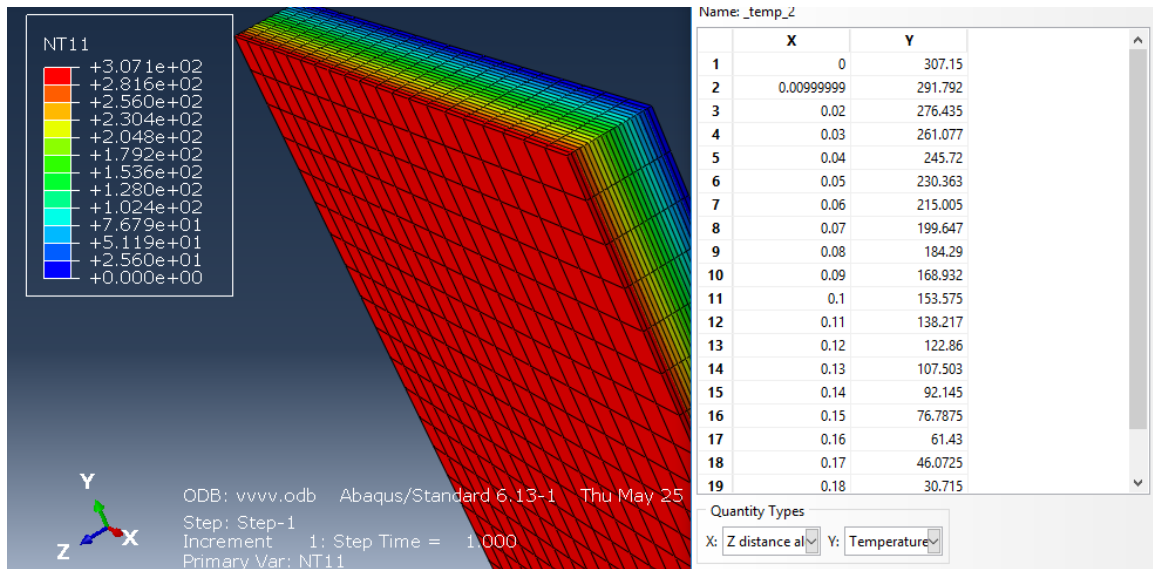


Figure 6.15 Abaqus model Nodal Temperature values for the simplified model

Table 6.3 Nodal Temperature distribution for simplified model

Nodal temperature					
Thickness(m)	Abaqus	Analytical	Thickness(m)	Abaqus	Analytical
0	307.15	307.15	0.11	138.217	138.2175
0.01	291.792	291.7925	0.12	122.86	122.86
0.02	276.435	276.435	0.13	107.503	107.5025
0.03	261.077	261.0775	0.14	92.145	92.145
0.04	245.72	245.72	0.15	76.7875	76.7875
0.05	230.363	230.3625	0.16	61.43	61.43
0.06	215.005	215.005	0.17	46.0725	46.0725
0.07	199.647	199.6475	0.18	30.715	30.715
0.08	184.29	184.29	0.19	15.3575	15.3575
0.09	168.932	168.9325	0.2	6.21E-36	0
0.1	153.575	153.575			

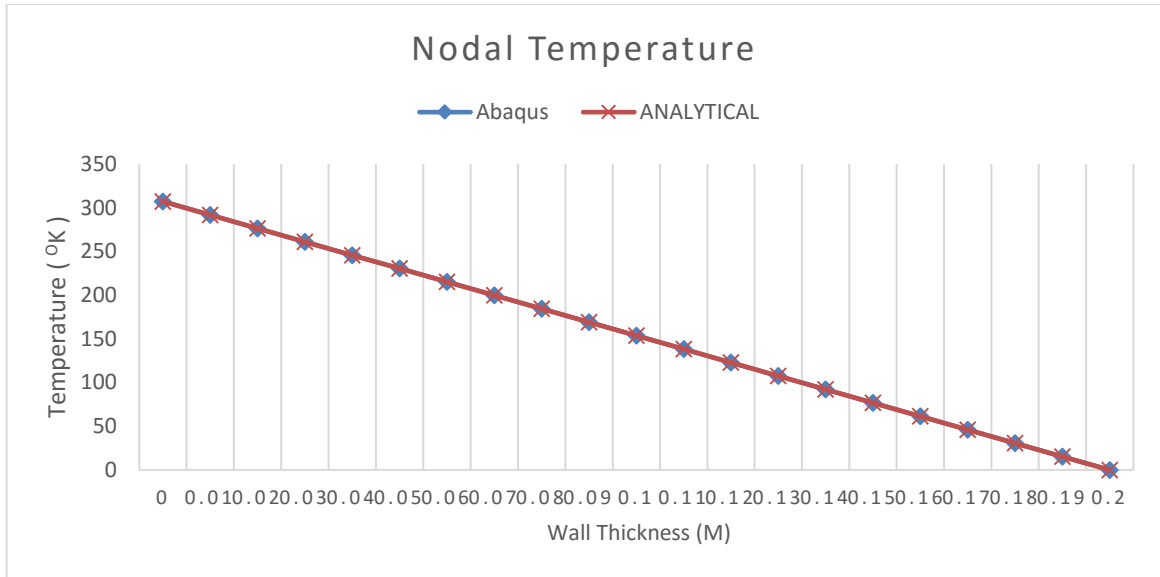


Figure 6.16 Abaqus and Analytical result comparison for simplified model

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

Nonstructural walls are not considered in analysis and design of RC frame buildings in current design practice in many countries. They are assumed to not carry any vertical or lateral forces and their thermal contribution is mostly ignored. This assumption causes a large gap between the building that is considered in analysis and design. Thus, due consideration should be given to these elements for their structural and thermal contributions. This thesis is mainly concerned with the thermal contributions and enhancement of the thermal properties of such walls.

- Based on observations of the results, a thickness of 25cm is recommended for concrete wall to create a thermal comfort. However, as the temperature increases other thermal storage mechanisms should be considered.
- For lower temperatures heat can be stored in thermal mass. However, for higher temperatures, latent heat storage system should be provided for additional heat storage capacity. The drop of temperature is not sudden rather it is gradual throughout thickness for wall containing PCM.
- Observation of the result shows grater Heat Flux value can be obtained for wall containing PCM rather than the one without PCM. The elevated storage in PCM walls is ascribed to the high latent heat capacity and heat retaining susceptibility.

7.2 Recommendation

Cumulative movement due to creep and shrinkage may be significantly large to cause distress in nonstructural elements. Thermal cracking occurs due to excessive temperature difference within a concrete or its surrounding. The temperature difference causes the cooler portion to contract more than the warmer portion, which results in tensile stress that exceed the in-place concrete tensile strength. In most cases, thermal cracking can occur when concrete surfaces are exposed to extreme temperature rapidly. The heat dissipates quickly in thin sections and cause no problems. However, in thicker sections, the internal temperature rises and drops slowly. Consequently, thermal cracks appear. Further studies should be done for thick concrete sections, to visualize the role of thermal and moisture variation on mass concrete, as this thesis is only concerned with thin sections, where this problem is not significant. Some of the other recommendations are listed below.

- Emphasis should be given on the lifecycle evaluation of construction materials. And should be done prior to selection process.
- Structures should be both economically and environmentally Sustainable. Thus, during structural design, thermal comfort considerations should also be considered.
- Careful selection process of phase changing materials should be done prior to its application. In addition, compatibility check with the temperature and the host material should be considered.
- Further study on the detailed country specific economic feasibility assessment and the financial return period of PCM should be done.
- There is lack of research regarding successful utilization of PCM especially into cement based materials. Some of the Cases that should be studied are, the effect on the bonding between the paste and the aggregate, effect on the mechanical properties and the durability properties. If the encapsulation of the container is rigid enough, it can also add mechanical stability to a system, if not, leakage of the PCM may interfere with the hydration products and may affect the mechanical and durability properties of the system.

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APPENDIX A: TEMPERATURE DATA EVALUATED USING STATISTICAL ANALYSIS

In this appendix, the values of mean temperature for ten-year data, are analyzed by using the Procedure specified in Section 4.2.1. Separate table is created for the various stations consisting of the upper and lower values for 95% and Standard Deviation values.

Table A.1 Temperature data evaluated for Addis Ababa Bole station

Addis Ababa Bole										
Temp (Max)	Year	Mean	Standard Deviation	Upper Limit	Lower Limit	Temp (Min)	Mean	Standard Deviation	Upper Limit	Lower Limit
	2006	23.233	1.632	23.704	22.762		10.800	1.322	11.182	10.418
	2007	22.983	1.800	23.503	22.464		10.458	2.107	11.067	9.850
	2008	23.433	1.829	23.961	22.905		10.000	1.924	10.555	9.445
	2009	23.800	2.176	24.428	23.172		10.792	1.493	11.223	10.361
	2010	22.873	1.159	23.222	22.523		11.042	1.730	11.541	10.542
	2011	23.355	1.502	23.807	22.902		10.700	1.765	11.232	10.168
	2012	24.009	1.986	24.608	23.410		10.855	1.639	11.349	10.360
	2013	23.908	1.819	24.434	23.383		11.192	1.634	11.663	10.720
	2014	23.975	1.727	24.474	23.476		11.383	1.606	11.847	10.920
	2015	25.500	1.473	26.350	24.650		10.167	1.804	11.208	9.125
μ	23.707	σ	0.750		μ	10.739	σ	0.433		

Table A.2 Temperature data evaluated for Akaki station

Akaki										
Temp (Max)	Year	Mean	Standard Deviation	Upper Limit	Lower Limit	Temp (Min)	Mean	Standard Deviation	Upper Limit	Lower Limit
	2006	26.250	1.491	26.681	25.819		15.417	0.411	15.535	15.298
	2007	26.108	1.652	26.585	25.631		16.275	0.842	16.518	16.032
	2008	26.425	1.969	26.994	25.856		15.850	1.599	16.356	15.344
	2009	27.011	2.031	27.688	26.334		16.370	1.210	16.753	15.987
	2010	26.108	1.405	26.514	25.703		12.850	3.076	13.738	11.962
	2011	26.950	1.471	27.415	26.485		11.800	2.959	12.736	10.864
	2012	26.536	1.648	27.033	26.040		9.729	3.386	11.008	8.449
	2013	26.650	1.794	27.168	26.132		7.525	1.543	7.971	7.079
	2014	25.827	1.737	26.351	25.303		10.891	2.137	11.535	10.247
	2015	26.920	1.329	27.340	26.500		11.000	2.115	11.669	10.331
μ	26.479	σ	299.629		μ	12.771	σ	3.093		

Table A.3 Temperature data evaluated for Intoto station

Intoto										
Temp (max)	Year	Mean	Standard Deviation	Upper Limit	Lower Limit	Temp (Min)	Mean	Standard Deviation	Upper Limit	Lower Limit
	2006	19.267	1.834	19.796	18.737		8.783	0.695	8.984	8.583
	2007	19.450	2.123	20.063	18.837		8.550	1.010	8.842	8.258
	2008	16.175	1.375	16.572	15.778		8.342	0.869	8.593	8.091
	2009	17.100	1.646	17.722	16.478		9.043	0.814	9.351	8.735
	2010	16.475	1.279	16.844	16.106		8.675	0.620	8.854	8.496
	2011	17.667	1.629	18.137	17.196		8.792	0.715	8.998	8.585
	2012	17.511	2.676	18.403	16.619		8.878	0.774	9.136	8.620
	2013	17.592	2.418	18.290	16.894		8.900	1.111	9.221	8.579
	2014	18.467	2.354	19.146	17.787		9.267	1.437	9.682	8.852
	2015	18.480	3.129	19.469	17.491		8.520	2.254	9.233	7.807
	μ	17.818	σ	1.096			μ	8.775	σ	0.269

Table A.4 Temperature data evaluated for Dengego station

Dengego										
Temp (max)	Year	Mean	Standard Deviation	Upper Limit	Lower Limit	Temp (Min)	Mean	Standard Deviation	Upper Limit	Lower Limit
	2006	24.582	1.016	24.888	24.276		12.255	1.438	12.688	11.821
	2007	24.282	1.596	24.763	23.801		11.544	2.137	12.257	10.832
	2008	23.455	1.560	23.925	22.984		11.373	2.075	11.998	10.747
	2009	23.967	1.768	24.477	23.456		11.883	1.976	12.690	11.077
	2010	23.433	1.588	23.892	22.975		13.083	1.862	13.621	12.546
	2011	24.508	1.934	25.067	23.950		12.117	1.849	12.650	11.583
	2012	24.250	1.704	24.742	23.758		12.533	1.559	12.983	12.083
	2013	24.183	1.283	24.554	23.813		12.608	0.719	12.816	12.401
	2014	25.300	1.936	25.912	24.688		15.600	1.911	16.204	14.996
	2015	25.760	2.197	26.743	24.777		12.540	2.701	13.748	11.332
	μ	24.372	σ	0.730			μ	12.554	σ	1.188

Table A.5 Temperature data evaluated for Dire Dawa station

Dire Dawa										
	YEAR	Mean	Standard Deviation	Upper Limit	Lower Limit		Mean	Standard Deviation	Upper Limit	Lower Limit
2007	32.725	2.250	33.375	32.075	18.683	2.873	19.513	17.854		
2008	33.218	2.225	33.889	32.547	18.545	3.190	19.507	17.584		
2009	33.473	2.532	34.236	32.709	19.264	2.894	20.136	18.391		
2010	32.658	2.213	33.297	32.020	19.150	3.108	20.047	18.253		
2011	33.375	2.190	34.007	32.743	18.708	3.456	19.706	17.711		
2011	33.000	1.873	33.565	32.435	19.691	2.807	20.537	18.844		
2012	33.475	2.022	34.059	32.891	18.825	3.063	19.709	17.941		
2012	33.370	1.831	33.949	32.791	19.690	2.771	20.566	18.814		
2013	32.909	2.446	33.646	32.172	19.217	3.002	20.083	18.350		
2013	32.644	2.477	33.470	31.819	20.078	3.079	21.104	19.051		
2014	32.718	2.031	33.330	32.106	19.336	3.189	20.298	18.375		
2015	32.800	2.765	34.183	31.417	19.683	3.135	20.963	18.404		
	μ	32.986	σ	0.351		18.200	3.663	20.032	16.368	
						μ	19.162	σ	0.572	

APPENDIX B: TOTAL CASES AND THEIR CORRESPONDING CONDUCTIVITY VALUES

Appendix B introduces varying variables of conductivity values of concrete and PCM based on Section 4.1.1 and 4.1.2 respectively. The conductivity of concrete is dependent on temperature and the conductivity of PCM is dependent on the compatibility of the melting temperature with the station average temperature value.

Cases having temperature below the melting temperature of PCM, use the solid thermal conductivity of the PCM. On the other hand, for temperature values above the melting temperature use liquid thermal conductivity is used. Such kind of designation is used for Table B.3, B.5 and Table B.7

For Cases on Table B.4 and Table B.6, Since the solid thermal conductivity is not specified liquid thermal conductivity is used for all temperatures.

Table B.1 Concrete conductivity values for Procedure one

Case numbers for Procedure 1 (concrete only)	Maximum Temperature (°C)	Conductivity of Concrete (W/m k)
Case 1	Addis Ababa Max (28°C)	1.627
Case 2		1.627
Case 3		1.627
Case 4		1.627
Case 5	Dire Dawa Max (34°C)	1.616
Case 6		1.616
Case 7		1.616
Case 8		1.616

Table B.2 Concrete conductivity values for Procedure two

Case numbers for Procedure 2 (concrete +gypsum)	Prevailing temperatures (°C)	Conductivity of Concrete (W/m k)
Case 9	7	1.667
Case 10	8	1.665
Case 11	9	1.663
Case 12	10	1.661
Case 13	11	1.659
Case 14	12	1.657
Case 15	13	1.655
Case 16	14	1.653
Case 17	15	1.652
Case 18	16	1.650
Case 19	17	1.648
Case 20	18	1.646
Case 21	19	1.644
Case 22	20	1.642
Case 23	21	1.640
Case 24	23	1.638
Case 25	24	1.635
Case 26	25	1.633
Case 27	26	1.631
Case 28	27	1.629
Case 29	28	1.627
Case 30	31	1.622
Case 31	32	1.620
Case 32	33	1.618
Case 33	34	1.616

Table B.3 Conductivity values for Procedure three, Addis Ababa Bole station

Case Numbers for (Concrete +PCM) Addis Ababa Bole	Conductivity of Concrete (W/Mk)	Conductivity of PCM (W/m k)
Case 34	1.663	1.090 solid k
Case 35	1.661	1.090 solid k
Case 36	1.659	1.090 solid k
Case 37	1.657	1.090 solid k
Case 38	1.637	0.540 liquid k
Case 39	1.635	0.540 liquid k
Case 40	1.633	0.540 liquid k

Case Numbers for (Concrete +PCM) Addis Ababa Bole	Conductivity of Concrete (W/Mk)	Conductivity of PCM (W/m k)
Case 41	1.631	0.540 liquid k

Table B.4 Conductivity values for Procedure three, Akaki station

Case Numbers for (Concrete +PCM) Akaki	Conductivity of Concrete (W/m k)	Conductivity of PCM (W/m k)
Case 42	1.667	0.210
Case 43	1.665	0.210
Case 44	1.661	0.210
Case 45	1.657	0.210
Case 46	1.652	0.210
Case 47	1.650	0.210
Case 48	1.648	0.210
Case 49	1.633	0.210
Case 50	1.631	0.210
Case 51	1.629	0.210
Case 52	1.627	0.210

Table B.5 Conductivity values for Procedure three, Intoto station

Case Numbers for (Concrete +PCM) Intoto	Conductivity of Concrete (W/m k)	Conductivity of PCM (W/m k)
Case 53	1.665	1.090 solid k
Case 54	1.663	1.090 solid k
Case 55	1.661	1.090 solid k
Case 56	1.650	0.540 liquid k
Case 57	1.648	0.540 liquid k
Case 58	1.646	0.540 liquid k
Case 59	1.644	0.540 liquid k
Case 60	1.642	0.540 liquid k

Table B.6 Conductivity values for Procedure three, Dengego station

Case Numbers for (Concrete +PCM) Dengego	Conductivity of Concrete (W/m k)	Conductivity of PCM (W/m k)
Case 61	1.659	1.000
Case 62	1.657	1.000
Case 63	1.655	1.000
Case 64	1.653	1.000
Case 65	1.652	1.000
Case 66	1.650	1.000
Case 67	1.637	1.000
Case 68	1.635	1.000
Case 69	1.633	1.000
Case 70	1.631	1.000
Case 71	1.629	1.000

Table B.7 Conductivity values for Procedure three, Dire Dawa station

Case Numbers for (Concrete +PCM) Dire Dawa	Conductivity of Concrete (W/m k)	Conductivity of PCM (W/m k)
Case 72	1.646	1.090
Case 73	1.663	1.090
Case 74	1.642	1.090
Case 75	1.640	1.090
Case 76	1.622	0.540
Case 77	1.620	0.540
Case 78	1.618	0.540
Case 79	1.616	0.540

APPENDIX C: HEAT FLUX AND NODAL TEMPERATURE ABAQUS RESULTS

Appendix C presents Abaqus Heat Flux output values for all Cases and Nodal Temperature values for Procedure 1

Table C.1 Heat Flux results for the total Cases

Heat Flux (W, J/s)							
Case1	15.410	Case21	14.320	Case41	15.080	Case61	14.410
Case2	15.380	Case22	14.370	Case42	13.840	Case62	14.460
Case3	15.360	Case23	14.420	Case43	13.890	Case63	14.510
Case4	15.330	Case24	14.530	Case44	13.990	Case64	14.560
Case5	15.710	Case25	14.570	Case45	14.090	Case65	14.610
Case6	15.690	Case26	14.610	Case46	14.230	Case66	14.670
Case7	15.660	Case27	14.660	Case47	14.280	Case67	15.020
Case8	15.640	Case28	14.710	Case48	14.330	Case68	15.070
Case9	13.730	Case29	14.760	Case49	14.730	Case69	15.120
Case10	13.780	Case30	14.910	Case50	14.780	Case70	15.170
Case11	13.830	Case31	14.960	Case51	14.830	Case71	15.220
Case12	13.880	Case32	15.010	Case52	14.880	Case72	14.780
Case13	13.930	Case33	15.050	Case53	14.270	Case73	14.830
Case14	13.980	Case34	14.320	Case54	14.320	Case74	14.880
Case15	14.030	Case35	14.370	Case55	14.370	Case75	14.930
Case16	14.080	Case36	14.420	Case56	14.580	Case76	15.330
Case17	14.130	Case37	14.470	Case57	14.630	Case77	15.380
Case18	14.170	Case38	14.930	Case58	14.680	Case78	15.430
Case19	14.220	Case39	14.980	Case59	14.730	Case79	15.480
Case20	14.270	Case40	15.030	Case60	14.780		

Table C.2 Nodal Temperature results for Procedure one

Nodal Temperature Values (°k)								
Thickness(m)	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
0	301.150	301.150	301.150	301.150	307.150	307.150	307.150	307.150
0.01	301.055	301.055	301.056	301.056	307.053	307.053	307.053	307.053
0.02	300.961	300.961	300.961	300.962	306.956	306.956	306.956	306.956
0.03	300.866	300.866	300.867	300.867	306.858	306.859	306.859	306.860
0.04	300.771	300.772	300.772	300.773	306.761	306.762	306.762	306.763
0.05	300.677	300.677	300.678	300.679	306.664	306.665	306.665	306.666
0.06	300.582	300.583	300.584	300.585	306.567	306.568	306.569	306.569

Nodal Temperature Values (°k)								
Thickness(m)	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
0.07	300.487	300.488	300.489	300.490	306.469	306.471	306.472	306.473
0.08	300.393	300.394	300.395	300.396	306.372	306.373	306.375	306.376
0.09	300.298	300.299	300.301	300.302	306.275	306.276	306.278	306.279
0.1	300.203	300.205	300.206	300.208	306.178	306.179	306.181	306.182
0.11	300.109	300.110	300.112	300.113	306.081	306.082	306.084	306.086
0.12	300.014	300.016	300.017	300.019	305.983	305.985	305.987	305.989
0.13	299.919	299.921	299.923	299.925	305.886	305.888	305.890	305.892
0.14	299.825	299.827	299.829	299.831	305.789	305.791	305.793	305.795
0.15	299.730	299.732	299.734	299.737	305.692	305.694	305.696	305.699
0.16	293.735	299.638	299.640	299.642	299.578	305.597	305.599	305.602
0.17		299.543	299.546	299.548	293.464	305.500	305.502	305.505
0.18		299.449	299.451	299.454		305.403	305.406	305.408
0.19		299.354	299.357	299.360		305.306	305.309	305.312
0.2		299.259	299.262	299.265		305.209	305.212	305.215
0.21		293.274	299.168	299.171		299.104	305.115	305.118
0.22			299.074	299.077		293.000	305.018	305.021
0.23			298.979	298.983			304.921	304.924
0.23			298.885	298.888			304.824	304.828
0.24			298.791	298.794			304.727	304.731
0.25			292.815	298.700			298.633	304.634
0.26				298.606			292.538	304.537
0.27				298.512				304.441
0.28				298.417				304.344
0.29				298.323				304.247
0.3				292.357				298.162
0.31								292.077

APPENDIX D: ANALYTICAL VERIFICATION FOR HEAT FLUX AND TEMPERATURE DISTRIBUTION EQUATION

For one dimensional conduction in a plane wall, temperature is a function of the x-coordinate only and the heat is transferred exclusively in this direction [22].

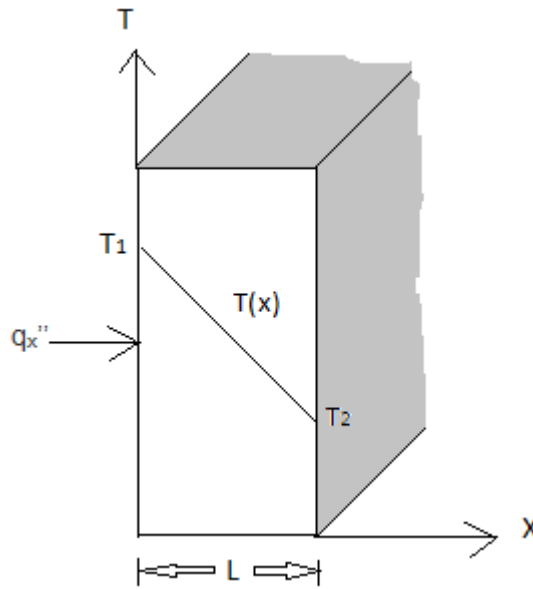


Figure D.1 Temperature and Heat Flux distribution through a plane wall

For a wall q_x depends on the following variables: ΔT , the temperature difference; Δx the wall thickness and A , the cross-sectional area. Fixing ΔT and Δx constant and varying A . It can be observed that q_x is directly proportional to A . Similarly, ΔT and A constant, we observe that q_x varies inversely with Δx . Finally, holding A and Δx constant, it can be observed that q_x is directly proportional to ΔT . The collective effect is then;

$$q_x \propto A \frac{\Delta T}{\Delta x} \quad \text{D.1}$$

In changing the material (e.g. From a metal to a plastic), it can be understood that this proportionality remains valid. However, it can also be found that, for equal values of A , Δx , and ΔT , the value of q_x would be smaller for the plastic than for the metal. This

suggests that the proportionality may be converted to an equality by introducing a coefficient that is a measure of the material behavior. Hence, it can be written

$$q_x = kA \frac{\Delta T}{\Delta x} \quad \text{D.2}$$

Where k , is the thermal conductivity (W/m.k) is an important property of the material. Evaluating this expression in the limit as $\Delta x \rightarrow 0$, it is obtained for the heat rate

$$q_x = -kA \frac{\Delta T}{\Delta x} \quad \text{D.3}$$

Or for Heat Flux

$$q''_x = \frac{q_x}{A} = -k \frac{\Delta T}{\Delta x} \quad \text{D.4}$$

The minus sign is necessary because heat is always transferred in the direction of decreasing temperature. Fourier's law, as written in Equation D.4, implies that the Heat Flux is a directional quantity. In particular, the direction of q''_x is normal to the cross-sectional area A . Or, more generally, the direction of heat flow will always be normal to a surface of constant temperature, called an isothermal surface. Figure D.1 illustrates the direction of heat flow q''_x in a plane wall for which the temperature gradient $\frac{\Delta T}{\Delta x}$ is negative. From Equation D.4, it follows that q''_x is positive. Note that the isothermal surfaces are planes normal to the thickness. For such a medium thermal conductivity is independent of the coordinate direction. In addition, Fourier's law is a vector expression indicating that the Heat Flux is normal to an isotherm and in the direction of decreasing temperature. Finally, note that Fourier's law applies for all matter, regardless of its state (solid, liquid, or gas).

The temperature distribution in the wall shown in Figure D.1 can be determined by solving heat equation with the proper boundary conditions. For steady state conditions

with no distributed source or sink of energy within the wall, the appropriate form of heat equation is Equation D.5.

$$\frac{d}{dx} \left(k \frac{dT}{dx} \right) = 0 \quad \text{D.5}$$

For one dimensional, steady state conduction in a plane wall with no heat generation, the Heat Flux is a constant, independent of x. If the thermal conductivity of the wall material is assumed to be constant, the equation may be integrated twice to obtain the general solution

$$T(x) = C_1 x + C_2 \quad \text{D.6}$$

To obtain the constants of integration, C_1 and C_2 , boundary conditions, must be introduced. For conditions of $X=0$ and $X=L$, in which Case

$$T(0) = T_1 \quad \text{and} \quad T(L) = T_2 \quad \text{D.7}$$

Applying the condition at $X=0$ and $X=L$ to the general solution, it follows that

$$T_1 = C_2 \quad \quad T_2 = C_1 L + C_2 = C_1 L + T_1 \quad \text{D.8}$$

In which Case

$$\frac{T_2 - T_1}{L} = C_1 \quad \text{D.9}$$

Substituting into the general solution, the temperature distribution is then

$$T(x) = (T_2 - T_1) \frac{x}{L} + T_1 \quad \text{D.10}$$

From the above equation it is evident that, for one dimensional, steady state conduction in a plane wall with no heat generation and constant thermal conductivity, the temperature varies linearly with x. From the temperature distribution equation above, we may use Fourier law Equation D.4 to determine the conduction heat flux. That is,

$$q''_x = \frac{q_x}{A} = \frac{k}{L} (T_1 - T_2) \quad \text{D.11}$$

For composite wall

$$q''_x = \frac{1}{\left(\frac{L_1}{k_1}\right) + \left(\frac{L_2}{k_2}\right) + \left(\frac{L_3}{k_3}\right)} * (T_1 - T_2) \quad \text{D.12}$$

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