Improving Thermal Comfort in Building and Reducing the Indoor Air Temperature Fluctuation in Cyprus by Utilizing the Phase Change Materials

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ABSTRACT

This study investigates the effect of phase change materials (PCMs) on improving building thermal comfort and reducing indoor air temperature fluctuations in Cyprus. Utilizing the phase change materials in building leads to increase residence satisfactory and energy saving.

The investigation has been carried out in terms of types, encapsulation, incorporation into building fabrics, and simulation software. In current study, specific PCM which is called RT 31 is employed together with construction materials for the thermal simulation in a typical building in Cyprus.

The description of the current state in Cyprus has been achieved in terms of, common building materials, low energy building researches and construction statistics. A typical building is found based on the number and the total floor area of constructed building in 2009.

The thermal simulation has been accomplished by Energy Plus software for the summer months, July to October. It is found that the mean indoor air temperature is reduced by 1.8% and the peaks of temperature fluctuation curve are become smooth. The graphs of temperature – days for each months are drawn separately. Finally, the hourly indoor air temperature graphs for 14^{th}, 15^{th}, and 16th of each month are plotted.

Keywords: Phase change materials, thermal simulation, building construction in Cyprus, thermal comfort.

ÖZ

Bu çalışma faz değişim materyallerinin (PCM) Kıbrıs'taki yapılarda termal konforu geliştirmekteki ve yapı içi sıcaklık değişimlerini azaltmaktaki etkilerini incelemektedir. Faz değişim materyallerinin binalarda kullanımı enerji tasarrufunu artırmakta ve bina sakinlerinin memnuyitetini olumlu yönde etkilemektedir.

Araştırma bina tipleri, kapsamı, yapı dokularına aktarım ve simülasyon yazılımları temel alınarak yürütülmüştür. Belirli bir PCM tipi olan RT 31, tipik bir Kıbrıs binasında ısı izolasyonu etkisi için kullanılan yapı materyallerine aktarıldı.

Kıbrıs'ın şu anki yapı durumu ile ilgili olarak varılan yorumlar ortak yapı malzemeleri, yapıda düşük enerji araştırmaları ve yapı istatistiklerine bakılarak öne sürülmüştür. Tipik bir bina, 2009 senesinde üretilmiş, belirli bir sayısı ve yüzey alan genişliği olan bir binadır.

Termal simülasyon Energy Plus yazılımı kullanılarak Temmuz ayından başlayıp Ekim ayına kadar olan yaz süreci için yapılmıştır. Yapı içerisi sıcaklık ortalama olarak %1.8 oranında düşmüş ve ısı değişim grafiğindeki tepe noktaları daha yassı hale gelmiştir. Her bir ayın için olan sıcaklık-gün grafikleri ayrı ayrı çizilmiştir. Son olarak da her ayın 14., 15. ve 16. günleri için saatlik yapı içi sıcaklık değerleri verilmiştir.

Anahtar kelimeler: Faz değişim materyalleri, termal simülasyon, Kıbrıs'ta bina yapımı, termal konfor

I would like to dedicate my thesis to my parents and sister

For their endless love, support and encouragement

ACKNOWLEDGEMENT

Foremost, I would like to express my special appreciation to my supervisor Prof. Dr. Tahir Çelik who has been tremendous supporter of my master research and study, for his patience, enthusiasm, and enormous knowledge. His guidance helped me in all the time of doing this thesis. I could not have imagined having a better supervisor and mentor.

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INTRODUCTION

1.1 Background

Primary energy, which is available in the nature, provides the world energy demand. Primary energy could be found in the form of renewable or non-renewable source such as oil, gas, coal, wind, sun and uranium.

Primary energy consumption rose by 2.3 % in 2013, with an acceleration of +1.8% throughout 2012 in the world (BP, 2014).

Oil production did not keep pace with the growth in global consumption. Its consumption increased by 1.4 % however, it grew up by only 0.6 %. Oil remains the world’s leading fuel with almost 33 % of global energy consumption. Global natural gas production and consumption were increased by 1.1 % and 1.4 % respectively. The growth of coal, nuclear and renewable energy consumption grew by 3 %, 0.9 % and 2.7 % respectively. Coal is the fastest growing fossil fuel (BP, 2014). Global primary energy consumption in 2013 is shown in Figure 1.1.

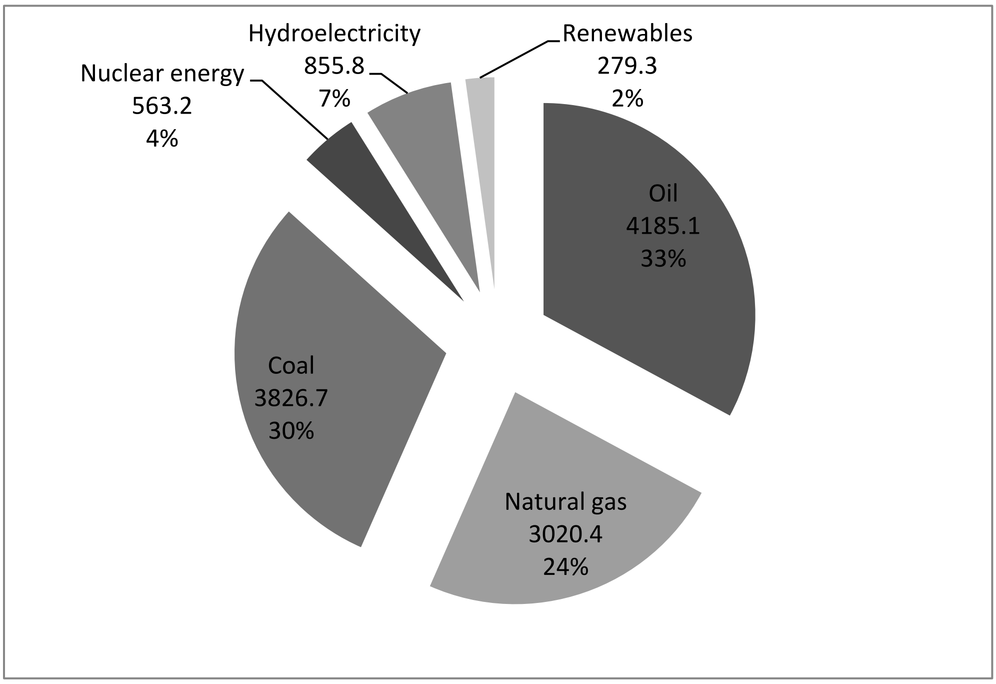

Figure 1.1: World primary energy consumption in 2013 (Million Tones oil equivalent) (BP, 2014)

The comparison of global primary energy consumption in 2012 and 2013 is given in Figure 1.2 (BP, 2014).

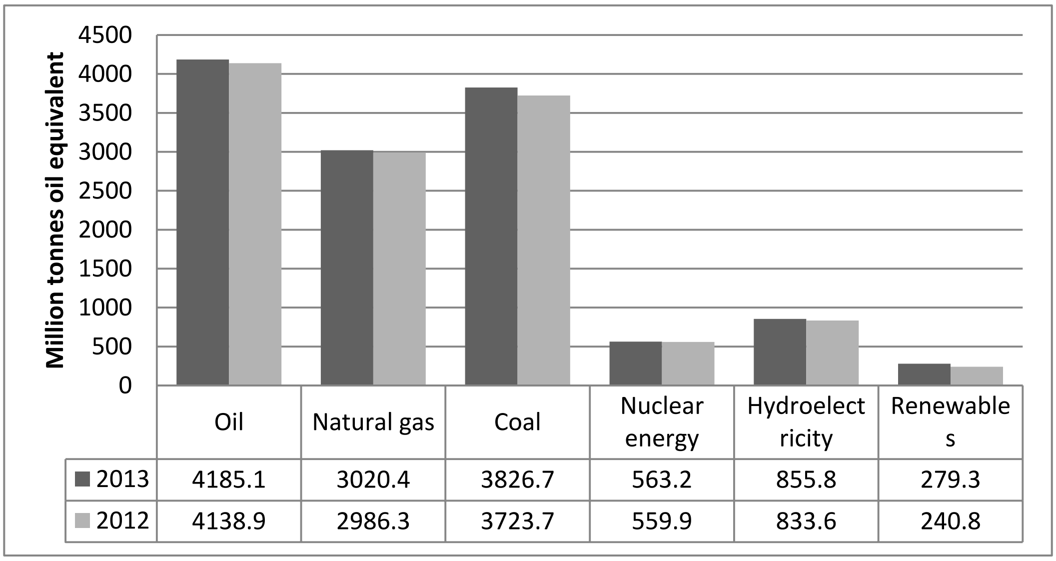

Figure 1.2: Global primary energy consumption in 2012 and 2013 (BP, 2014)

The smallest and greatest growth of energy consumption from 2012 to 2013 is in nuclear energy (by 0.6 %) and renewables (by 16 %) respectively. Oil and renewables have the greatest and smallest portion respectively in the energy consumption occurred in both 2012 and 2013.

The trends of primary energy consumption for the last ten years are indicated in Figure 1.3. As it demonstrates, the amount of all energy type is increased from 2003 to 2013 except the nuclear energy which has descending trend.

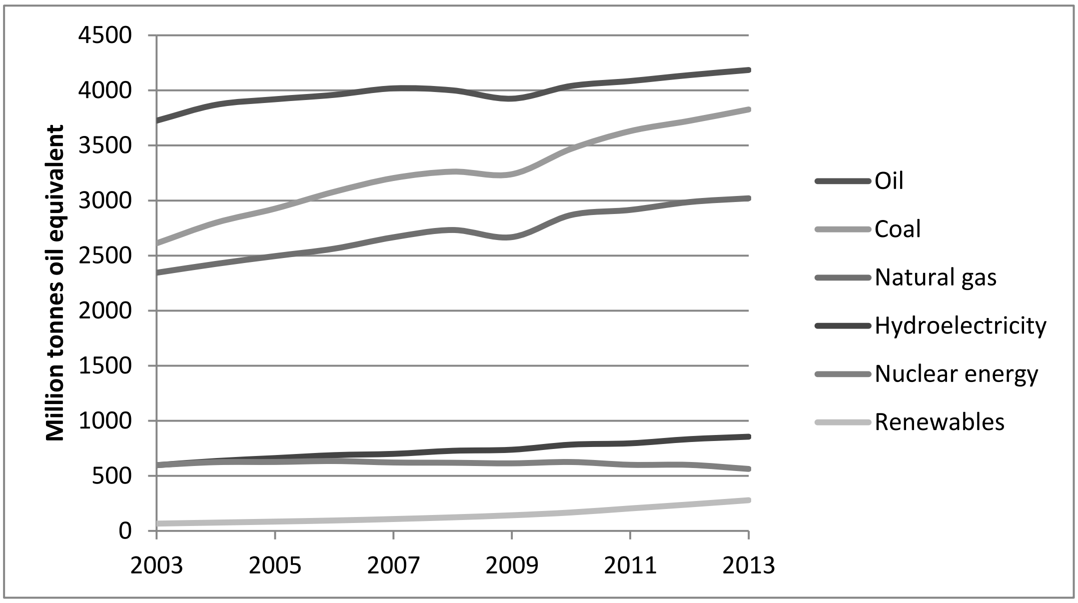

Figure 1.3: Primary energy consumption from 2003 to 2013 (BP, 2014)

The growth in fossil fuel consumption leads on to the elevation of CO_2 emission and thus, the global warming (BP, 2014).

Two solutions are suggested to decrease the undesirable results of fossil fuel consumption. The first one is to improve the energy consuming system in a way that they consume less energy and the second one is using the renewable source to produce energy.

Although the amount of produced energy from renewable sources is increased recently, it does not have a key role in the total energy production in comparison to other types of fuels. It will take a long time for the renewables to overcome the differences with fossil based fuels energy sources. It leads to rise the importance of energy saving (BP, 2014).

Buildings consume 40% of the world’s primary energy. Heating and cooling systems are heavy energy consumers in building, only HVAC equipment consumes around 15% (Kamali, 2014). Passive cooling techniques, which will be explained in chapter two, are recommended to decrease the largest part of consumed energy in building.

Buildings in Cyprus are not environmental friendly and have poor thermal comfort with high energy consumption, especially in heating and cooling (Atikol, Dagbasi, & Guven, 1999). During summer, the indoor air temperature is easily risen more than 45˚C. Energy saving is not considered by both builders and residents. Hence, a very wide research area is available for researchers to find out new technologies or techniques to decrease the amount of energy consumption along with increase thermal comfort.

The main aim of this thesis is to study the effect of phase change materials on improving thermal comfort and to decrease the indoor air temperature fluctuation as a passive cooling system in Cyprus. The energy simulation part is carried out by Energy Plus software on a prototype Cypriot building. This building is found according to evaluate the building statistical report.

1.2 Scope and Objectives

Current research principally focuses on assess the effect of phase change material on the indoor air temperature in a prototype building in Cyprus. The main objectives of this research are presented in the following points in chronological order:

- To determine the widely used or the most typical Cypriot building.
- To find the proper energy simulation software having the ability to model phase change materials (PCMs).
- To select the appropriate PCM in Cyprus climate.
- To assess the effect of PCM on thermal comfort and the indoor air temperature fluctuation.
- To find the economic feasibility

1.3 Works Undertaken

To achieve the aforementioned objectives, the following works and stages have been fulfilled in the same chronological order as the objectives:

- Building statistical report is investigated in detail regarding to the number of story, floor area and structural system according to the State Planning Organization report. Four different type of building is considered, residential, commercial, industrial and miscellaneous. Residential building include apartments, duplexes, triplexes and house; meanwhile, shops, offices, garages and entertainment buildings are defined as commercial buildings.
- Powerful widely used energy simulation software which has the ability to simulate phase change materials are evaluated. A simple comparison among them is done according to their features. User friendly interface, simulating phase change material directly and being open source are the most important criterion for evaluation.

- The various commercial phase change materials being produced by Rubitherm Company are assessed to select the appropriate phase change material in Cyprus climate. Phase change temperature or melting temperature and latent heat capacity of those materials are the criterion to choose proper one which has the best performance in Cyprus climate. Moreover, the cumulative temperature-enthalpy diagram of mentioned PCM is investigated according to its catalogue.
- Thermal simulation has been carried out for a typical Cypriot building, which will be found in second chapter, in summer period, from June to October. This simulation is carried out by energy modeling software which is selected in chapter four. It should be mentioned that, any air conditioning system is not considered during the modeling and simulation process.
- Finally, the life cycle cost analysis of application of phase change material in a Cypriot building is investigated to calculate the economic feasibility. Some economical parameters such as net present value, saving investment ratio, internal rate of return and simple payback period are investigated.

1.4 Achievements

Results corresponding to each stage are illustrated below in the same chronological order as the objectives and works undertaken.

- A duplex house is found as a typical Cypriot building having 101 to 200 square meters the total floor area.
- Energy Plus is selected as building energy simulation software among the other software which will be mentioned in chapter 5.
- RT 31, a commercial PCM, is chosen for current research as phase change material. Its phase change temperature, 31˚C, is suitable in Cyprus climate.

Besides, its high heat storage capacity nominates it as an appropriate candidate in this research.

- The average daily indoor air temperature are illustrated in two cases, with and without PCM, during summer period months. The maximum peak reduction is occurred on 12th June by 4.24%. Moreover, the hourly air temperature in mentioned cases for 14th, 15th and 16th of each month are presented. It is found that, phase change process does not work well in the middle days of August. Finally, the minimum and the maximum of temperature difference is calculated separately for each month.
- Regarding to life cycle cost analysis, payback period of this system is around 10 years with the 8% internal rate of return (IRR). Moreover, According to saving to investment ratio, application of phase change material in Cypriot building could be feasible in terms of economic and environmental matters.

1.5 Guide to Thesis

In the second chapter – BACKGROUND – the energy consumption in building is analyzed. Furthermore, low energy building is briefly explained and some passive cooling techniques are described. Other researches about building with low energy consumption in Cyprus are quickly reviewed. Moreover, Energy consumption in Cypriot building is evaluated.

In the third chapter – BUILDING IN CYPRUS – buildings, geographical and climate features of Cyprus are studied. Building elements which are widely used are presented. Moreover, building construction statistics in North Cyprus are evaluated to find a typical Cypriot building based on the number of story, total floor area and structural system.

In the fourth chapter – PHASE CHANGE MATERIALS (PCMs)– PCMs and their types are presented. Four types of incorporation PCM into building materials are assessed. Additionally, the widely used energy simulation software are briefly described and evaluated. Finally appropriate PCM is selected and its latent heat capacity is compared to normal weight concrete.

In the fifth chapter – DYNAMIC THERMAL SIMULATION – building model and its specification are described. In addition, simulation parameters which are essential to be defined are evaluated and presented in detail.

In the sixth chapter – RESULT AND DISCCUSION – the result of thermal simulation which has been done in chapter 5 are discussed and demonstrated using chart. Moreover, life cycle cost analysis has been carried out to find the economic feasibility. Furthermore, additional explanation is provided where needed.

In the seventh chapter – CONCLUSION – the results are summarized and the conclusion is presented.

Chapter 2

BACKGROUND

2.1 Introduction

This chapter gives cursory information about the energy consumption in building sector. In addition, some building passive cooling techniques which are common are briefly presented. Moreover, low energy building researches which were done in Cyprus are reviewed at the end.

2.2 Energy in Buildings

Electricity and heat are two source of energy which are used for various proposes like heating, cooling, lighting, air conditioning and ventilation. The total final energy use, globally accounts for 7209 Mtoe (Mega Tonnes Oil Equivalents). The commercial and residential building sectors account for 638 and 1951 Mtoe respectively. Buildings consume 40 % of final energy use in the world, which is the biggest share compared with others. Energy consumption in different sectors is given in Figure 2.1. According to Figure 2.1, energy consumption in residential and commercial buildings is about 36 % of the total final energy use. Moreover, some amount of energy which is considered in industry section belongs to buildings. Thus buildings account for 40 % of the total end use energy (IEA, 2008).

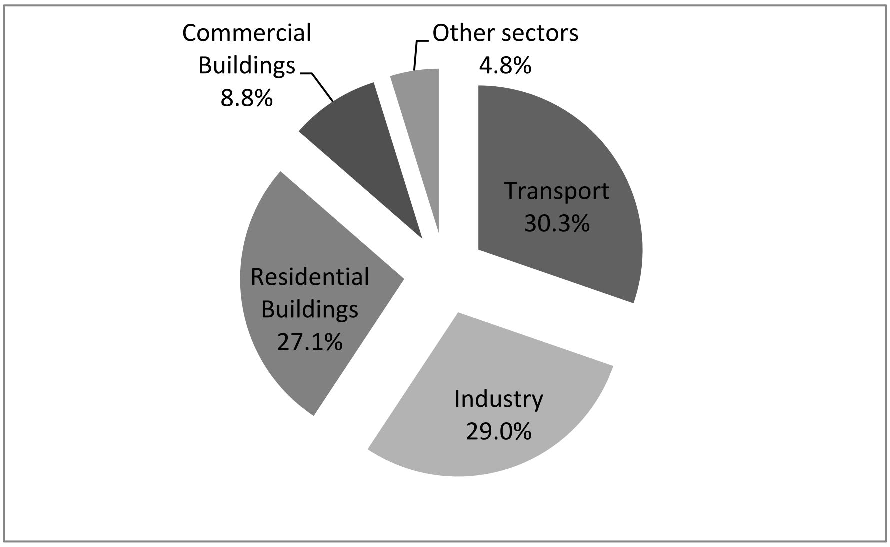

Figure 2.1: Energy consumption in different sectors (IEA, 2008)

Buildings account fifty percent of the total fossil fuel consumption to supply their energy demands. Building sector is greatest consumer in comparison with transport and industry sectors which each of them accounts twenty five percent (Roaf, Crichton, & Nicol, 2005).

The greatest energy consumer in the United State is building sector which accounts 41 % of the primary energy use in US. More detail about energy consumption in different sectors is given in Figure 2.2. The amounts of primary energies which are consumed in residential and commercial sector are shown in Figure 2.3 (U.S. Department of Energy, 2012).

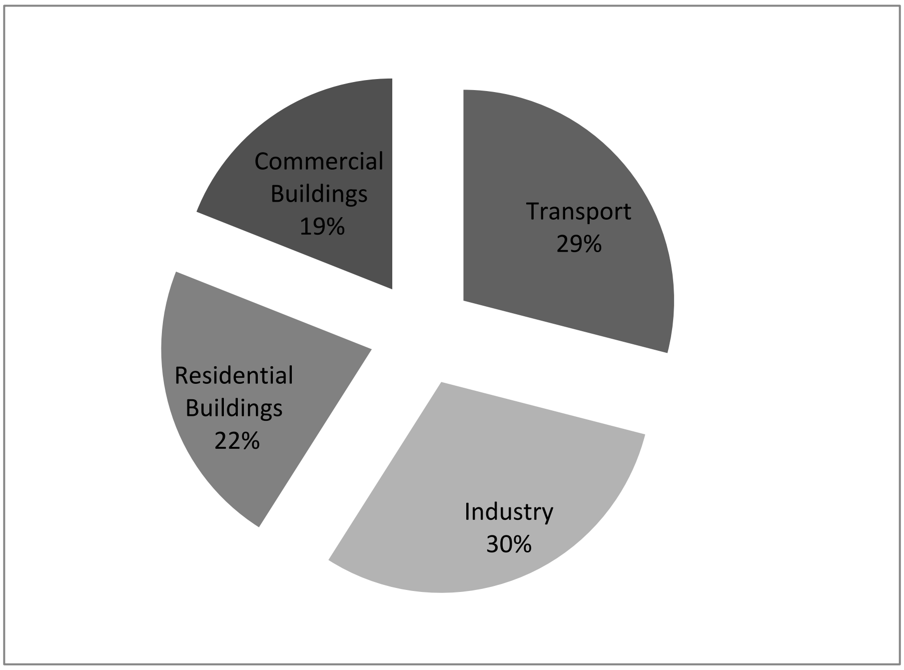

Figure 2.2: Primary energy consumption in different sectors in United State (U.S. Department of Energy, 2012)

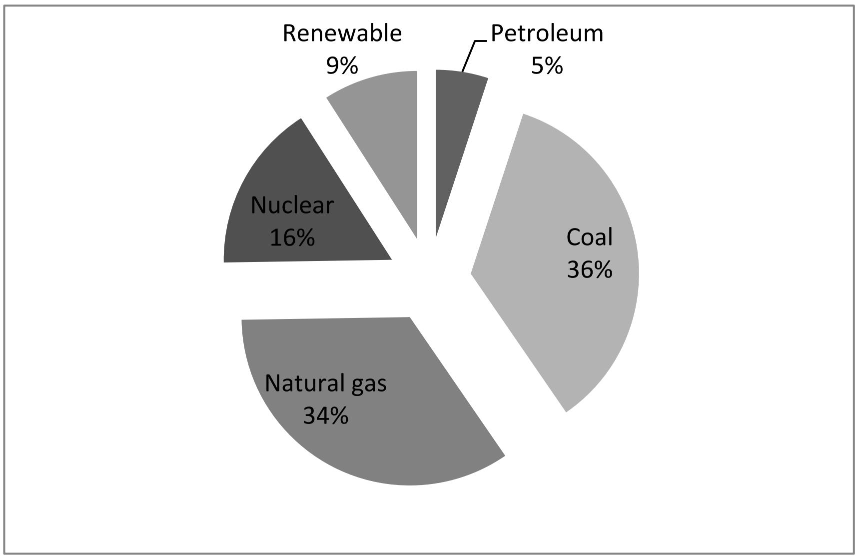

Figure 2.3: Primary energy consumption in residential and commercial building in United State (U.S. Department of Energy, 2012)

Building energy consumption depends on various items such as climate, design and type of the building. It is clear that, the biggest part of consumed energy is used in cooling system in a hot climate; however, in cold climate, heating system consumes more energy. Besides, the higher amount of energy is consumed for lighting and appliances in commercial buildings in comparison with residential.

The breakdown of end use energy in commercial and residential buildings in United Stated is shown in Figure 2.4 (U.S. Department of Energy, 2012).

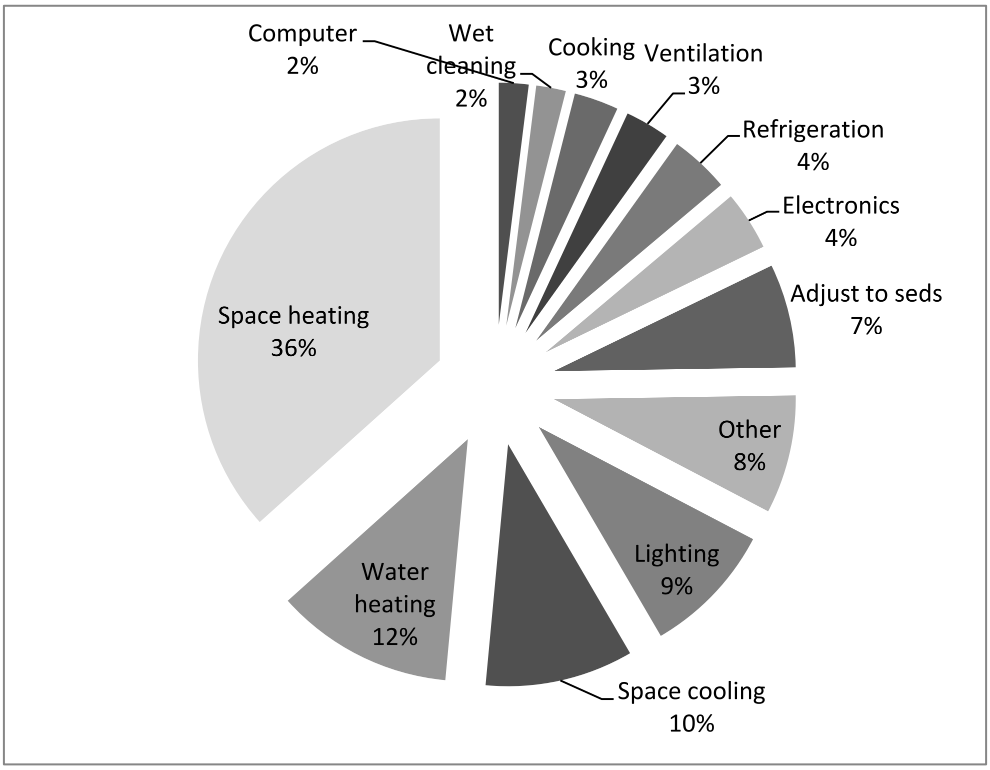

Figure 2.4: Breakdown of end use energy consumption in commercial and residential building in United State (U.S. Department of Energy, 2012)

Breakdowns of end use energy in an office building in Hong Kong and a thirteen story building in Berlin are given in Figure 2.5 and Figure 2.6 (Harvey, 2006).

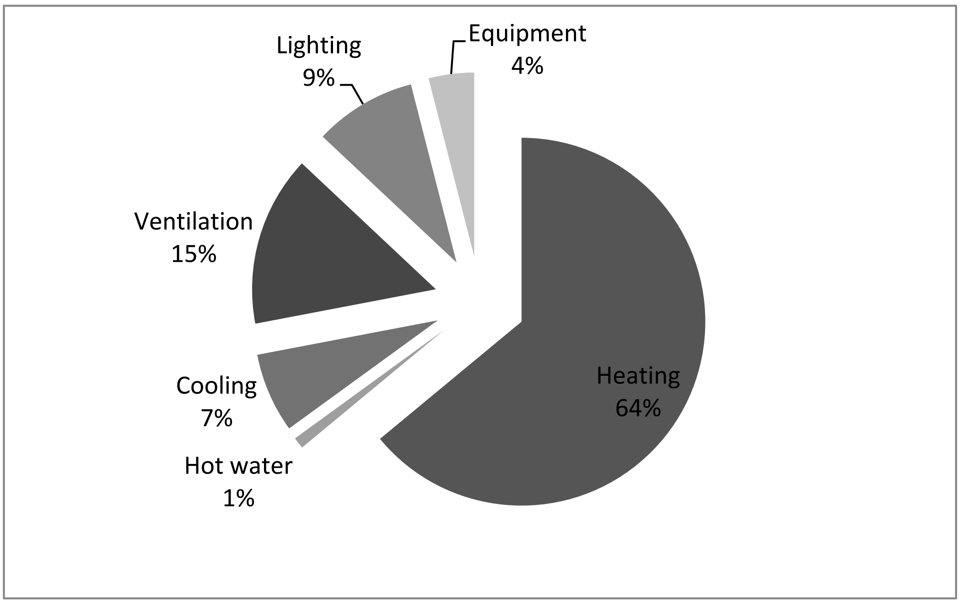

Figure 2.5: End use energy consumption in an office building in Hong Kong (Harvey, 2006)

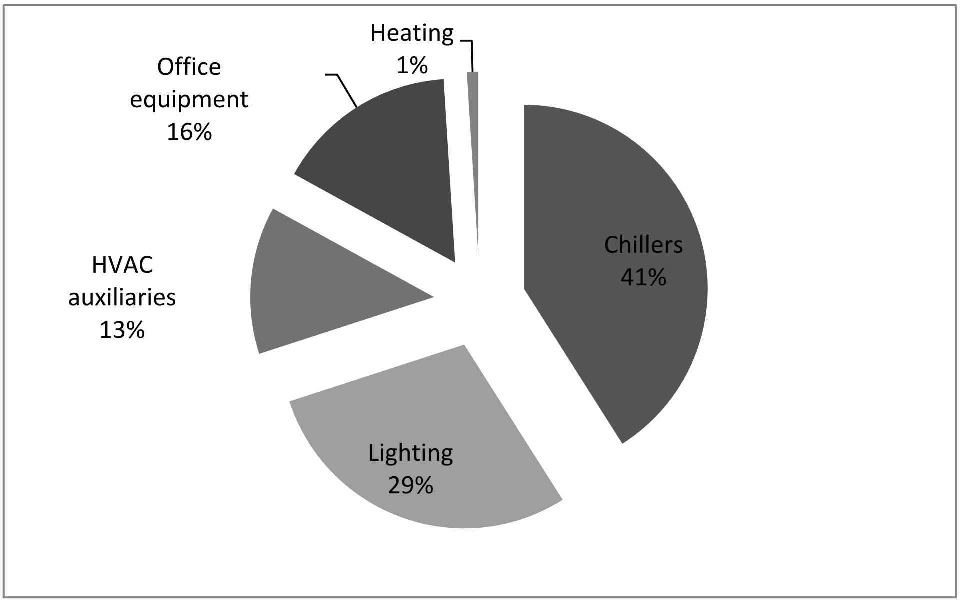

Figure 2.6: End use energy consumption in a thirteen story building in Berlin (Harvey, 2006)

Heating, cooling and ventilation consume the highest energy in comparison with other applications. Hence, any improvement in air conditioning system and built environment in energy point of view leads to decrease building energy consumption. As it mentioned before the main source of building energy is fossil fuel. Therefore, any improvement in air conditioning system leads to reduce the fossil fuel consumption and decrease greenhouse gases emission.

2.3 Energy Consumption in Cypriot Buildings

As it was mentioned, the largest amount of energy is used by different application in building; meanwhile, the air conditioning application such as heating, cooling and ventilation consume the greatest part of this energy. Hence any improvement in air conditioning energy consumption, use low energy air conditioning or improving the built environment, leads to building energy reduction.

The energy consumption in Northern Cyprus is similar as the world's. Space heating and cooling consume biggest part of building end use energy in N. Cyprus though any recent research is not found to show the precise amount and shares of the building end uses energy.

The share of the electricity consumers in Northern Cyprus in 2008 are shown in Figure 2.7 (KIBTEK, 2008). The residential buildings are the greatest electricity consumer in Northern Cyprus. Moreover, the considerable amount of electricity consumption in tourism and commercial sectors is consumed in building.

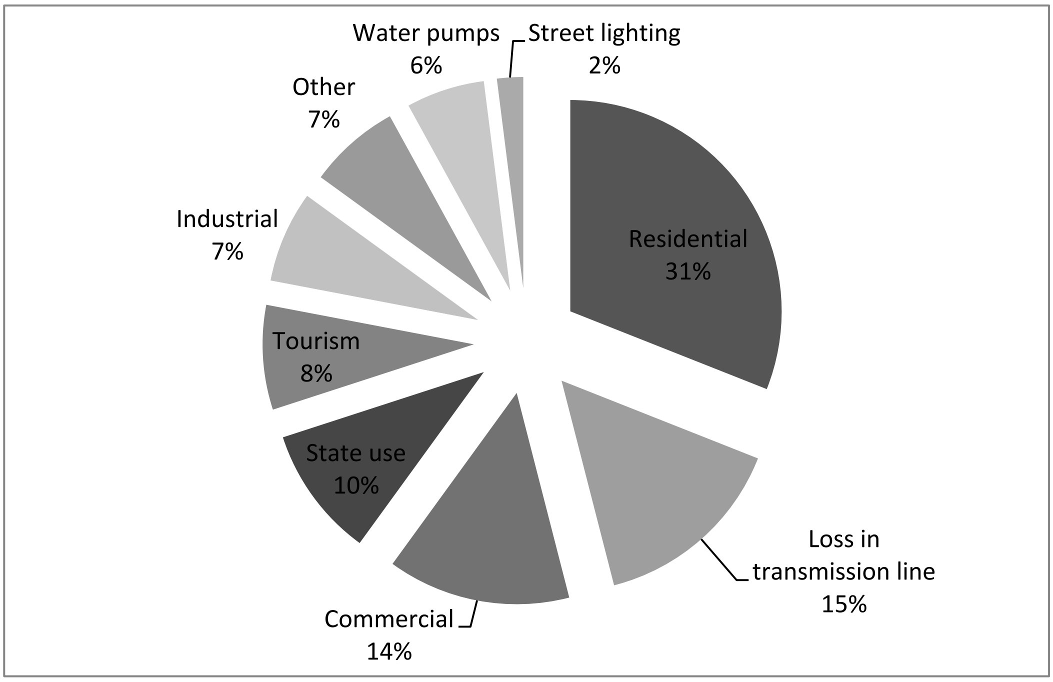

Figure 2.7: Share of electricity consumption in Northern Cyprus in 2008

2.4 Building with Low Energy Consumption

The amount of energy which are consumed by air conditioning in buildings are the greatest among the others. Thus the passive methods or low energy air conditioning grow critical by means of reducing end use energy. Primary energy demand which is used for cooling and heating applications significantly decreases if the passive methods and low energy air conditioning are applied in the buildings.

Passive methods are techniques which can cool building without or with less energy consumption. Term "Passive" includes the cooling methods which use pumps or fans when their application might improve the cooling performance (Givoni, 1984), (Givoni, 1994), (Szokolay, 2012), (Santamouris & Asimakopoulos, 2013). Some passive techniques which are used for cooling the building are given below:

2.4.1 Appropriate orientation:

The first stage in design of passive system is minimizing solar heat gains for the purpose of improving thermal comfort. Proper orientation can decrease solar heat gain. West and east surface of the buildings are the critical ones in term of heat gain. They exposed to higher solar radiation in comparison to south and north surfaces. Since overhangs cannot prevent these faces from solar heat, orienting building longitudinally in east-west direction leads to decrease and increase solar heat gain during the summer and winter respectively (Harvey, 2006).

2.4.2 Surface characteristics

Temperatures of walls and roofs surfaces which are exposed to solar radiation reach higher temperature in comparison with ambient temperature. It leads to increase heat conduction to the inside of the building. A white coated roof absorbs only 15 % of the solar radiation whereas a roof with black asphalt shingles absorbs 95%. Conduction process releases the absorbed heat in the building exterior surfaces into indoor environment and leads to increase the air temperature. Thus, exterior surface characteristics and properties should be considered to reduce surface temperature (Harvey, 2006). It is clear that, bright colors are more advised rather than dark ones for the external surfaces of the buildings.

2.4.3 Earth Cooling System

Earth can be used as a cooling source due to its extremely thermal capacity. In desert climate, it can drop the peak indoor temperature by 3˚C during the summer months meanwhile in mild climate, the temperature of soil at 3 meters below the ground level is sufficient to provide cooling (Al- Ajmi, Loveday, & Hanby, 2006), (Santamouris & Asimakopoulos, 2013). Hot outdoor air can be cooled down by circulating into embedded pipes at the depth of 2 to 3 meters below the ground level before it enters inside the building (Sanchez-Guevara, Urrutia del Campo, & Neila, 2011). This method can decrease the indoor temperature by 10˚C (Givoni, 1991). Schematic representation of this method is given in Figure 2.8.

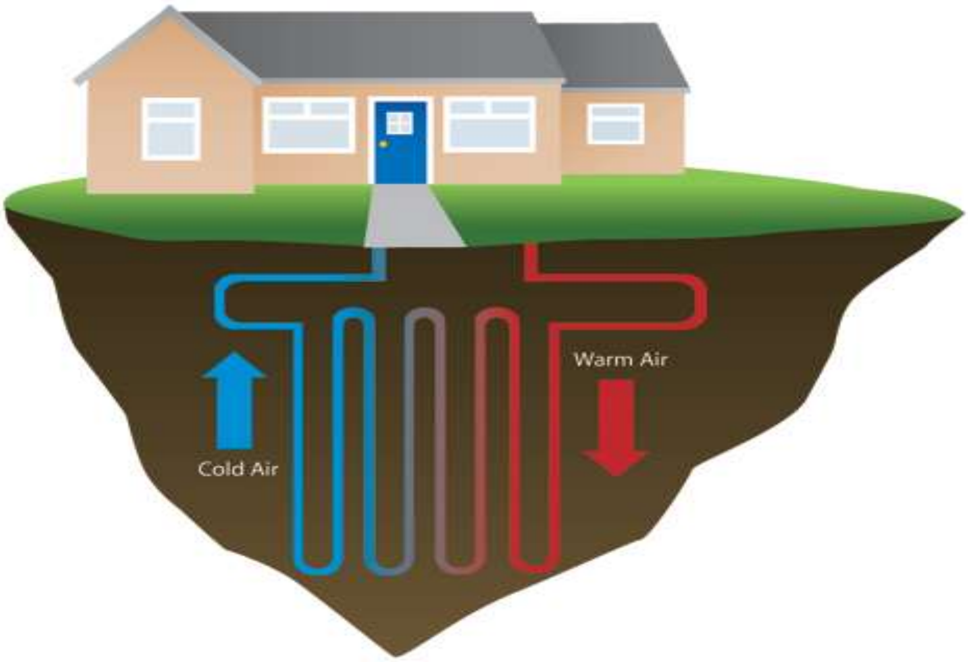

Figure 2.8: Schematic representation of earth cooling system

2.4.4 Evaporative Cooling

Cooling air by water evaporation is named evaporative cooling techniques. Water needs heat to evaporate so it absorbs heat from hot air. As result of that process, the air temperature is dropped (Figure 2.9). Evaporated water enters the air as a vapor and transmits the absorbed heat to the air in the form of latent heat. Hence enthalpy of the humidified air is changed. In hot-dry climate, the cooled and humidified air is used for cooling inside the building (Xuan, Xiao, Niu, Huang, & Wang, 2012). Moreover, this system with slight modification can be used in humid climates (Tiwari, Upadhyay, & Rai, 1994), (Xuan, Xiao, Niu, Huang, & Wang, 2012).

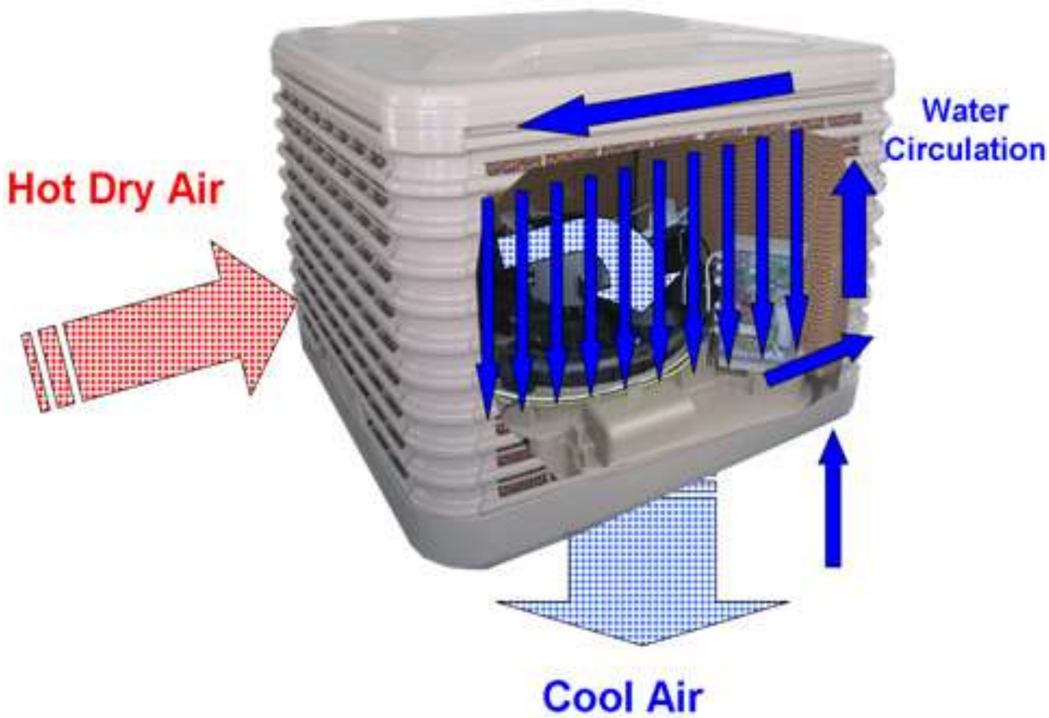

Figure 2.9: Schematic representation of evaporative cooling techniques

2.4.5 Natural Ventilation

Natural ventilation is a flexible strategy that uses outdoor air to supply cooling to the building. It is induced by wind or temperature difference. An air vent at upper section of a building exhausts heated air to the outside while cold air comes to building through a stack at lower section of a building. Wind can cross air flow through two opening which are placed at both side of the buildings. This method is depicted in Figure 2.10. This method reduces mechanical cooling demand or mechanical ventilation systems. Eventually it decrease the energy consumption by eradicate cooling plant (Parsloe, 2005).

Figure 2.10: Schematic representation of natural cooling technique

2.4.6 Thermal Mass

It keeps heat during the day when the air temperature goes up and discharges this stored heat during night when air temperature goes down. It prevents building from overheating. Phase change materials can provide thermal mass in building by higher heat storage capacity in comparison with conventional building materials. Heat storage capacity of phase change material drywall is almost 10 times more than a regular wall (Harvey, 2006). This feature makes it a proper candidate to solve poor thermal comfort and overheating problem in a building.

2.5 Studies on Cypriot Buildings with Low Energy Consumption

Most of the buildings in North Cyprus have not any thermal comfort or have poor thermal comfort because of less consideration in building thermal behavior during construction. Although few amount of studies has been done on energy saving in building, a huge room for this area is available and necessary in Cyprus (Panayiotou, et al., 2010), (Pilavachi, Kalampalikas, Kakouris, Kakaras, & Giannakopoulos, 2009).

Energy flows of a modern Cypriot houses which are located in Nicosia with different type of construction materials are analyzed by TRNSYS (Florides, Kalogirou, Tassou, & Wrobel, 2000). It was found that, indoor temperature reaches 10 to 20˚C during winter and 30 to 50˚C during summer when it does not have any air conditioning system. Moreover, heating and cooling demands reduced by 75 % and 45 % respectively if roof is isolated properly. Window shading leads to decrease cooling load by 8 – 20 % meanwhile, blowing outdoor air (when its temperature is less than indoor air temperature) to building with 3-5 ACH (Air changes per hour) flow rate decreases cooling load by 6.3% during the summer.

Another simulation (Florides, Tassou, Kalogirou, & Wrobel, 2002) in the same building was shown that annual cooling load can be reduced by 7% if overhands with 1.5 meters length are installed. Meanwhile, this reduction can reach almost 8% by 9 ACH ventilation flow rate. It is found that, long side of rectangular shaped buildings should be orientated in south side. Low emissivity double glazed windows can reduce 24% of annual cooling load.

14 different types of roofs were tested in Famagusta to find best thermal comfort construction in hot weather throughout a year (Özdeniz & Hançer, 2005). Humidity and indoor air temperature were monitored. Although those roofs are not considerable differences in terms of thermal comfort in winter, noteworthy differences were shown in buildings with air conditioning system in summer. Thus, design the roof for the summer period is advised. A flat roof with thermal insulation on the inner surface and inclined timber roof with a ventilated attic space have the best performance during the summer.

Thermal mass application was investigated in Cyprus (Kalogirou, Florides, & Tassou, 2002). A four zone building with dense concrete wall at south side and insulated roof was simulated with TRNSYS. The optimum value of wall thickness is 25 cm. It is found that, heating load was reduced about 47%; nevertheless, cooling load was grown slightly at the same time. Thermal mass applications were suggested due to diurnal temperature variation in Cyprus.

The combination of building information modeling and building performance modeling was studied to found the best construction materials among the conventional ones in Cyprus based on energy consumption criterion. Moreover, thermal comfort of building in Cyprus will be increased more than 40% by applying high density Rockwool insulation in the outer layer of roof, using solid core doors and double glazed windows (Mohamadi, 2012).

Chapter 3

BUILDING IN CYPRUS

3.1 Introduction

In this chapter, buildings of Northern Cyprus will be discussed; geographical and climate features of Cyprus will be explained, configuration of buildings elements are given and building statistics are focused in more detail. Finally a most typical Cypriot house will be described.

It is found that, during the summer, maximum and minimum air temperatures have 16 $^{\circ}$C differences in the inland part whilst they have 9 to 12 $^{\circ}$C differences for other part. Relative humidity is 30% for a summer and 65% and 95% for a day time and night time during winter. The Larnaca weather data format is selected for simulation because is the only available Cyprus location in Energy Plus database.

It is found that, residential buildings are the most in both number and total floor area properties according to private building statistics in Northern Cyprus which is provided by state planning organization of TRNC. More investigation in residential buildings brings results out. First, the duplex buildings have the majority in number of the residential buildings (a little less than three times of apartments); nevertheless, their total floor area is almost equal to apartments. Second, majority of the buildings have two stories with 69% distribution. Third, most of the building having total floor area in the range of 101 to 200 square meters. Finally, two stories duplex building with concrete structure having total floor area between 101 to 200 square meters can be adequate as a typical building in Northern Cyprus.

3.2 Geographical and Climate Features

Cyprus, third largest and third most populated island in the Mediterranean Sea, is situated at latitude 35˚ 10' North and longitude 33˚ 22' East. The area of island is 9251 Km^2 including Northern Cyprus (3355 Km^2), UN buffer zone and Akrotiri and Dhekelia (254 Km^2). It has distance of 95 Km from Syria, 750 Km from Greece, 65 Km from Turkey and 350 Km from Egypt (Palmer, 1990) see Figure 3.1. The Trodos and Kyrenia mountains are some part of Taurus Chain Mountain in Turkey. The first one is located on the south part with 1951 meters height from the sea level and the second one is situated on the north part with 1023 m height from the sea level. Cyprus has warm and rainy winter which is from December to March, and hot and dry summer which is from June to October. This is named as Mediterranean climate (Isik & Tulbentci, 2008).

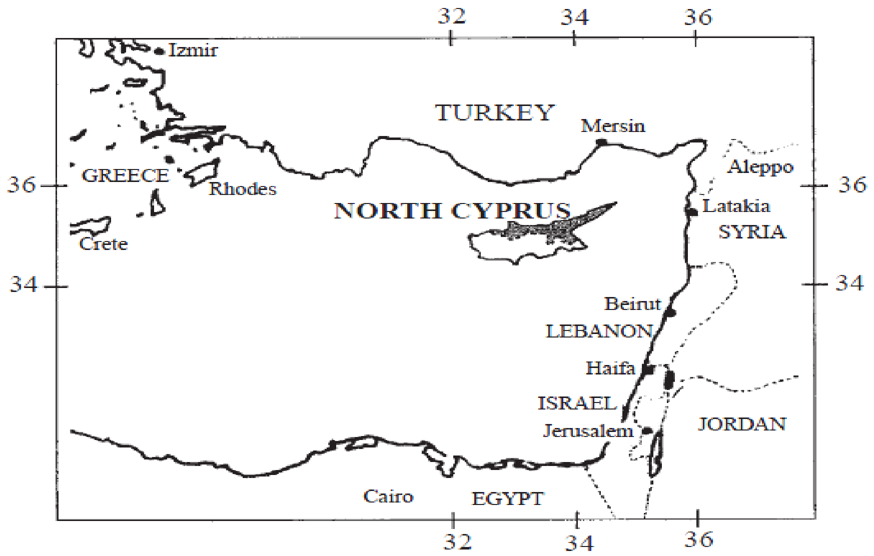

Figure 3.1: Map of Cyprus (Palmer, 1990)

The difference between the maximum and minimum temperature in a day is large in Cyprus and it is increased up to 16°C in the inland part meanwhile it is 9 to 12°C for other part during the summer. These differences go down to 5 to 6°C for the highland and 8 to 10°C for the lowlands in winter. The average daily temperature in July and August is 22°C and 29°C for highland and lowlands respectively whilst it reduces in January to 3°C and 10°C for mountains and central plane respectively. Air temperature ranges are between 9 to 12°C and 37 to 40°C in winter and summer respectively (Cyprus Meteorological Department, 2014).

Substantial daily and seasonal differences among sea and inland are engendered by high sunshine rate and clear sky. It leads to local effect by the sea. The seasonal temperature differences among the winter and summer for shore and inland are 14°C and 18°C respectively. There is 5 hour of sunlight per day in winter and it is increased to 12 hour during the summer. Relative humidity is almost 95% during nighttime and it is decreased to 65% during daytime in winter meanwhile it is around 30% during noontime in summer (Cyprus Meteorological Department, 2014)

It is obvious that, the inland regions have lower relative humidity than coastal regions. Average on 5.5 hours of sunshine occurs per day in cloudiest months; however, this value increases to 11.5 hours per day in summer. Although the winds over the island are mostly northerly and north westerly in summer, they are westerly and south westerly in winter (Cyprus Meteorological Department, 2014).

Weather data for more than 2000 locations around the world are available in U.S. department of energy web site in EPW format. These files are arranged by World Metrological Organization (WMO) regions and country. Cyprus is in the region 6

(Europe) and has only one weather data file which is belong to Larnaca (U.S. Department of Energy). The years between 1982 and 1999 are used as a reference to generate the IWEC weather data file (U.S. Department of Energy).

3.3 Construction Industry

The construction industry has a significant effect on the economy of Turkish Republic of Northern Cyprus. The demand for new building rises due to population growth.

Stone, yellow limestone and adobe were the main construction materials during Ottoman and British Colonia period in Cyprus. The bay windows and thick adobe walls were widely observed in building especially in Ottoman period. Meanwhile, balconies were utilized instead of the bay windows during British Colonia period. These are some of the traditional method which were utilized in the past.

Reinforced concrete started to be used in building industry after 1960 in Cyprus; meanwhile, traditional fabrics, stone and adobe, lost their popularity however the general design techniques are kept such as orientation of the buildings, shading devices, size of the opening and vegetation (Ozay, 2005) and colour of the buildings. In order to reflect sunrays and accordingly reduce the building cooling demand in summer, bright colours are used on the outer façade (Oktay, 2002). The white colour has more reflection than others.

Traditional methods are efficient for building climatic design but usages of those methods are decreased because of growing housing demand, which resulted in low quality buildings and inefficient design. They lead to unsatisfied environment and social comfort (Ozay, 2005).

Lack of sun devices, wrong fabric and orientations, and large windows have negative impact on climatic comfort. Although aluminum shutters protect house from direct sunlight, this material has a high thermal conductivity so it transfers heat from outside to indoor easily which leads to rising indoor temperature (Ozay, 2005), (Dincyurek & Turker, 2007).

Based on a research, most of the residents are not satisfy about inadequate comfort. Only 13% of them feeling comfortable in summer while 20% of them are satisfy in winter (Lapithis, Efstathiades, & Hadjimichael, 2007).

As it was mentioned before, reinforced concrete is the main common building material. Generally it is used in columns, beams, roofs, floors, and shear walls. Bimsblock, horizontally perforated brick, and ytong are three ubiquitous bricks in masonry work. Floors are mostly covered by Parquet or marbles; moreover, roofs are coated by tiles.

3.3.1 Walls

Different type of wall layout can be built by arrange various bricks and insulation materials. 5 types of common wall which are used in Cyprus are described below (Figure 3.2 to Figure 3.6). The amounts of the overall heat transfer coefficient (U value) of them are shown in Table 3.1 (Mohamadi, 2012).

The U value measures how well building elements transfer heat. It is expressed in watts per meter squared kelvin. A low U value usually indicates high levels of insulation.

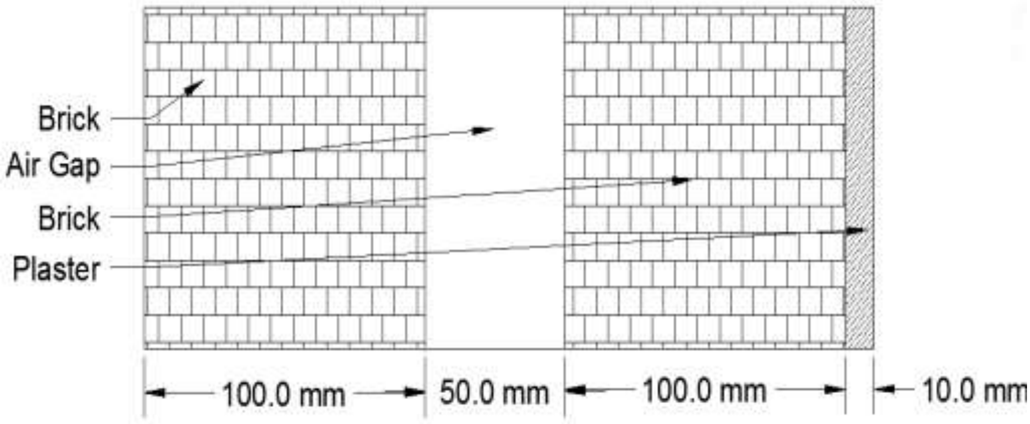

Figure 3.2: Wall type I

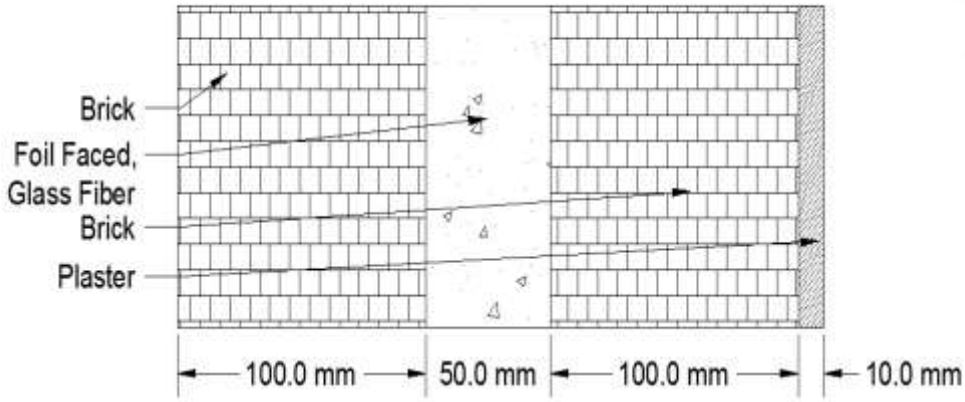

Figure 3.3: Wall type II

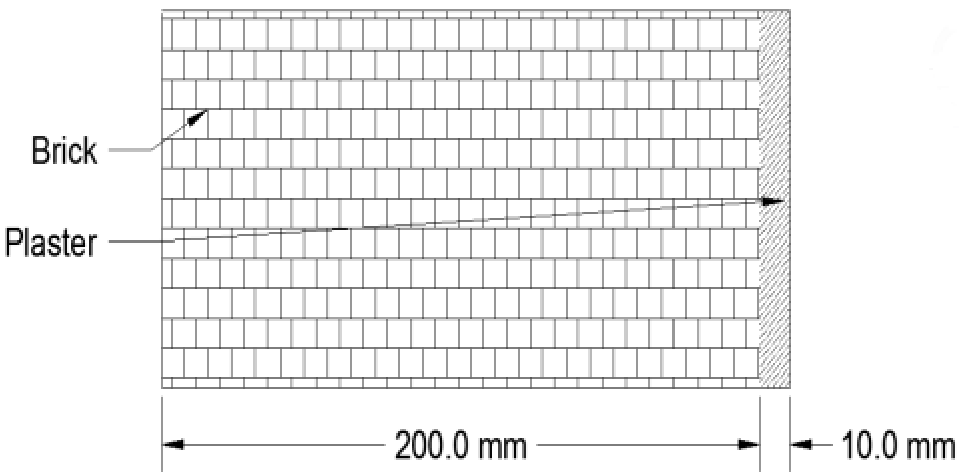

Figure 3.4: Wall type III

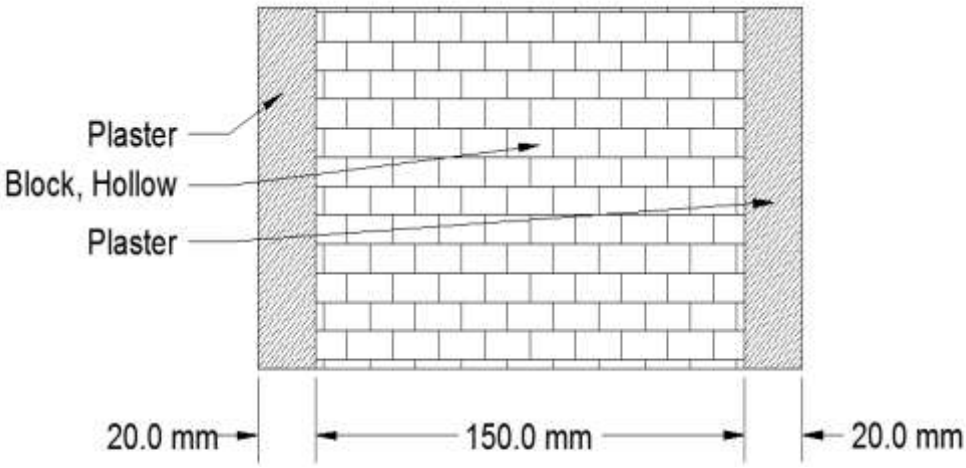

Figure 3.5: Wall type IV

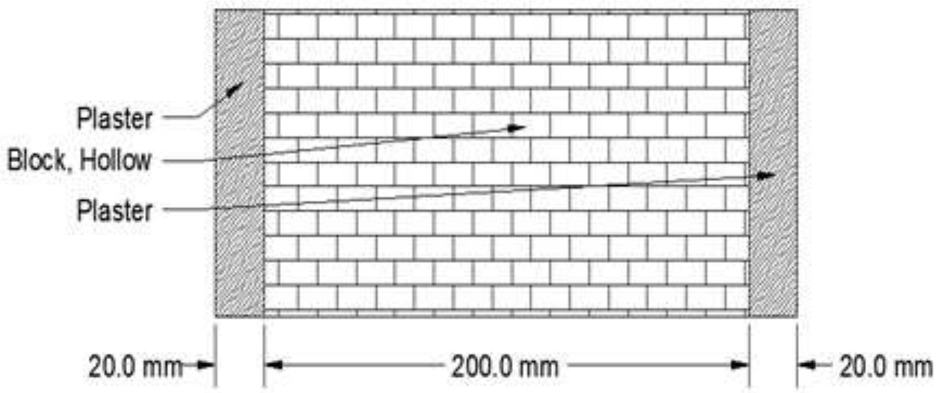

Figure 3.6: Wall type V

Table 3.1: Description and U value of walls (Mohamadi, 2012)

Type	Description	U value (W/m^2K)
I	Exterior wall made of masonry brick with plaster and air gap	1.510
II	Exterior wall made of masonry brick and foil-faced or glass-fibre with plaster	0.320
III	Exterior wall made of masonry brick with plaster	2.070
VI	Exterior wall made of lightweight or hollow brick with 2 layer plaster	2.140
VII	Exterior wall made of lightweight or hollow brick with 2 layer plaster	1.870

3.3.2 Roof

Three types of roof constructions are predominantly used in buildings of Cyprus which are shown from Figure 3.7 to Figure 3.9. The amounts of U value for them are brought out in Table 3.2 (Mohamadi, 2012).

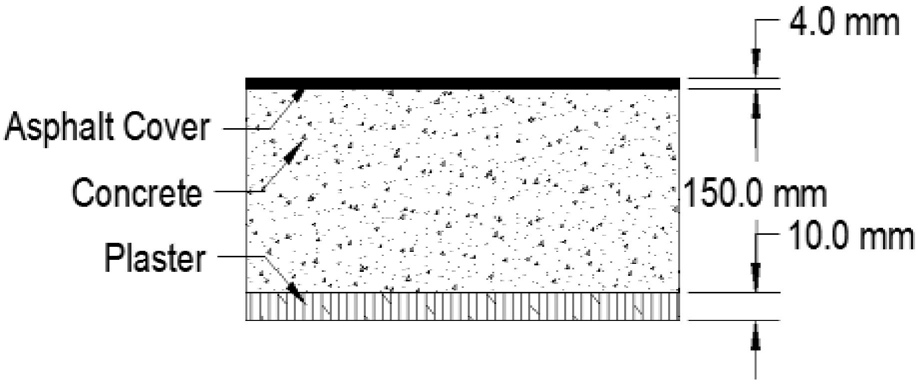

Figure 3.7: Roof type I

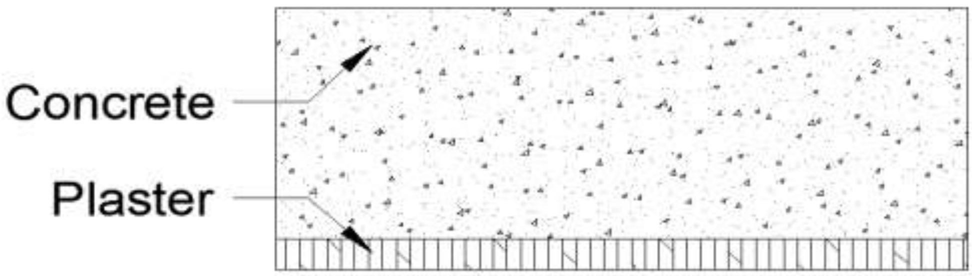

Figure 3.8: Roof type II

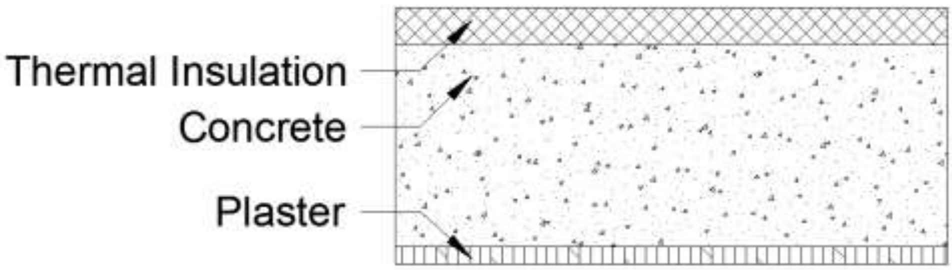

Figure 3.9: Roof type III

Table 3.2: Description and U value of roofs (Mohamadi, 2012)

Type	Description	U value (W/m^2K)
I	15 cm concrete slab with asphalt cover and plaster	1.040
II	15 cm concrete slab with plaster	3.76
III	15 cm concrete slab with 5 cm thermal insulation and plaster	0.51

3.3.3 Floor

Five types of common floors which are constructed in Cyprus are explained below in detail (Figure 3.10 to Figure 3.13).

The most widely used grade level floor usually has five layers. The top layer is marble with 30 mm thickness. 20 mm of screed is used for the second layer. Underneath the screed, 50 mm sand layer is used. In the next layer 100 mm concrete is used. Finally, at the bottom, 15 cm hardcore layer standing on the compressed earth is used.

The amounts of U value for all floor types are illustrated in Table 3.3 (Mohamadi, 2012).

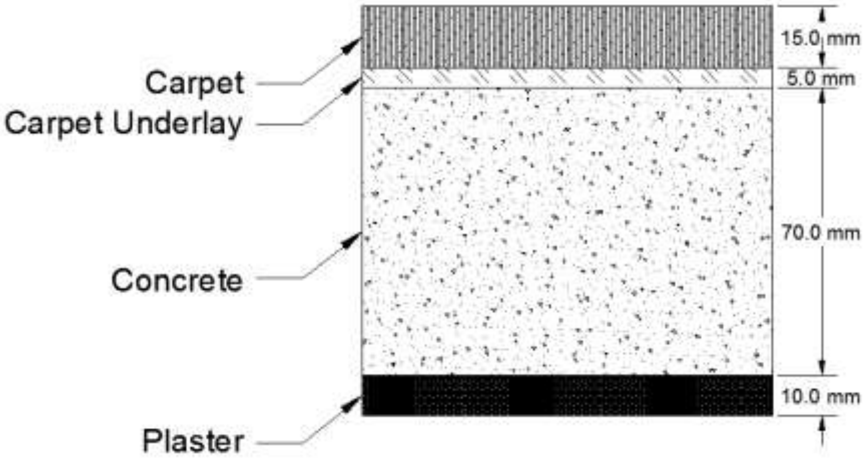

Figure 3.10: Floor type I

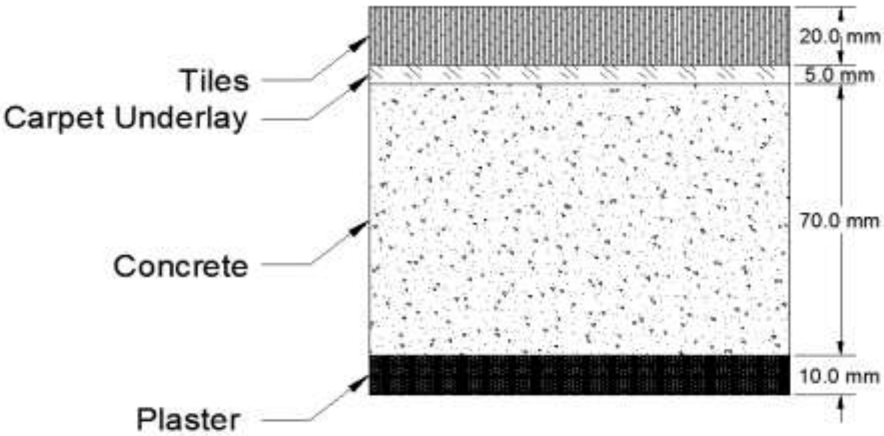

Figure 3.11: Floor type 2

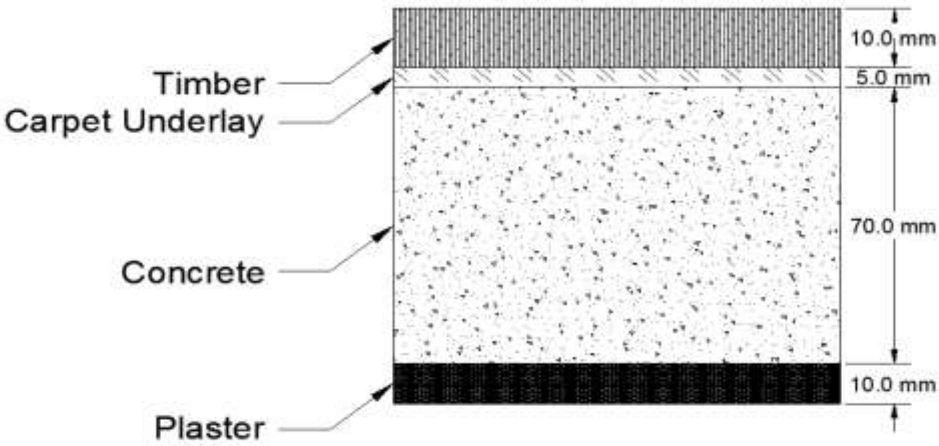

Figure 3.12: Floor type III

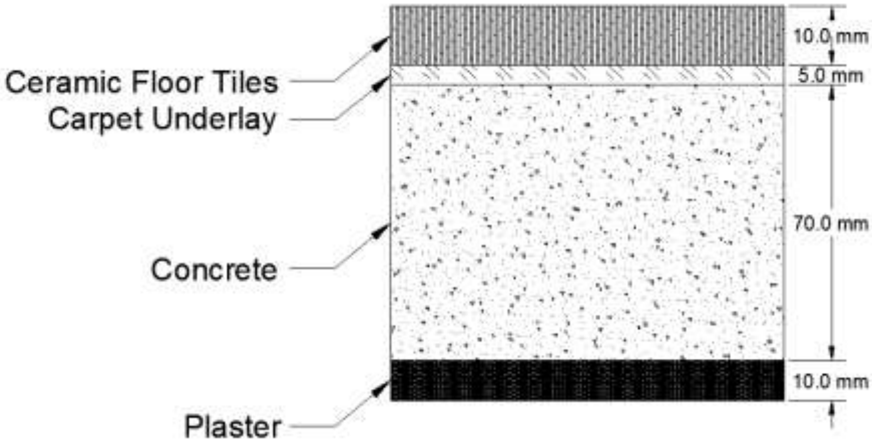

Figure 3.13: Floor type IV

Table 3.3: Description and U Value of floors (Mohamadi, 2012)

Type	Description	U value (W/m^2K)
I	Floor with carpet	1.470
II	Floor with tiles	1.960
III	Floor with timber	2.100
IV	Floor with ceramic floor tiles	2.390
Grade level floor		2.719

3.3.4 Door and Window

The widely used doors and windows in Cyprus are illustrated in Figure 3.14 to Figure 3.17. The amounts of U value for each of them are shown in Table 3.4 (Mohamadi, 2012).

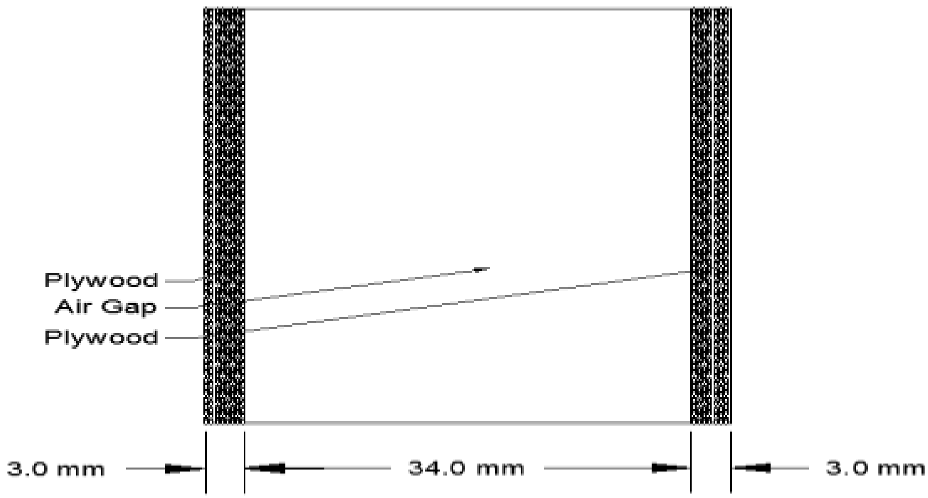

Figure 3.14: Door type I

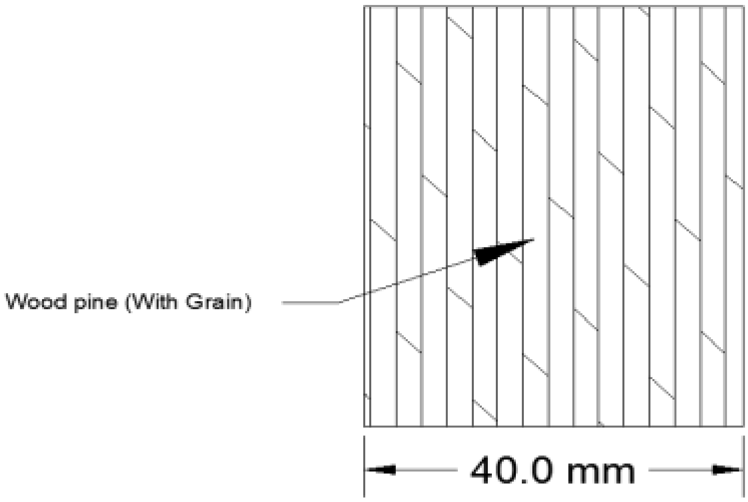

Figure 3.15: Door type II

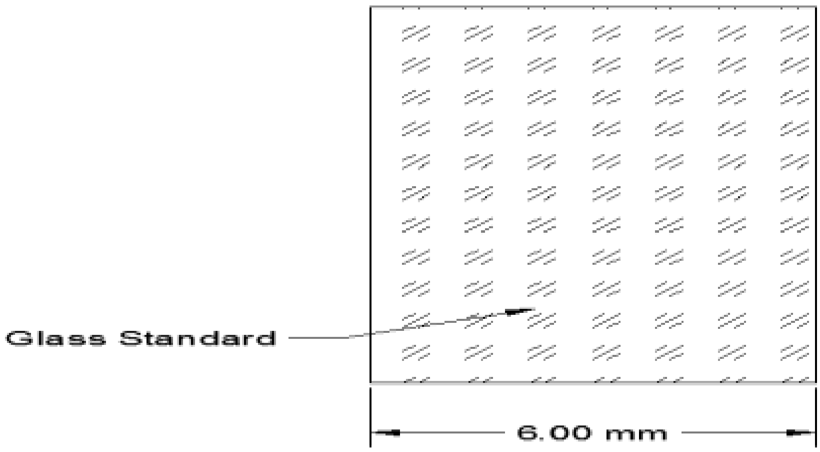

Figure 3.16: Window type I (single glazing)

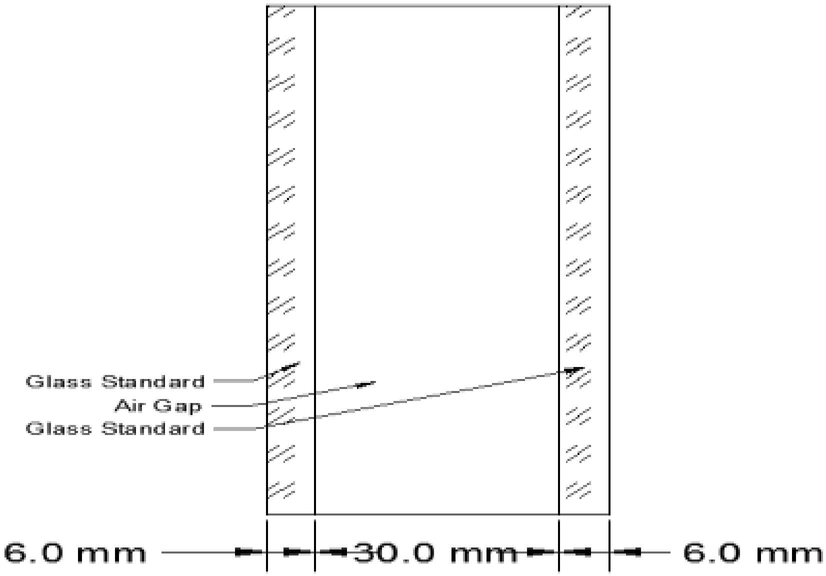

Figure 3.17: Window type II (double glazing)

Table 3.4: U value of doors and windows (Mohamadi, 2012)

	Type	Description	U value (W/m^2K)
Doors	I	Plywood	2.980
	II	Wood pine (With Grain)	2.310
Windows	I	Single glazing	6.000
	II	Double glazing	2.410

3.4 Building Construction Statistics of 2009

Building statistical data is published by the State Planning Organization (SPO) in Turkish Republic of Northern Cyprus. Recent publication of SPO, which released in June 2011, is used for further investigation in this study (State Planning Organization of TRNC, 2011). Buildings in North Cyprus are classified in four types. Residential buildings are composed the apartment, duplex, triplex and house whilst commercial buildings involve offices, retail shops, restaurants, nightclubs, hotels, car parking and cafes; whereas, factories and warehouses are categorized in Industrial buildings classification. Other types of buildings which exclude from these mentioned categories are named miscellaneous building. The miscellaneous buildings are cellars, garages, sport facility buildings, dormitories and agricultural buildings.

Whole information about the construction industry, which is explained below, belongs to private construction because the number of public buildings is much less than private ones. Moreover there is not sufficient data about them. Distribution of different type of buildings based on their number and total floor area are shown in Table 3.5 and Table 3.6 respectively. According to the Statistics and Research Department of State Planning Organization (SPO) report, reinforce concrete is used as a structural system in all buildings and bricks are employed to build all walls (State Planning Organization of TRNC, 2011).

Table 3.5: Number of constructed buildings in 2009 (State Planning Organization of TRNC, 2011)

Residential buildings				
Apartment	Duplex	Triplex	House	Total
367	985	8	242	1602
Commercial buildings				
Shops	Offices	Garages	Entertainment	Total
82	17	157	17	273
Industrial buildings				
Storage	Factories			Total
28	42			70
Miscellaneous				Total
407				407
Total				2352

Table 3.6: Total floor area (square meters) of constructed buildings in 2009 (State Planning Organization of TRNC, 2011)

Residential buildings				
Apartment	Duplex	Triplex	House	Total
191,663	186,851	3,477	29,875	411,866
Commercial buildings				
Shops	Offices	Garages	Entertainment	Total
20,774	4,145	15,731	6,925	47,575
Industrial buildings				
Storage	Factories			Total
4,830	20,744			25,574
Miscellaneous				Total
33,976				33,976
Total				518,991

The pie charts which are shown in Figure 3.18 are Figure 3.19 are drawn based on Table 3.5 and Table 3.6 data. They show that the residential buildings play and important role in construction industry. They should be focused in detail because they have the highest percentage, 68% and 79% in both number and total floor area respectively, in all constructed building in 2009.

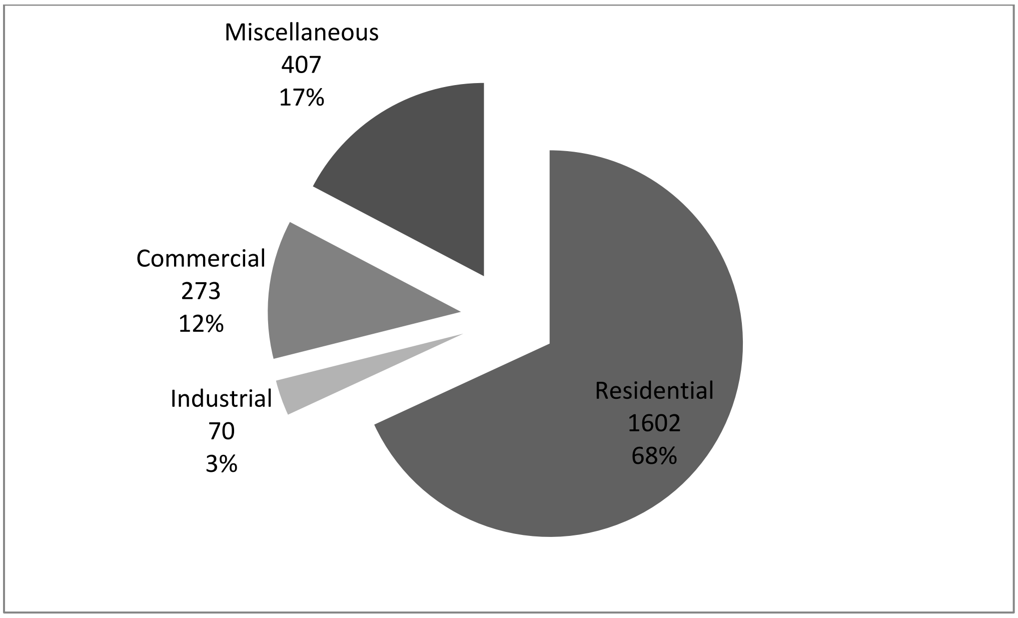

Figure 3.18: Distribution of building categories based on their number

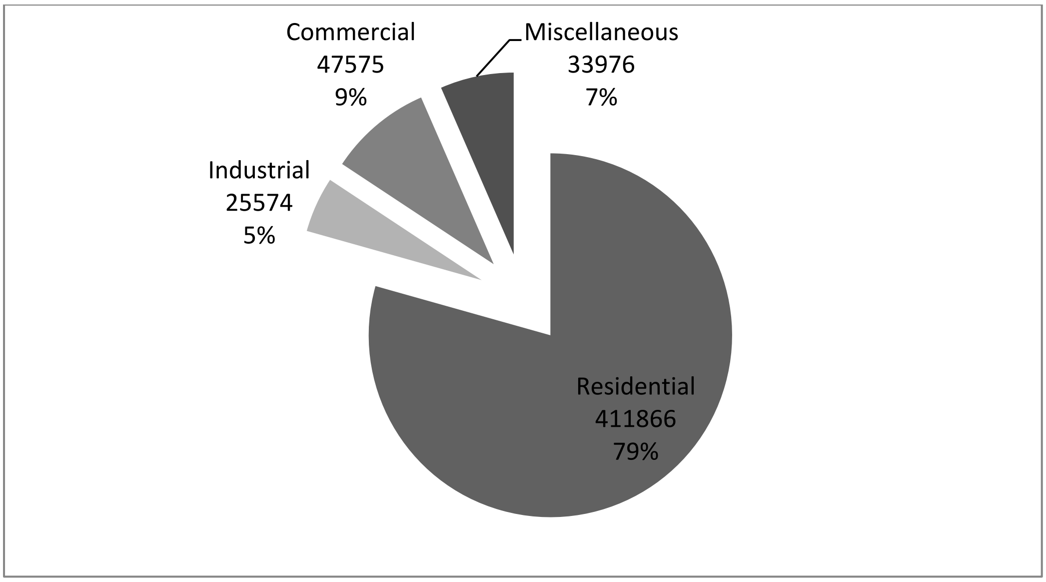

Figure 3.19: Distribution of building categories based on their floor area (square meters)

The Numbers and floor areas of different types of residential buildings are given in Figure 3.20 and Figure 3.21 respectively. It is shown that the number of duplex buildings accounts for 61% of total residential buildings meanwhile their total floor area accounts for 45% of total floor area of residential buildings. In other words, duplex buildings are in the first stage between numbers of residential buildings but it is in second stage, after the apartment with 47%, in total floor area of residential buildings.

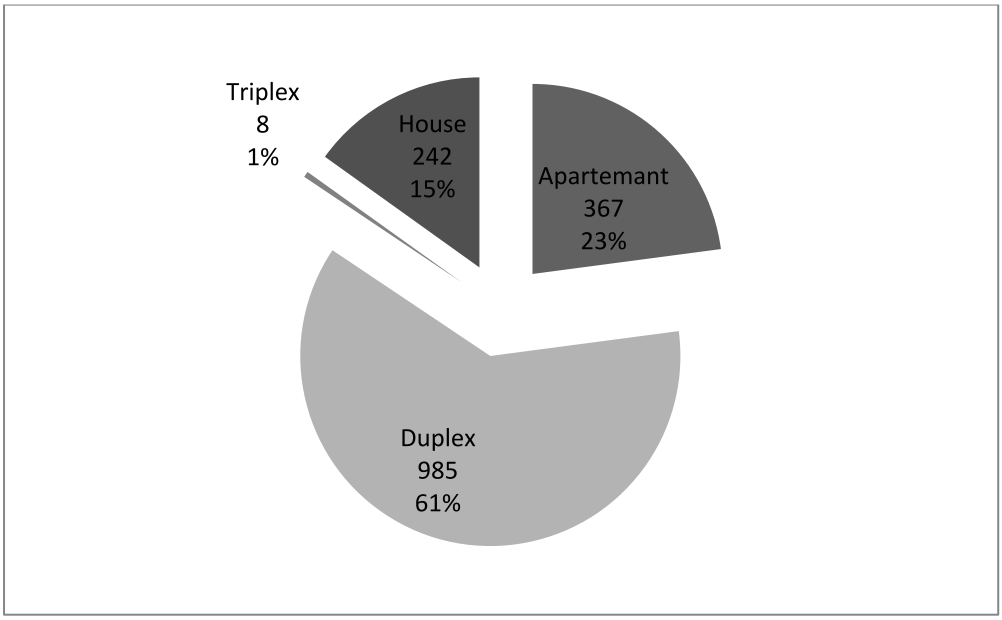

Figure 3.20: Distribution of residential building categories based on their number

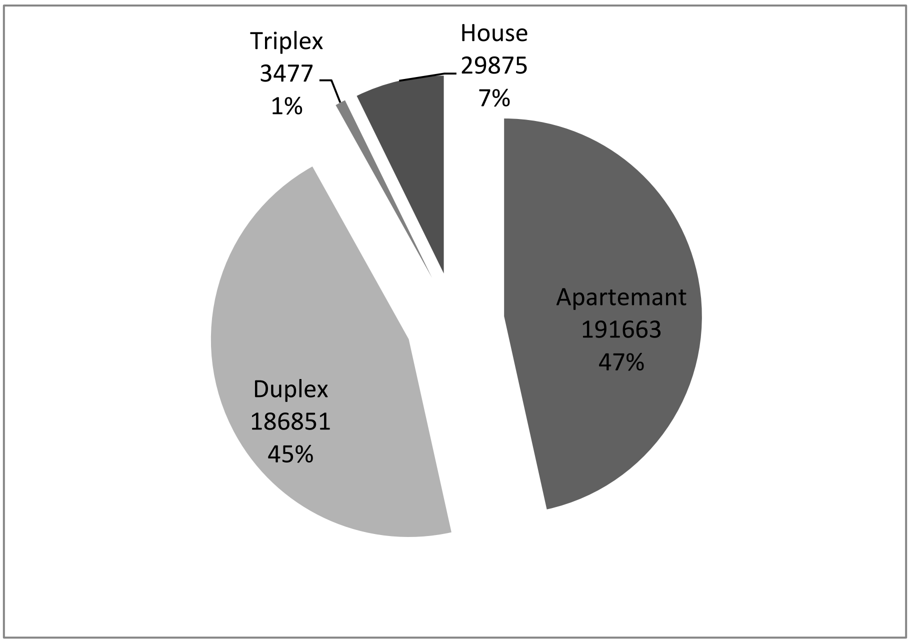

Figure 3.21: Distribution of residential building categories based on their number (square meters)

Distribution of residential buildings based on their number of stories and range of total floor area are given in Figure 3.22 and Figure 3.23 respectively. According to them, the 69% of residential buildings have two stories meanwhile the higher buildings accounts for less or equal than 10% of residential buildings.

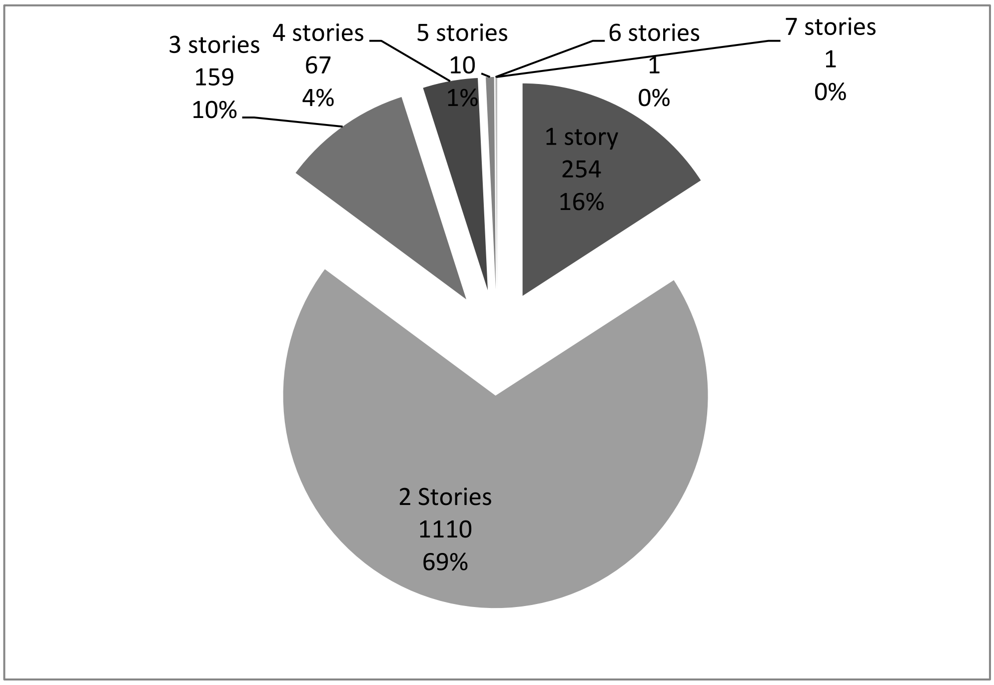

Figure 3.22: Distribution of residential buildings based on number of stories

The residential buildings with total floor area between 101 to 200 square meters are most widely built, which account 56% of total floor area, whilst the other ranges account less than 20% according to Figure 3.23.

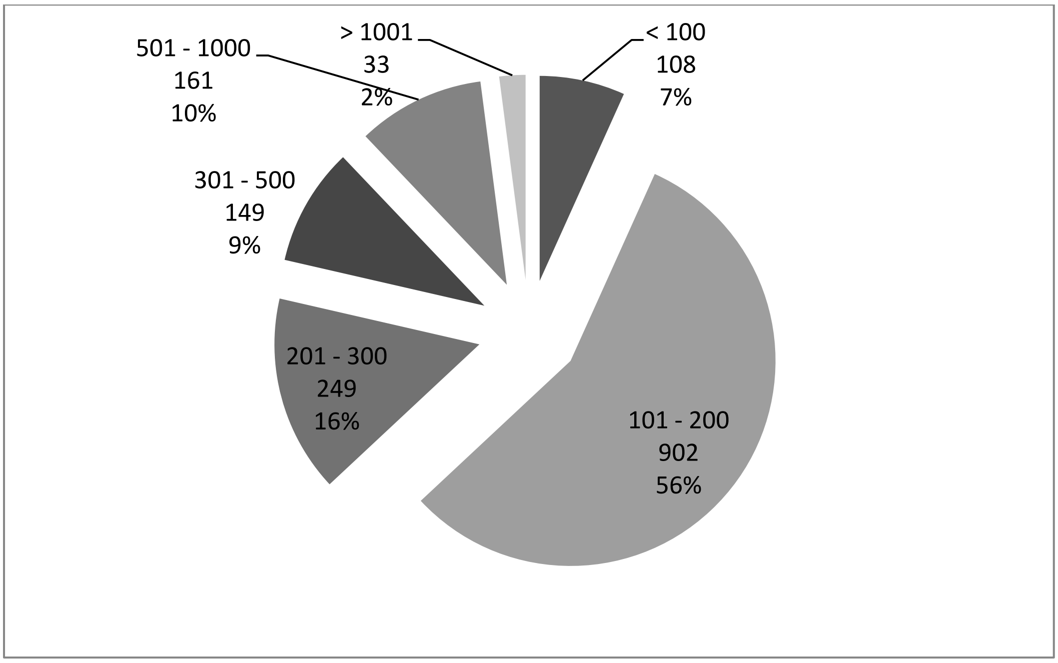

Figure 3.23: Distribution of residential building categories based on various band of floor area (square meters)

Chapter 4

PHASE CHANGE MATERIALS (PCMs)

4.1 Introduction

Description of phase change materials, which are used to control the indoor air temperature, and their type are depicted in the early section, incorporation method of PCMs into building fabrics are described subsequently and modeling software are named briefly at the end of this chapter.

Although each type of incorporation methods has their own advantages and disadvantages, micro-encapsulation method seems to be more proper method among others. Thus it is selected for this research study.

Since the Energy Plus software has ability to model and simulate the PCMs directly, it is selected as energy simulation software to carry out the dynamic thermal simulation. Finally, RT 31 is selected from Rubitherm company as a phase change material because of its melting temperature to simulate in Energy Plus and apply inside the building.

4.2 Overview

All of building materials have thermal capacity and resistant. Heat can be reserved in them either in latent or sensible form. Thermal energy is stored by both changing the internal energy (sensible heat storage), and changing the phase (latent heat storage) of fabrics. Heavy fabrics are used for sensible heat storage. Phase change material can be used for latent heat storage.

PCM keeps the indoor environment thermally stable by reserving more heat, achieved by storing latent heat, in comparison to other materials. When the environment temperature goes up, PCM melting is started and it turns from solid to liquid state. This process absorbs heat and prevents environment temperature increase. When the temperature falls below the PCM melting point, solidification process is started and it turns from liquid to solid form. It is an exothermic process thus released heat increase environment temperature. These processes decrease both heating and cooling load (Baetens, Jelle, & ustavsen, 2010).

Phase change materials to be used in building application should possess some specific properties which are mentioned below (Baetens, Jelle, & ustavsen, 2010) (Tyagi & Buddhi, 2007) (Sharma, Tyagi, Chen, & Buddhi, 2009) (Raj & Velraj, 2010) (Zalba, Marin, Cabeza, & Mehling, 2003) (Khudhair & Farid, 2004) (Pasupathy, Velraj, & Seeniraj, 2008) (Oro, Gracia, Castell, Farid, & Cabeza, 2012)

Thermo-physical specifications

- Melting temperature should be in the desired operation range.

- High thermal conductivity in both solid and liquid phase to assist in charging of PCM within the limited time.

- High latent heat per unit volume to store as much heat as possible.

- High specific heat capacity for propose of benefit additional sensible heat.

- Small volume change on phase transformation in order to inhibit thermal expansion of the containers.

- No phase segregation.

Chemical specification

- No degradations after a large number melting/freezing cycle.

- Non-corrosive, non-explosive, non-toxicity and non-flammable material for safety.

- Long-term chemical stability.

Kinetic specifications

- High nucleation rate in order to prevent supercooling or subcooling during liquefaction and solidification processes

- Sufficient crystallization rate to meet demands of heat recovery from the storage system

Economics and environmental

- Abundant and available

- Effective cost or low cost

- Easy recycling (separate from different materials easily)

- Less effect on environment

4.3 Type of Phase Change Materials

PCMs are divided into three groups, organic, inorganic, eutectics (Zalba, Marin, Cabeza, & Mehling, 2003) (Khudhair & Farid, 2004) (Pasupathy, Velraj, & Seeniraj, 2008). Each category has different range of melting temperature and enthalpy which shown in Figure 4.1 (Dieckmann, 2014).

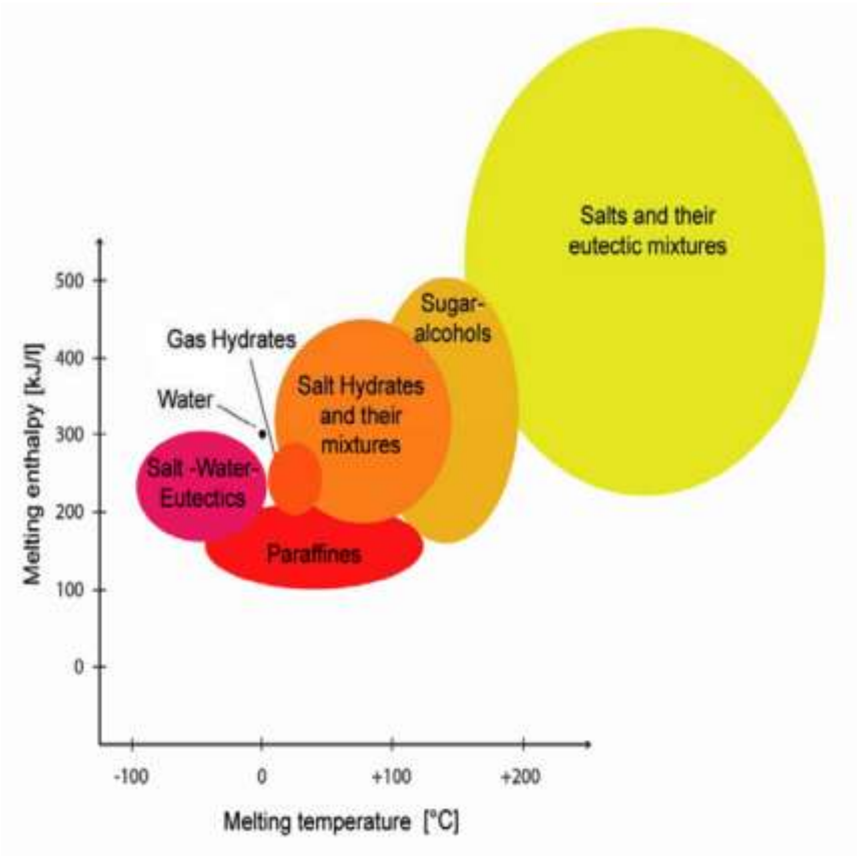

Figure 4.1: The melting temperature Vs. enthalpy for various PCMs (Dieckmann, 2014)

Organic compounds are subdivided into paraffin and non-paraffin. They crystallize with little or no subcooling and are usually non-corrosive (Oro, Gracia, Castell, Farid, & Cabeza, 2012). They provide wide melting temperature range; moreover, they are chemically stable and recyclable and good compatibility with others fabrics. However, they are low thermal conductive and flammable (Zhou, Zhao, & Tian, 2012) (Raj & Velraj, 2010). Widely used organic phase change materials, with melting temperature between 20˚C and 32˚C, are indexed below in Table 4.1.

Table 4.1: Common organic PCMs with melting point range from 20˚C to 32˚C

Compounds	Melting point ˚C	Heat of fusion KJ/Kg	References
Butyl stearate	19	140	(Hawes, Feldman, & Banu, 1993)
Paraffin C_{16} C_{18}	20 – 22	152	(Zalba, Marin, Cabeza, & Mehling, 2004)
Capric Lauric acid	21	143	(Hawes, Feldman, & Banu, 1993)
Dimethyl sabacate	21	120	(Feldman, Shapiro, & Banu, 1986)
Polyglycol E 600	22	127.2	(Dincer & Shapiro, 2002) (Lane, 1980)
Paraffin C_{13} C_{24}	22 – 24	189	(Abhat, 1983)
34% Mistiric acid + 66% Capric acid	24	147.7	(Lane, 1980)
1-Dodecanol	26	200	(Hawes, Feldman, & Banu, 1993)
Paraffin C18 (45 55%)	28	244	(Abhat, 1983)
Vinyl stearate	27 – 29	122	(Feldman, Shapiro, & Banu, 1986)
Capric acid	32	152.7	(Dincer & Shapiro, 2002) (Lane, 1980)

Paraffins are usually cheap chemically inert PCMs. They have a moderate thermal storage density, approximately 200 KJ/Kg or 150 MJ/m^3 (Figure 4.2). However; they have low thermal conductivity, approximately 0.2 W/m.˚C, and large volume change. They do not undergo phase segregation. Theirs melting temperature range is between

20˚C and 70˚C (Hasnain, 1998) (Farid, Khudhair, Razack, & Al-Hallaj, 2004) (Baetens, Jelle, & ustavsen, 2010).

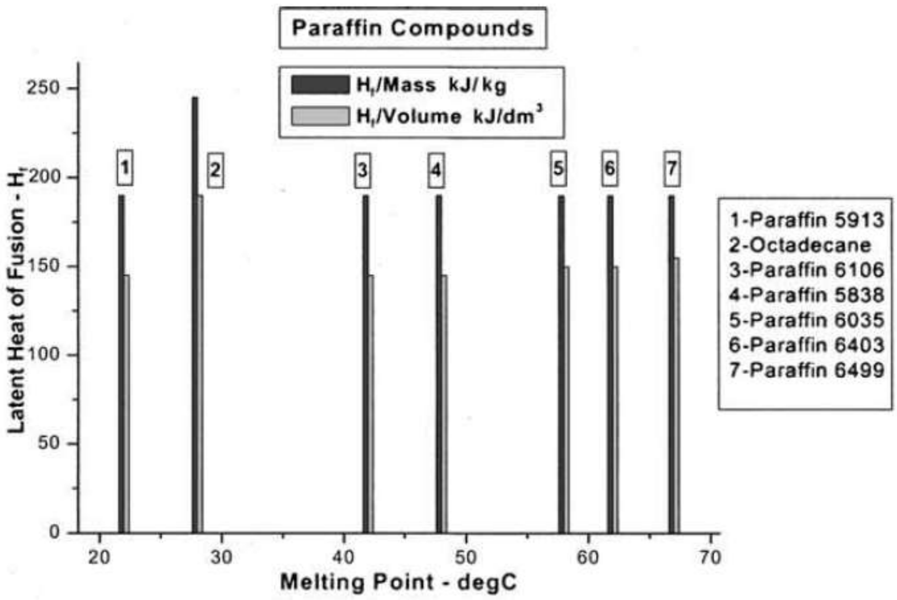

Figure 4.2: Latent heat of melting of paraffin compounds (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

The non-paraffins can be fatty acids, esters, glycols and alcohols. They have a wide melting temperature range between 7 and 187˚C. Their heat of fusion is between 42 and 250 KJ/Kg (Figure 4.3). Fatty acids exhibit excellent freezing/melting characteristics without any supercooling. Their higher cost which is rough three times greater than paraffins is their main drawback (Hasnain, 1998).

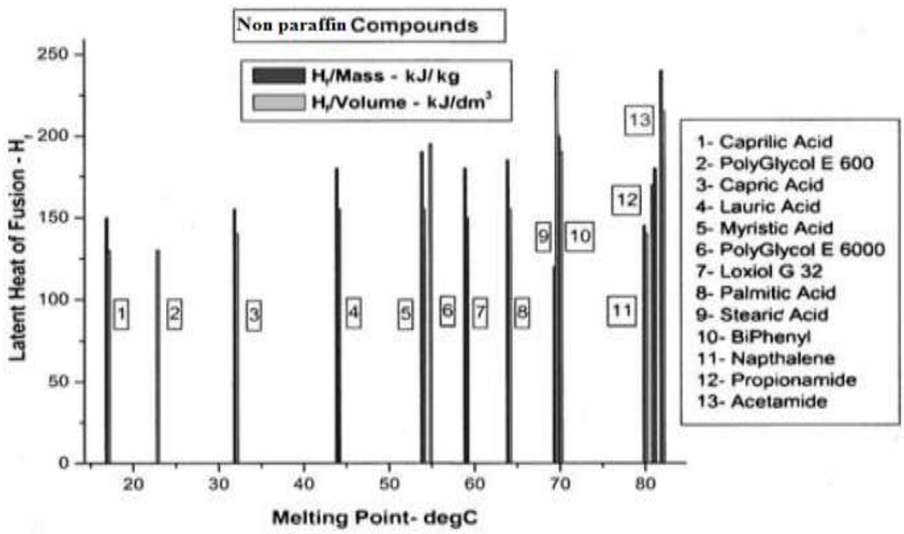

Figure 4.3: Latent heat of melting of Non paraffin compounds (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

Inorganic compounds are composed mainly from hydrated salts such as sodium sulfate decahydrate, calcium chloride hexahydrate, sodium thiosulphate pentahydrate, sodium acetate trihydrate and barium hydroxide octahydrate (Hasnain, 1998). These materials have high heat of fusion and desirable thermal conductivity, about 0.5 W/m°C. These have high volumetric storage density, about 350 MJ/m^3. (Farid, Khudhair, Razack, & Al-Hallaj, 2004) Low price, non-flammability and readily availability are their main advantages; however, their most problems are corrosive, subcooling, supercooling and phase segregation. Their melting temperature is about 18 to 36 °C and their latent heat is between 147 and 281 KJ/Kg (Hawes, Feldman, & Banu, 1993). Widely used inorganic PCMs, with the melting temperature between 20°C and 32°C, are shown in Table 4.2. The melting temperatures and the latent heat of fusion of some in-organic are given in Figure 4.4 and Figure 4.5.

Table 4.2: Common inorganic PCMs with melting point range from 20 ˚C to 32 ˚C

Compound	Melting point ˚C	Heat of fusion KJ/Kg	Refrences
$KF.4H_2O$	18.5	231	(Abhat, 1983) (Naumann & Emons, 1989)
$Mn(No_3)_2 .6H_2O$	25.8	125.9	(Wada, Yokotani, & atsuo, 1984)
$CaCl_2 .6H_2O$	29	190.8	(Dincer & Shapiro, 2002) (Lane, 1980)
$LiNO_3 .3H_2O$	30	296	(Heckenkamp & Baumann, 1997)
$Na_2SO_4 .10H_2O$	32	251	(Hawes, Feldman, & Banu, 1993) (Abhat, 1983) (Naumann & Emons, 1989)

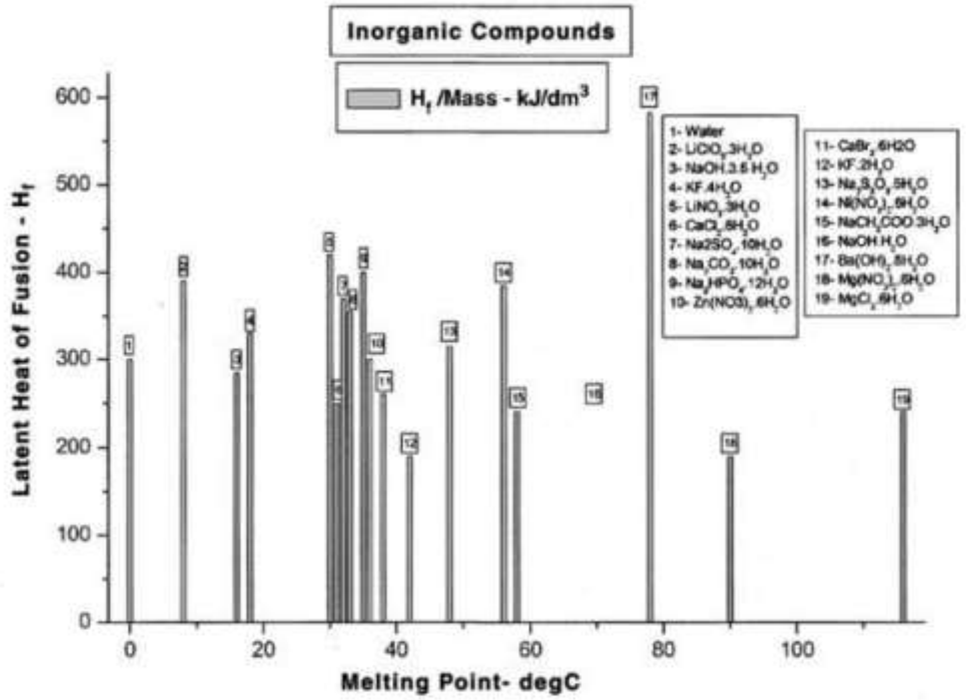

Figure 4.4: Latent heat of melting/mass of inorganic compounds (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

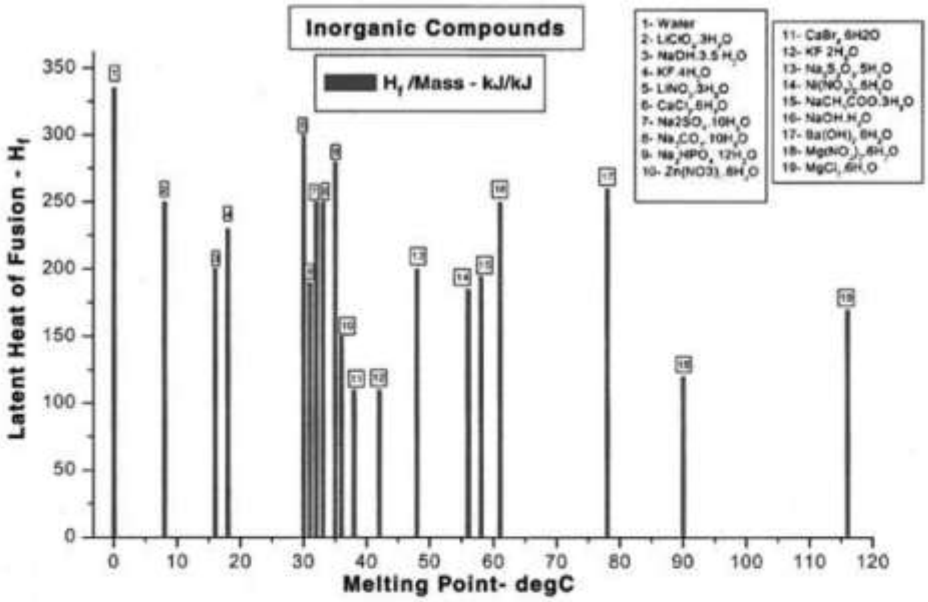

Figure 4.5: Latent heat of melting/volume of inorganic compounds (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

Eutectics are mixtures of two or more constituents which have congruent melting/freezing points. This prevents the phase segregation and makes the material more stable after melting and freezing cycles. Their volumetric storage density is slightly higher than that of organic compounds. (Baetens, Jelle, & ustavsen, 2010) (Mehling & Cabeza, 2008). Eutectics may be divided in 3 groups according to the materials of which they consist: (I) organic-organic, (II) inorganic-inorganic and (III) inorganic-organic eutectics (Baetens, Jelle, & ustavsen, 2010). Some of eutectics have the range of melting points between 18 and 51 ˚C and freezing points between 16 and 51˚C, with a heat of fusion between 120 and 160 KJ/Kg (Baetens, Jelle, & ustavsen, 2010). Commonly used eutectics PCMs are listed in Table 4.3.

Table 4.3: Common eutectics PCMs

Compound	Melting point ˚C	Heat of Fusion KJ/Kg	References
66.6% $CaCL_2.6H_2O$ + 33.3%$Mgcl_2.6H_2O$	25	127	(Heckenkamp & Baumann, 1997)
48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O	26.8	188	(Abhat, 1983)
47% $Ca(NO_3)_2$ .4H_2O + 53% $Mg(NO_3)_2$ .6H_2O	30	136	(Abhat, 1983)
60% $Na(CH_3COO)$ .3H_2O + 40% $CO(NH_2)_2$	30	200.5	(Li., Zhang, & Wang, 1991)
Lauric-capric acid	18	120	(Feldman, Shapiro, Banu, & Fuks, 1989)
Palmitic stearic	51	160	(Feldman, Shapiro, Banu, & Fuks, 1989)

The melting temperatures and the latent heat of fusion of some eutectics are given in Figure 4.6.

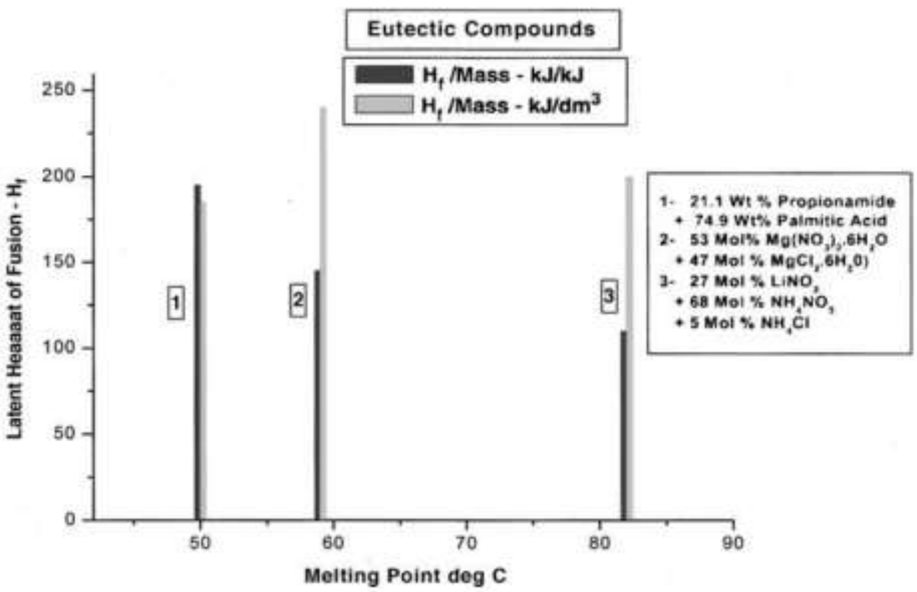

Figure 4.6: Latent heat of melting of eutectic compounds (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

4.4 Incorporation of PCMs into Construction Materials

Incorporation of PCMs within building materials is noteworthy to prevent leakage problem at least. Some incorporation methods are direct incorporation, encapsulation, shape-stabilized and immersion (Hawes, Feldman, & Banu, 1993) (Zhou, Zhao, & Tian, 2012).

4.4.1 Direct Incorporation Method

PCMs in the form of powder or liquid are combined directly in building materials like aggregate, concrete, gypsum and plaster in the course of production stage. It is simplest and economical method. However, the drawbacks of this method are leakage, incompatible with construction materials and degradation (Zhou, Zhao, & Tian, 2012) (Schossig, Henning, Gschwander, & Haussmann, 2005). The porous aggregate which absorbed butyl stearate PCM are mixed with cement and other materials to produce heat storage concrete (Zhang, Li, & Wu, 2004). The porous aggregate is shown in Figure 4.7.

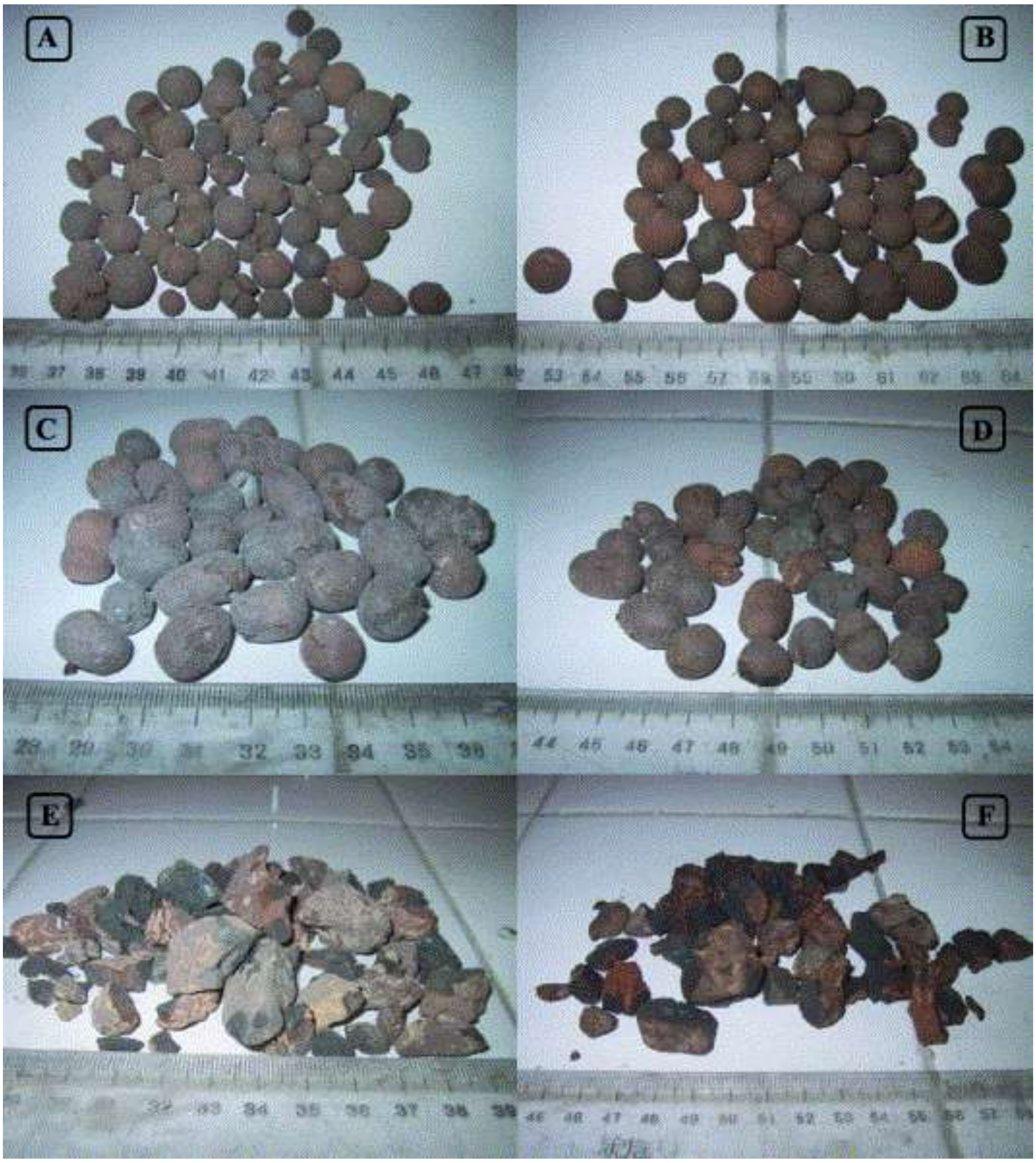

Figure 4.7: Porous aggregates (plain ones at the left side, absorbed PCM ones at the right side) (Zhang, Li, & Wu, 2004)

4.4.2 Encapsulation

In this method, containers encapsulate PCMs before they incorporate with building materials. Thus, building materials have no any contact or interaction with PCMs and building materials degradation is reduced. Containers protect PCMs from detrimental interaction with the environment. They should provide easy handling and flexibility thermal stability. Adequate surface for heat transfer satisfaction should be provided by containers (Regin, Solanki, & Saini, 2008). There are two types of encapsulation methods, macro-encapsulation and micro-encapsulation. More detail about encapsulation method are available in (Raj & Velraj, 2010) (Zalba, Marin, Cabeza, & Mehling, 2003) (Pasupathy, Velraj, & Seeniraj, 2008) (Farid, Khudhair, Razack, & Al-Hallaj, 2004)

PCMs are encapsulated in containers, for instance, spheres, panels, tubes or other receptacles in the first technique. Heat transfer characteristics, melting duration and capability of PCM storage are directly affected by geometric and thermal specification of the containers (Agyenim, Hewitt, Eames, & Smyth, 2010). The operation of the building material is less affected and PCM flammability and leakage problems are overcome with this method. Nevertheless poor thermal conductivity, complex integration to building fabrics and tendency for solidification at the edges are the main drawbacks of this method (Zhou, Zhao, & Tian, 2012).

Micro-encapsulate which have few micrometers of diameter coat or surround PCMs. They mix with building fabrics during the construction phase therefore extra process to incorporate them into building fabrics is avoided. Micro-encapsulation technique prevents leakage problem during phase-change processes and building materials degradation by keeping PCMs and building fabric separately (Tyagi, Kaushik, Tyagi, & Akiyama, 2011).

Different methods have been researched for micro-capsules production: vibrational nozzle; air-suspension coating; spray drying; matrix polymerization; pan coating; centrifugal extrusion; in situ polymerization and interfacial polymerization (Tyagi, Kaushik, Tyagi, & Akiyama, 2011) (Hawlader, Uddin, & Khin, 2003). Micro-encapsulation may change mechanical strength of building fabrics (Khudhair &

Farid, 2004). Nonetheless two same concrete cubicles, with and without micro-encapsulated PCMs, are designed to find the possibility of using micro-encapsulated PCMs without decreasing the mechanical strength in a same time. It found that concrete with micro-encapsulated PCMs reached a tensile splitting and compressive strength over 6 and 25 MPa respectively after 28 days (Cabeza, Castellón, Nogués, Medrano, Leppers, & Zubillag, 2007). Some supercooling problems are viewed (Zhang, Fan, Tao, & Yick, 2005). Heat transfer for thermally charging and discharging the PCMs will improved due to the tiny size of the encapsulation (Schossig, Henning, Gschwander, & Haussmann, 2005).

4.4.3 Shape-Stabilized

Shape-stabilized PCMs, has been a favorite topic for research in recent years (Zhu, Wang, Xu, & Ma, 2010), (Xiao, Feng, & Gong, Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity, 2002), (Sarı, 2004), (Xiao, Feng, & Gong, 2001), (Zhou, Yang, & Xu, 2011). The PCM is dispersed in another phase of supporting material, for example high-density polyethylene, to form a firm composite material (Zhou, Zhao, & Tian, 2012). It deals with the solid-liquid or solid-solid phase change (Whitman, Johnson, & White, 2012). Some advantages of this technique are suitable thermal conductivity, large specific heat and good performance of thermal cycles. The shape of PCM is kept stabilised in phase-change process (Inaba & Tu, 1997), (Xiao, Feng, & Gong, Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity, 2002), (Sarı, 2004) (Zhou, Zhao, & Tian, 2012). Due to needless any special containers to encapsulate PCM, thermal storage system will be simpler and attainable (Zhang, Lin, Yang, Di, & Jiang, 2006). Application of this method in building walls, floors and ceilings have been considered by number of researchers (Zhou, Yang, & Xu, 2011) (Zhou, Yang, Wang, & Che, 2010) (Zhou, Zhang, Wang, & Lin, 2007) (Zhou, Zhang, Lin, & Xiao, 2008) (Zhou, Yang, Wang, & Zhou, 2009) (Zhang, Lin, Yang, Di, & Jiang, 2006) (Xu, Zhang, Lin, & Rui , 2005) (Xiao, Wang, & Zhang, 2009). Sample of shape stabilized PCM is shown in Figure 4.8.

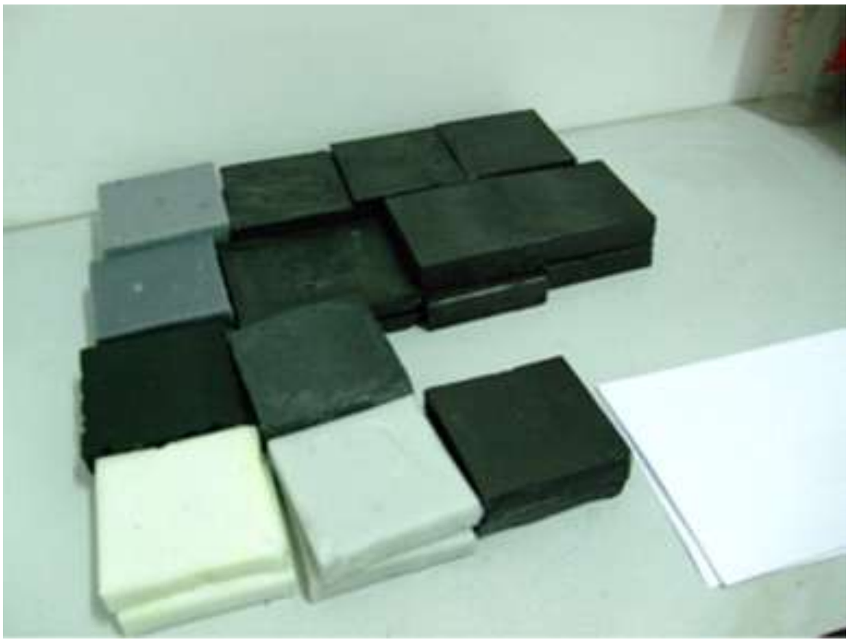

Figure 4.8: Sample of shape stabilized PCM which look like a homogeneous material (Cheng, Zhang, Xie, Liu, & Wang, 2012)

4.4.4 Immersion

This technique incorporates PCMs in building fabrics directly. Building constituents, such as gypsum board, concrete block, wallboard or brick, are dipped into melted PCMs. PCMs are absorbed into elements internal pores by capillarity action. This method can be used everywhere and applied to any products (Zhang, Zhou, Lin, Zhang, & Di, 2007) however the leakage and interaction with building fabrics in long time are the drawbacks of this technique (Schossig, Henning, Gschwander, &

Haussmann, 2005). Thermal storage capacity of incorporated building elements were increased while the leakage problem was occurred (Kaasinen, 1992).

4.5 PCM Modeling Software

PCMs phase transition elaborations and complicated such as thermo-physical materials properties changing, latent heat storage and release and unspecified temperature range for phase change lead to absolutely complex computer modeling.

There are large numbers of energy simulation software can model PCMs directly and indirectly. Energy Plus, ESP-r, IES virtual environment and TRNSYS are some of them.

One of the energy simulation software which able to model PCMs directly is Energy Plus. It is widely used, open source and powerful thermal simulation software. Energy Plus take advantages of algorithms which able to simulate located PCMs in any position in a multilayer wall while other aspect of thermal simulation are fixed (Pedersen, 2007). This software was simulated polyurethane foam and micro-capsulated paraffin PCM which was used in camper van (Cardinale, Stefanizzi, Rospi, & Augenti, 2010).

ESP-r software was used to simulate the PCMs in building directly. ESP-r is able to model PCM as result of refinement by adding the effect of phase transition (Heim & Clarke, 2004). It can be done in the ESP-r special materials facility that allows software to model active building fabrics.

IES virtual environment software needs additional processes to carryout PCMs modeling and simulation. In other words, IES virtual environment models PCMs indirectly. A room was modeled which has a conditioned cavity behind the PCM (Kendrick & Walliman, 2007) Melting point of PCM is set to this cavity. The conditioning is switched on when set temperature is reached and it is switched off when latent heat of PCM is dissipated. Moreover, in freezing part, the room is conditioned until release of all PCM's latent heat is done. The conditioning should be switched off or on based on its heat energy which should be recorded frequently. The biggest downside of this method is major manual intervention, which is mentioned before. The authors confined their simulations only for a hottest month, August, due to mentioned drawback (Kendrick & Walliman, 2007).

TRNSYS is another energy simulation program which simulate and model PCM indirectly however it has specific component named Type 56 which models thermally active building element. Radiant floor heating, radiant ceilings and wall cooling and heating are conditioning systems in building which involve fluid flow within them. The Type 56 can model the PCMs due to the similarity between radiative walls and PCM walls. In melting process, thermal energy will be discharged by fluid until all of the latent heat is released when the PCM temperature reach melting point. Conversely, energy will be stored into wall when the PCM temperature reach freezing point until the latent heat is discharged (Ibáñez, Lázaro, Zalba, & Cabeza, 2005).

Eventually, Energy Plus software has been selected to accomplish the dynamic thermal simulation according to its capability such as modeling PCMs directly, being open source software and having simple interface.

4.6 PCM Selection

Less than ten companies produce phase change materials for building application around the world. ***RUBITHERM***® Technologies GmbH is one of the principal PCM suppliers worldwide (Rubitherm, 2014). It is producing different type of PCMs with wide range melting point which can be used in various applications. Four types of productions which are suitable for building application are shown in Table 4.4, with more detail (Rubitherm, 2014).

Table 4.4: RUBITHERM® Products and their properties (Rubitherm, 2014)

Products name		RT 27	RT 28 HC	RT 31	RT 35
	Unit				
Melting Point	˚C	27	28	31	35
Heat storage capacity	KJ/Kg	179	245	170	170
Specific heat capacity	Wh/kg	2	2	2	2
Density	Kg/m^3	820	825	820	815
Heat conductivity	W/m.K	0.2	0.2	0.2	0.2
Flash point	˚C	146	165	157	167
Max. operation temperature	˚C	50	50	50	65

RT 31 is selected for current study due to its melting temperature and heat storage capacity. Melting temperature of PCM for cooling application in building should be around the average temperature of the summer months (Kamali, 2014).

For simulation with Energy Plus, temperature and corresponding enthalpy value are needed. The amounts of enthalpy for a range of temperature are given by producer as it is shown in Table 4.5 (Rubitherm, 2014). These values are used to draw temperature and enthalpy relationship curve in Figure 4.9. And cumulative enthalpy – temperature diagram is given Figure 4.10.

Table 4.5: Temperature vs. enthalpy for RT 31 (Rubitherm, 2014)

Temperature (˚C)	Enthalpy (KJ/Kg)		
	Heat	Cool	Average
23	3	6	4.5
24	5	6	5.5
25	4	8	6
26	5	14	9.5
27	10	14	12
28	10	19	14.5
29	20	23	21.5
30	27	23	25
31	27	24	25.5
32	27	19	23
33	17	14	15.5
34	11	3	7
35	5	5	5
36	3	4	3.5
37	3	4	3.5
38	3	3	3

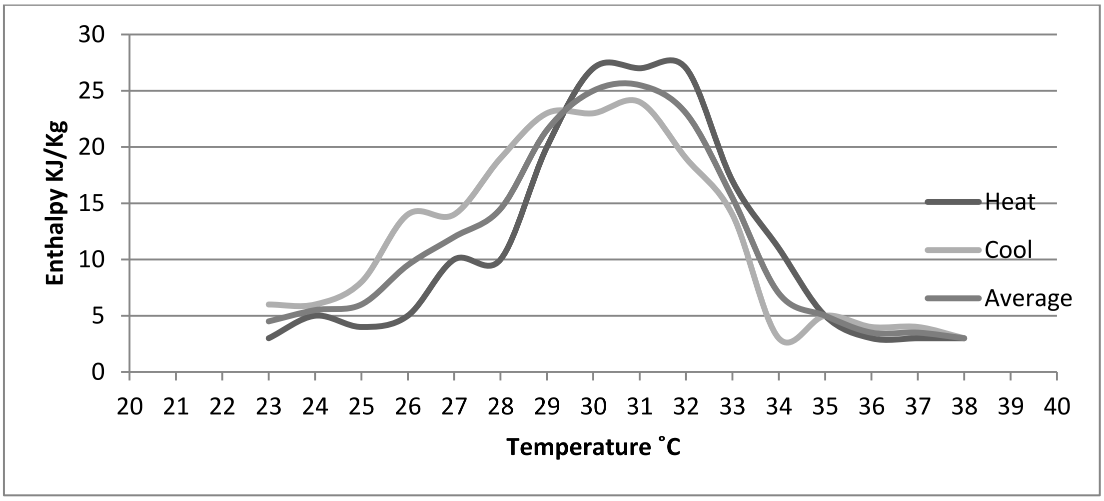

Figure 4.9: Temperature and enthalpy relationship

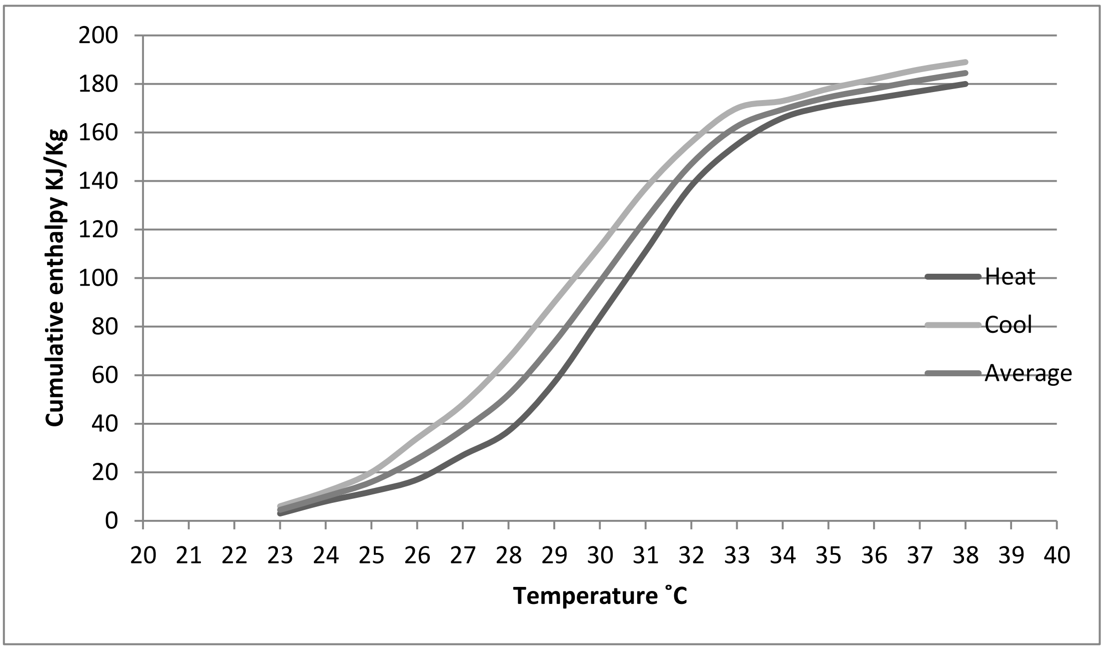

Figure 4.10: Cumulative enthalpy – temperature diagram

The enthalpy – temperature values should cover all the temperatures seen by the materials in Energy Plus. Based on the Cyprus weather condition, these values should be in the range of 10˚C to 50˚C. A linear line can be fitted to first and last values. Thus the cumulative temperature-enthalpy which is covered 10˚C to 50˚C is investigated in Figure 4.11.

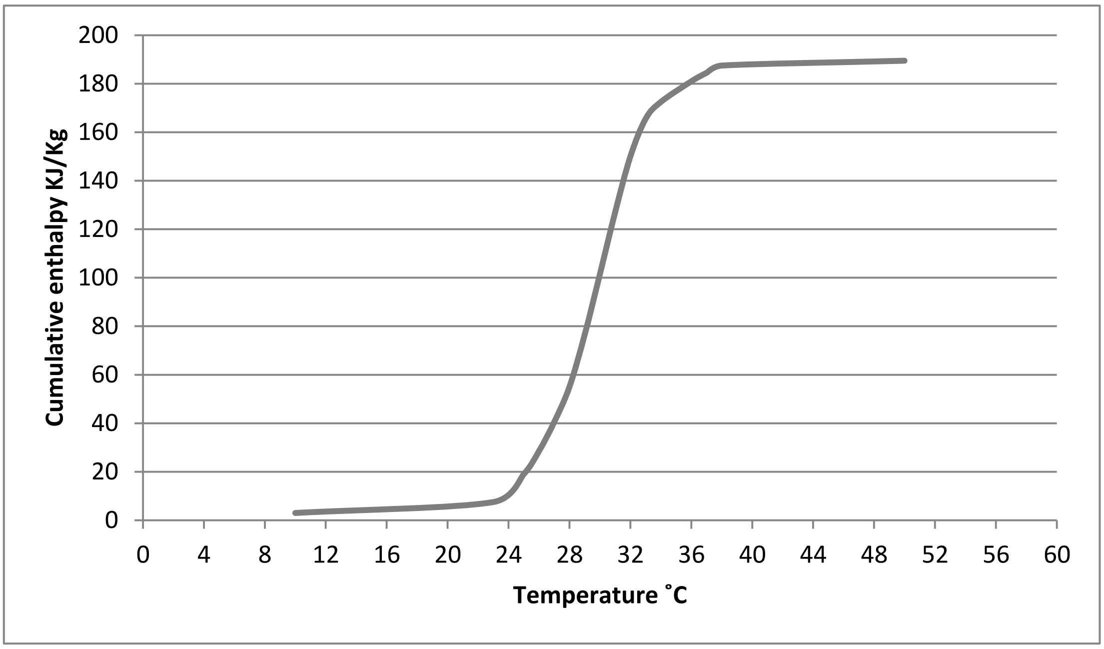

Figure 4.11: Cumulative enthalpy – temperature curve

The latent heat capacity of this product is calculated manually to compare with concrete heat storage capacity for 4˚C differentials. Equation 4-1 and Equation 4-2 are used to calculate the heat capacity of RT 31 and concrete respectively.

$$Q = m.\Delta H \qquad \text{Equation 4-1}$$

Where,

$Q = \text{Latenet heat capacity} \left({}^{J}/_{K} \right)$

$m = \text{Mass (Kg)}$

$\Delta H = \text{enthalpy change} ({}^{J}/_{Kg.\,K})$

$$Q = m \, . \, C_p \, . \, \Delta T \qquad \text{Equation 4-2}$$

Where,

$Q = \text{Latenet heat capacity} \left({}^{J}/_{K} \right)$

$m = \text{Mass (Kg)}$

$C_p = \text{Specific heat} \left({}^{J}/_{Kg.\,K} \right)$

$\Delta T = \text{Temperature differential (°C)}$

Enthalpy change in RT 31 between 30 ˚C to 34 ˚C is 18000 (J/Kg.K), Thus the amount of heat which can be stored in 1 kg of RT 31 is 18000 J/K.

To find the mass of concrete for storing same amount of heat, 18000 J/K, Equation 4-2 will be used. Density and specific heat of normal weight concrete are 2400 Kg/m^3 and 750 KJ/Kg.K. It is found that in order to achieve the same amount of heat storage as 1 Kg RT 31 around 6 Kg normal-weight concrete is needed.

Chapter 5

DYNAMIC THERMAL SIMULATION

5.1 Introduction

Energy plus is one of the powerful building energy simulation software without any doubts. As it mentioned before, it can model phase change materials without any change in other aspect of thermal simulation (Zhuang, Deng, Chen, Li, Zhang, & Fan, 2010), (Tabares-Velasco, Christensen, & Bianchi, 2012), (Pedersen, 2007). In this chapter, thermal properties of the building which modeled in Energy Plus are explained. Moreover, the simulation parameters which are necessary to thermal simulation are briefly illustrated. Finally, thermal simulation of a typical building under the Cyprus climate condition is done and results of simulation are investigated.

5.2 Building Specifications

It has been considered to select the modeled building as similar as widely used Cypriot buildings in terms of both architectural and structural view. It has 180 square meters total floor area in two stories. Ground floor contains kitchen, living room and lavatory meanwhile three bedrooms and lavatory are placed in the first floor (Figure 5.1). In the modeled building (Figure 5.2), the most widely used fabrics are used. The walls composed of perforated clay bricks and floor is made up from marble and concrete whereas reinforced concrete slab is used as roof. The Phase change materials lining is applied to all inner surfaces of walls and ceiling. For analyzing the effect of phase change material lining same building was modeled with the same lining but without phase change feature.

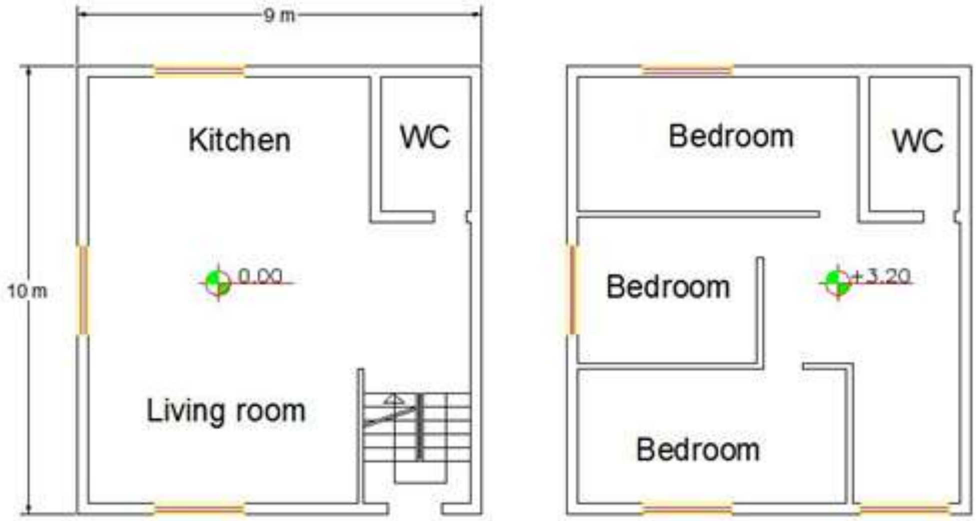

Figure 5.1: Architectural plan of modeled building

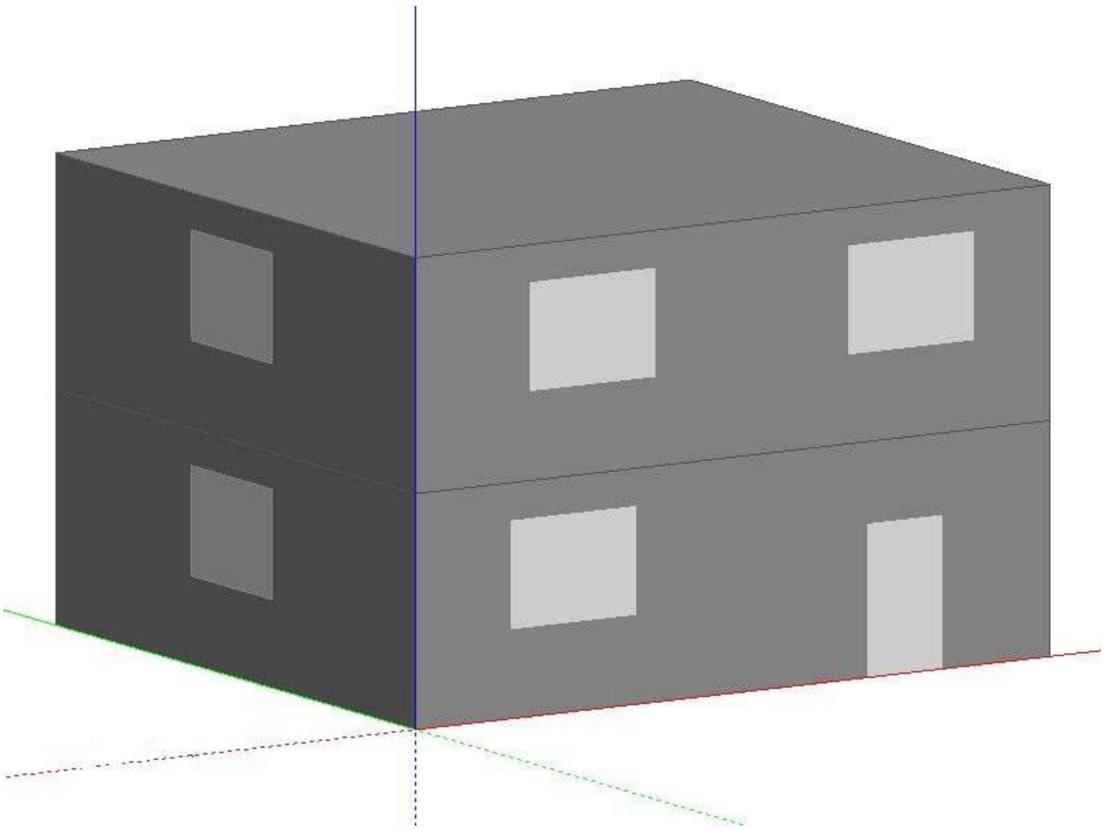

Figure 5.2: Modeled building in software

Eight different values are needed in Energy Plus to define a specific material. They are roughness, density, thickness, specific heat capacity, heat conductivity, visible absorptance, solar absorptance and thermal absorptance. It is not possible to obtain all this values from one source therefore many sources are used to obtain them for a specific material.

5.2.1 Wall

As it was mentioned before, perforated clay bricks with 200 mm thickness are used in wall construction. Inner and outer surfaces of wall are covered by 40 mm of lining (PCM) layer and 25 mm of cement plaster respectively. Painting both side of wall with white color is more common in Cyprus. Although paint layer has negligible thermal resistance, solar and thermal absorptances of white color have noteworthy effect in heat gain via short wave radiation. Thus these values are considered for surface properties of wall. Thermal properties of external and internal wall are given in Table 5.1 and Table 5.2 respectively.

Table 5.1: External wall thermal specifications

Layers (outer to inner)	Plaster	Perforated clay brick	Lining
Roughness	M. smooth	M. rough	M. smooth
Thickness (mm)	25	200	40
K (W/m.k)	1.4 (I)	0.4 (VI)	0.2 (VIII)
d (Kg/m^3)	2000 (I)	700 (VII)	820 (VIII)
C_p (J/kg.k)	650 (II)	840 (II)	2000 (VIII)
Thermal	0.9 (III)	0.9 (III)	0.9 (III)
Solar	0.26 (IV)	0.63 (IV)	0.26 (IV)
Visible	0.1 (V)	0.7 (III)	0.1 (V)

Table 5.2: Interior wall thermal specifications

Layers	Lining	Perforated clay brick	Lining
Roughness	M. smooth	M. rough	M. smooth
Thickness (mm)	40	100	40
K (W/m.k)	0.2 (VIII)	0.4 (VI)	0.2 (VIII)
d (Kg/m^3)	820 (VIII)	700 (VII)	820 (VIII)
C_p (J/kg.k)	2000 (VIII)	840 (II)	2000 (VIII)
Thermal	0.9 (III)	0.9 (III)	0.9 (III)
Solar	0.26 (IV)	0.63 (IV)	0.26 (IV)
Visible	0.1 (V)	0.7 (III)	0.1 (V)

5.2.2 Roof

It is a 150 mm reinforced concrete slab which is the most common in Cyprus. Its thermal properties are given in Table 5.3.

Table 5.3: Roof thermal specifications

Layers (outer to inner)	Reinforced Concrete	Lining
Roughness	Rough	M. smooth
Thickness (mm)	150	40
K (W/m.k)	2.1 (I)	0.2 (VIII)
d (Kg/m^3)	2400 (I)	820 (VIII)
C_p (J/kg.k)	840 (II)	2000 (VIII)
Thermal	0.9 (III)	0.9 (III)
Solar	0.7 (IV)	0.26 (IV)
Visible	0.7 (V)	0.1 (V)

5.2.3 Floor

Grade level floor is made up from five layers. The top layer is marble with 30 mm thickness. 20 mm of screed is used for the second layer. Underneath the screed, 50 mm sand layer is used. In the next layer 100 mm concrete is used. Finally, at the bottom, 15 cm hardcore layer standing on the compressed earth with coarse gravel is used. Its thermal specifications are given in Table 5.4.

Table 5.4: Grade floor thermal specifications

Layers (up to down)	Marble	Screed	Sand	Concrete	Hardcore
Roughness	Smooth	Rough	M. rough	Rough	V. rough
Thickness(mm)	30	20	50	100	150
K (W/m.k)	2.9 (II)	1.4 (I)	0.7 (I)	1.74 (I)	0.7 (I)
d (Kg/m^3)	2750 (II)	2000 (I)	1800 (I)	2200 (I)	1800 (I)
C_p (J/kg.k)	840 (II)	650 (II)	840(II)	840 (II)	840 (II)
Thermal	0.9 (III)	0.9 (III)	0.9 (III)	0.9 (III)	0.9 (III)
Solar	0.5 (II)	0.7 (IV)	0.7 (III)	0.7 (IV)	0.7 (III)
Visible	0.7 (III)	0.7 (III)	0.7 (III)	0.7 (III)	0.7 (III)

First level floor is composed to four layers. A 30 mm marble is the upper layer. Screed layer with 20 mm thickness is places under the marble layer meanwhile it is on the reinforced concrete. The down side of reinforced concrete is coated by 30 mm lining layer. Its thermal properties are illustrated in Table 5.5.

Table 5.5: Thermal properties of first level floor

Layers (up to down)	Marble	Screed	Reinforced concrete	Lining
Roughness	Smooth	Rough	Rough	M. smooth
Thickness (mm)	30	20	150	40
K (W/m.k)	2.9 (II)	1.4 (I)	2.1 (I)	0.2 (VIII)
d (Kg/m^3)	2750 (II)	2000 (I)	2400 (I)	820 (VIII)
C_p (J/kg.k)	840 (II)	650 (II)	840 (II)	2000 (VIII)
Thermal	0.9 (III)	0.9 (III)	0.9 (III)	0.9 (III)
Solar	0.5 (II)	0.7 (IV)	0.7 (IV)	0.26 (IV)
Visible	0.7 (III)	0.7 (III)	0.7 (III)	0.1 (V)

5.2.4 Windows

Double glazed window with PVC frames is very common in Cyprus. Two layer of clear glasses with 6 mm thickness and 3.2 mm space which filled by air without any frame (due to simplification) is used as a window in this work. Its thermal properties are taken from software database.

5.2.5 Door

Building has only one external door. It is made up from oak wood which has 40 mm thickness. Thermal properties of external door are illustrated in Table 5.6**.**

Table 5.6: Door thermal specification (U.S. Department of Energy, 2011)

	Wood (Oak)
Roughness	M. smooth
Thickness (mm)	40
K (W/m.k)	0.17
d (Kg/m^3)	705
C_p (J/kg.k)	1630
Thermal	0.9
Solar	0.7
Visible	0.7

Each Roman numeral next to the thermal parameter values figure out the source of them. These are referenced as I: (Genceli & Parmaksizoglu, 2006), II: (CIBSE, 2006), III: (U.S. Department of Energy, 2011), IV: (ASHRAE, 2009) , V: (Incropera & Dewitt, 1996), VI: (MCIT, 2007), VII: (Kudret Tugla A.S. (Brick Co.), 2009), VIII: (Rubitherm, 2014) .

5.3 Simulation Parameters

In this part, simulation parameters which are essential to be defined in software for thermal simulation will be explained.

The relevant parameters are grouped in “class”. One or more object, which consist thermal parameter, is available in each class. Related classes are also categorized as a “group”. According to Figure 5.3 “Simulation parameters” is a group which consist some classes such as “version”, “simulation control”, “building”, etc. each of these classes have some parameters (objective) which should be defined by user. For example, in “Building” class, name, north axis, Terrain and etc. are the parameters.

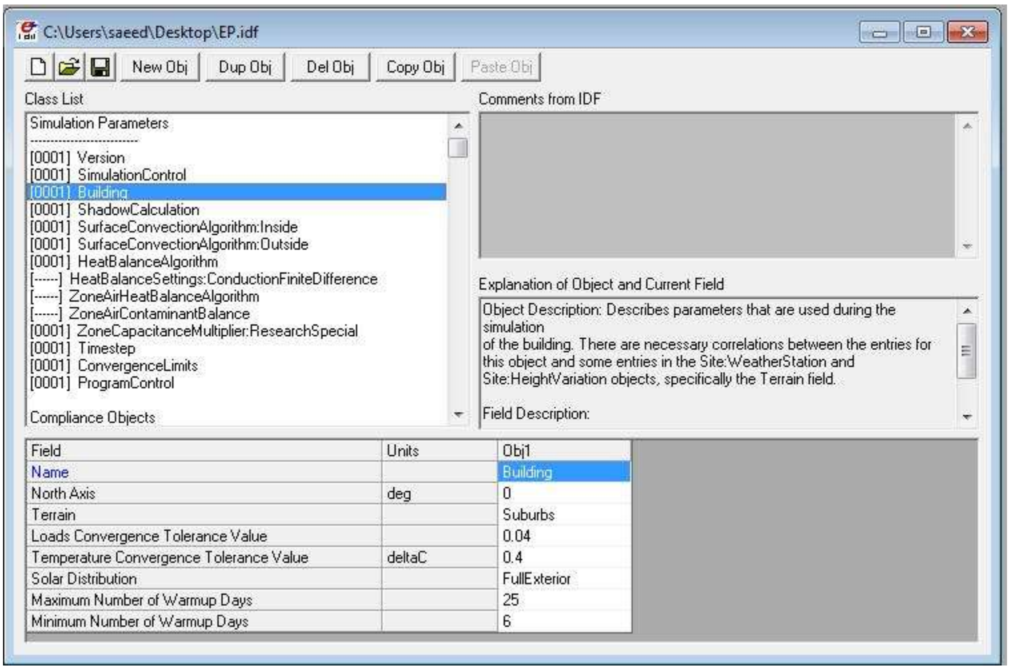

Figure 5.3: A snapshot from Energy Plus software showing Groups, Classes and objective

Since the simulation is carried out on the non-air conditioning building, only the thermal parameters which are related to without air conditioning system simulation and any other user input required parameters which are not related to thermal simulation will be explained here. All descriptions of parameters are obtained from the manual of Energy Plus software (U.S. Department of Energy, 2013).

5.3.1 Simulation Parameters Group

- North axis: Normally, building north axis dose not exactly on the true north, this parameter gives the ability of clockwise rotating of the building to user; it is shown in Figure 5.4. In this work building north axis is on the true north exactly so this field is filled by zero.

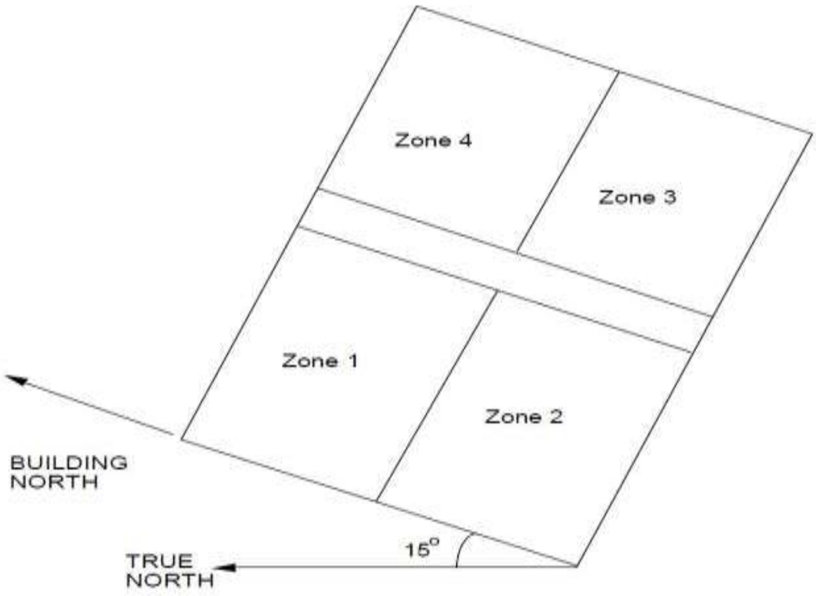

Figure 5.4: Building north axis (U.S. Department of Energy, Input/Output Reference, 2013)

- Terrain: This parameter shows how wind strikes building. It is playing role on the surface convection. The value for this parameter is given in Table 5.7. The value of country is considered for this study.

Table 5.7: Terrain description (U.S. Department of Energy, 2013)

Terrain type value	Description
Country	Flat, open country
Suburbs	Rough, wooded country, suburbs
City	Town, city outskirts, center of large cities
Ocean	Ocean, bayou flat country
Urban	Urban, industrial, forest

- Solar distribution: This object distinguishes how the software treats beam solar radiation and reflectance from exterior surfaces enter the zone. Five options are available, "Minimal Shadowing", "Full exterior", "Full interior and exterior", "Full exterior with reflections", "Full interior and exterior with reflections". The "Full interior and exterior" is selected for this study. This option enables the program to simulate the shade pattern on the exterior surfaces caused by other external surfaces such as: wings, detached shadings, door and window. The amount of beam solar radiation falling on each surfaces in the zone are considered in selected option by projecting the sunrays through windows. The amount of transmitted, absorbed and reflected beam radiation that falls on inside of an external window will be simulated and calculated.

- Shadow calculation frequency: It is the number of days which is using to simulate the sun position, related angles and other shadowing calculations instead of using one day. The default value, 20, is used because it is an averaged that noteworthy changes happen in sun position angles.

- Surface convection algorithm (inside): It gives an option for choosing the surface convection model for convection on all inner surfaces. Four algorithm are available for this object, “Simple”, “TARP”, Ceiling Diffuser”, and “Adaptive Convection Algorithm”. TARP is selected as inside surface convection algorithm because it correlates the heat transfer coefficient to the temperature difference for the various orientations.

- Surface convection algorithm (outside): Five algorithms are accessible here, “DOE-2”, “Simple Combined”, “TARP”, “MoWiTT”, “Adaptive Convection Algorithm”. Since wind affects heat transfer coefficients of exterior surfaces, “TARP” is selected to combine the natural and wind driven convection correlations together.

- Heat balance algorithm: Four different heat and moisture transfer algorithms are available to simulate the performance of building’s surface assemblies.

They are “Conduction Transfer Function”, “Moisture Penetration Depth Conduction Transfer Function”, “Conduction Finite Difference”, “Combined Heat and Moisture Finite Element”. In order to simulate phase change materials, “Combined finite difference” was selected. It is the only algorithm that can simulate PCMs in Energy Plus.

- Time step: When the combined finite difference is selected as a heat transfer algorithm, the minimum value of this object will be 20. It is the number of time steps per hour for heat transfer and load calculation. Smaller value leads to decrease simulation time and less accurate results; however, accurate results obtain in longer simulation time by selecting bigger value. Minimum value is selected due to simplicity of model.

5.3.2 Location and Climate Group

- Run period: This class defines the thermal simulation period by entering the first and last day of months (1=January, 2= February, 3= March, etc.). The beginning day is first of June and the last day is 31st of October are entered because this study is done for summer period, when cooling is required.

- Site ground temperature building surface: It is used for the ground heat transfer model. Although it is possible to enter different values for each month, one temperature (20 ˚C) is assigned for whole year, for simplicity, which is taken from Energy Plus sample file.

5.3.3 Schedule Group

- People occupancy: Since building is a residential building, it is unoccupied in weekdays from 7:00 to 18:00 (due to working hours). In any other hours, it is occupied. Working hours is considered from 8:00 to 17:00. The people occupancy schedule in weekdays and weekends are illustrated in Figure 5.5 and Figure 5.6 respectively.

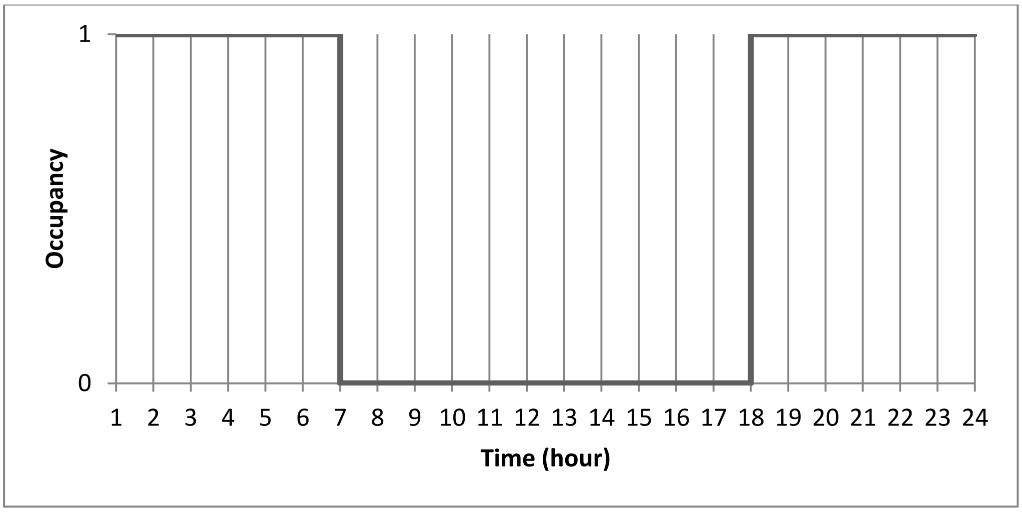

Figure 5.5: Occupancy schedule in weekdays

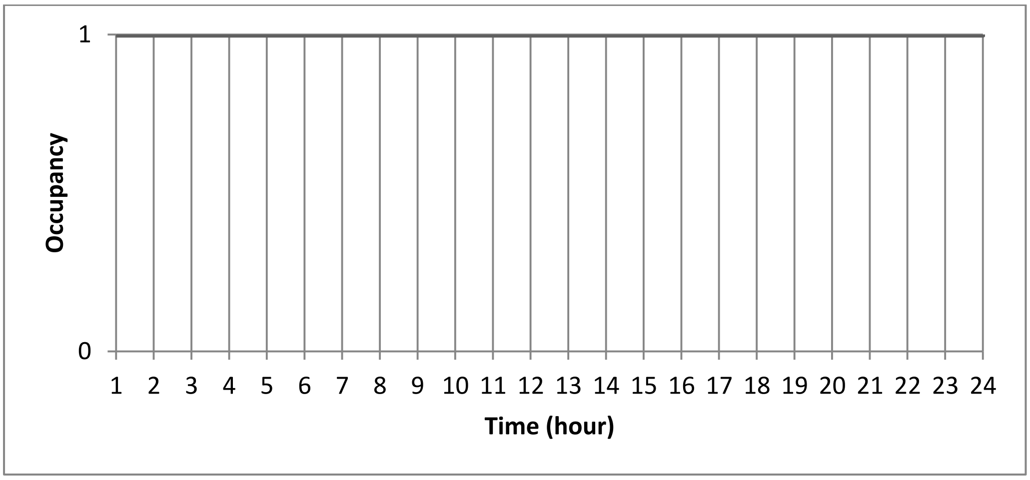

Figure 5.6: Occupancy schedule in weekends

- Light Schedule: As the simulation period is defined from first of May to end of October. The lighting needed is considered from 18:00 (at sunset) to midnight (residences go to bed). The time schedule is given in Figure 5.7.

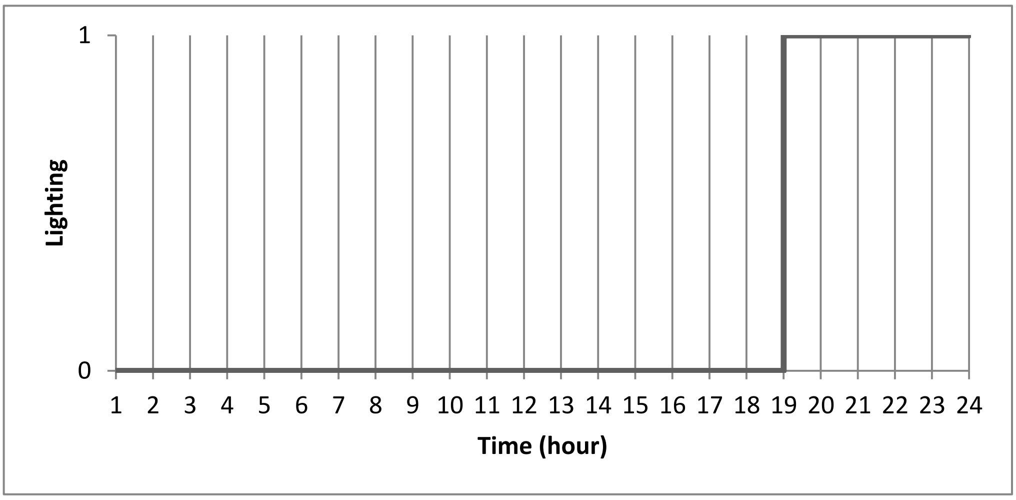

Figure 5.7: Lighting schedule

- Electric equipment schedule: The electric equipment schedule is different in weekdays and weekend because of difference in residence occupancy as shown Figure 5.8 and Figure 5.9.

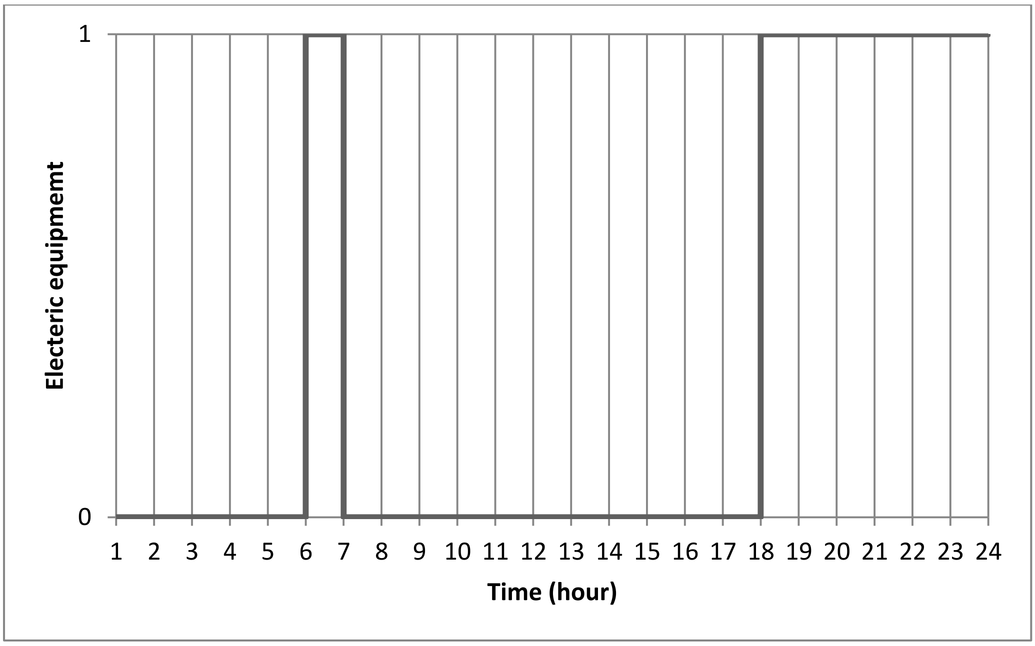

Figure 5.8: Electric equipment schedule in weekdays

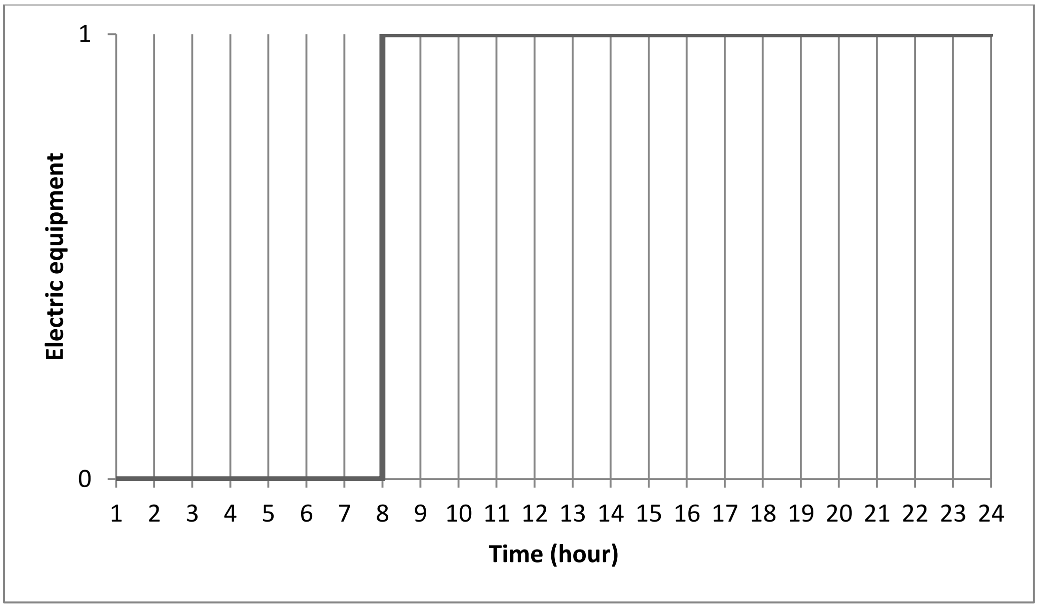

Figure 5.9: Electric equipment schedule in weekends

- Human activity schedule: The total heat gain from each person is changed in different situation. Each person releases 72 W and 126 W in sleeping and doing activity respectively (ASHRAE, 2009). Thus three values are considered for this schedule; 0 watt per person for unoccupied condition, 72 watts per person in sleeping time and 126 watts per person in other conditions. The human activity schedule is shown in Figure 5.10 and Figure 5.11.

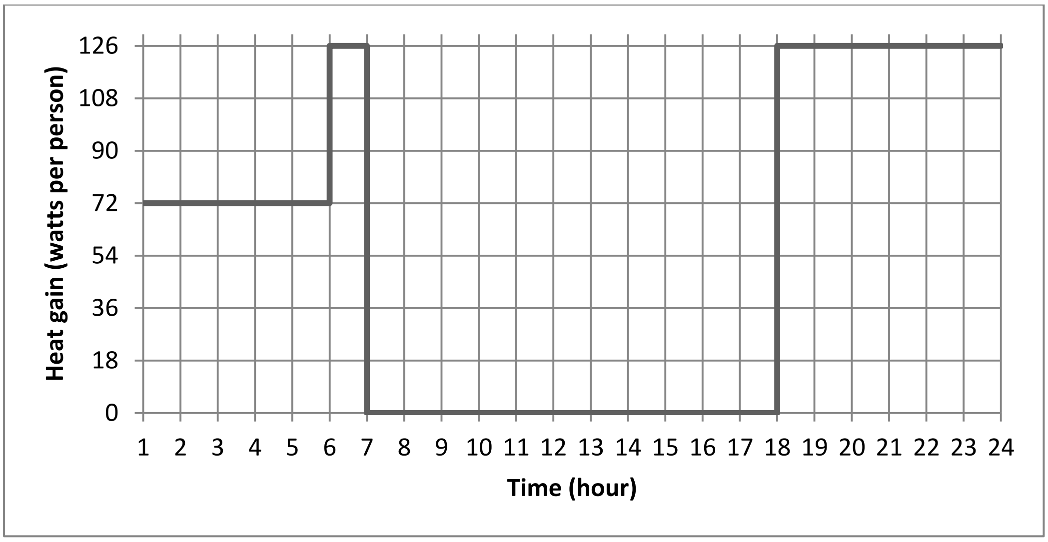

Figure 5.10: Human activity schedule in weekdays

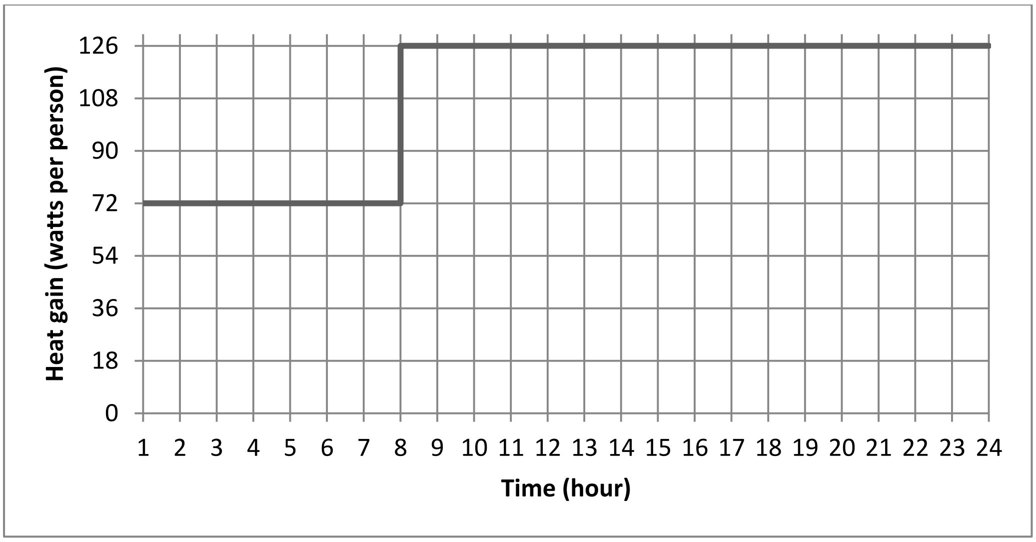

Figure 5.11: Human activity schedule in weekends

5.3.4 Thermal Zones and Surface Group

- Outside boundary condition: Boundary condition of the surfaces is defined by this object. “Ground” is selected for the ground floor, “Outdoor” is selected for the surfaces which connected to outdoor air, “Roof” is considered for the roof. For the same zone internal surfaces, “adiabatic” is defined because they will keep heat in thermal mass; however, they will not transfer heat out of the zone.

- Sun exposure: “Sun exposed” is used for surfaces which are exposed to the sun; however, “No sun” is selected for other surfaces. In this work for roof and exterior wall, “sun exposed” is defined.

- Wind exposure: As same as previous object, “wind exposed” is selected for surfaces which are exposed to the wind; otherwise, “No wind” will be selected. “Wind exposed” is used for roofs and all external walls; however, “No wind” is used for other surfaces.

- View factor to ground: Diffuse solar radiation from the ground which is visible from a surface is calculated by this item. A view factor to ground for horizontal upward facing surfaces is 0, for vertical surfaces is 0.5 and for horizontal downward facing surfaces is 1. “Autocalculate” is also available for this item which is entered for this study.

5.3.5 Internal Gains Group

- People: Number of people: It is the maximum number of people which are in the building. Number 4 is chosen for this work.

- Fraction radiant: This value is a decimal number between zero and one. It is considered to determine the type of human produced heat. Considering the manual of Energy Plus, 0.3 is selected (U.S. Department of Energy, 2013).

- Sensible heat fraction: Normally this fraction is calculated by software but it gives the option to the user to select the fraction of sensible heat gain from the people. “Autocalculate” is defined here.

- Lights: Design level calculation method: Three methods can be select for light electrical power input calculation; “Lighting level”, “Watts/area” and “Watts/person”. The second one is selected, which enables the user to define the light power input per zone floor area.

- Watts per zone floor area: lighting power input for each zone floor area should be fielded here. According to CIBSE guide, 8 watts per square meter is chosen for this item (CIBSE, 2006).

- Return air fraction: the fraction of light heat which release to the zone return air. 0 is entered here because any return air does not exist.

- Fraction radiant: the fraction of light heat which release into the zone as long wave radiation. Energy Plus calculates the amount of absorbed radiation by interior surface of the zone according to absorptance values and area. 0.7 is taken from the manual of Energy Plus (U.S. Department of Energy, 2013).

- Fraction visible: the fraction of light heat which release into the zone as short wave radiation. Energy Plus calculates the amount of absorbed radiation by interior surface of the zone according to absorptance values and area. 0.2 is chosen according to the manual of Energy Plus (U.S. Department of Energy, 2013).

- Electric equipment: Design level calculation method: Three methods can be selected as a nominal electric equipment calculation; “Equipment level”, “Watts/area” and “Watts/person”. The first one is selected because it enables the user to define the electric equipment level.

- Design level: The maximum electrical input to equipment is demonstrated by this item. 500 watts is chosen here, according to Energy Plus sample file which has same floor area (180 square meters).

- Fraction latent: it is a decimal number between zero and one which characterize the amount of released electric equipment latent heat in a zone. According to assumption, electric equipment does not release any latent heat thus 0 is entered for this item.

- Fraction radiant: the amount of long wave radiant heat which produced by electric is characterized by this decimal fraction which is between zero and one. Based on manual of Energy Plus, 0.3 is entered as fraction radiant (U.S. Department of Energy, Input/Output Reference, 2013).

- Fraction lost: the amount of lost heat which produced by electric equipment is evaluated with this fraction. Lost heat means the converted power to mechanical work. As the electric equipment dose not produced any lost heat based on consumption, thus 0 is entered for fraction lost.

5.3.6 Zone Airflow Group

- Design flow rate calculation: Five methods can be selected as a design flow rate calculation; "Flow/zone", "Flow/area", "Flow/exterior area", "Flow/exterior wall area", and "Air change per hour". ACH is selected for this option which number of air changes per hour with the zone volume is consider to assess the design volume flow rate.

- Air change per hour: 0.5 is considered as ACH to design the volume flow rate (Race, 2006).

- Ventilation type: Four different types of ventilation, "Natural", "Intake", "Exhaust" and "Balanced" can be selected as a ventilation method. Base on assumption, the air entering into indoor has same condition as outdoor, natural ventilation is considered.

- Minimum indoor temperature: If the indoor temperature decreases below this value the ventilation is shut down. In order to need ventilation in whole time, minimum value, -100 ˚C, is selected.

- Maximum indoor temperature: If the indoor temperature increases above this value the ventilation is shut down. In order to need ventilation in whole time, maximum value, 100 ˚C, is selected.

Chapter 6

RESULT AND DISCCUSION

6.1 Introduction

In this chapter, results of dynamic thermal simulation are presented. Daily and hourly air temperature are compared and investigated in two cases, with and without PCM layer. Moreover, minimum and maximum air temperature differences are also investigated in both conditions.

6.2 Daily Air Temperature

Daily mean indoor air temperature in two cases (with and without PCM) for summer months (June to October) are illustrated in Figure 6.1. As these two cases are completely the same except the phase change ability in lining (PCM) layer which is applied in "With PCM" case. According to this figure, phase change material decreases the temperature fluctuation by temperature peak reduction. Daily mean indoor air temperature for summer months are shown from Figure 6.2 to Figure 6.6 separately. It is clear that the maximum peak reduction is happened on 12th June when the indoor temperature is reduced by 4.24% meanwhile on 3rd October the indoor temperature is increased by 8.73%.

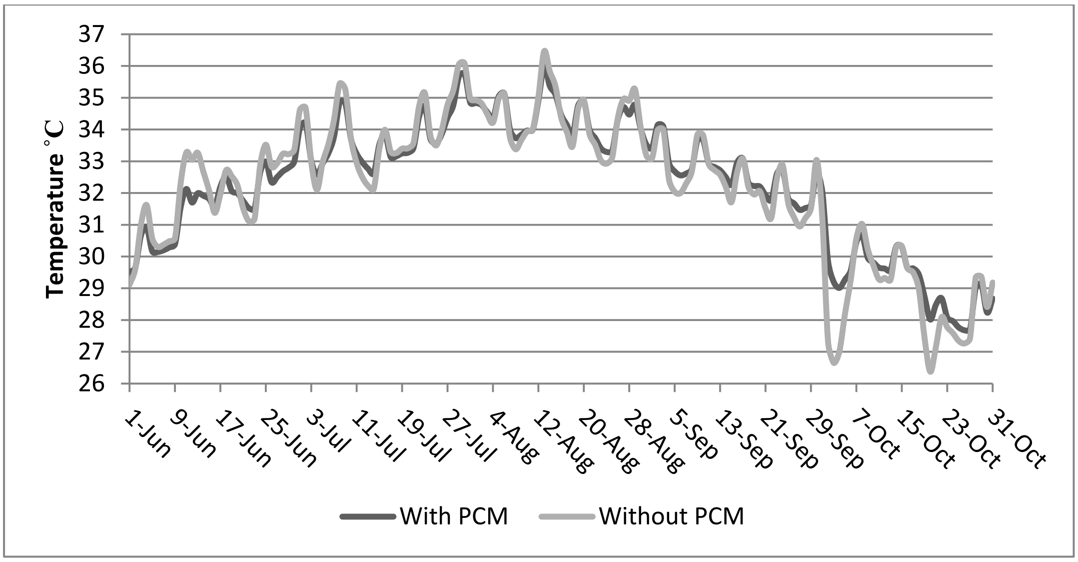

Figure 6.1: Daily mean indoor air temperature

According to Figure 6.2, the minimum and maximum daily indoor air temperature, in without PCM condition, are 29 ˚C and 33.5 ˚C occurring on 1^{st} and 25^{th} of June respectably. Besides, the maximum daily indoor air temperature reduction is occurred on 12^{th} by 1.34 ˚C when the phase change ability of lining (PCM) layer is active. Moreover, the minimum daily indoor air temperature reduction is happened on 6^{th} by 0.16 ˚C. Forasmuch as daily indoor air temperature has a good fluctuation around phase change temperature (31 ˚C), the phase change material work properly in with PCM condition and peak reduction is significantly observed in June.

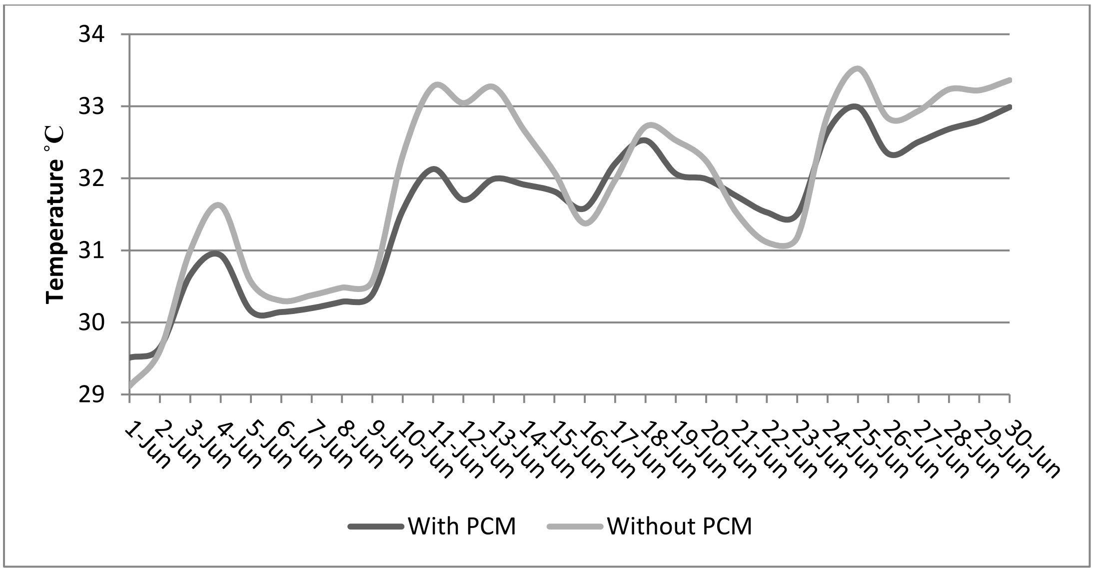

Figure 6.2: Daily mean indoor air temperature in June

Base on Figure 6.3, the minimum and maximum daily indoor air temperature, when the lining (PCM) layer is not active, are 32 ˚C and 36 ˚C happening on the 4th and the 30th of July respectably. Beyond, the maximum daily indoor air temperature reduction is turned out on the 8th by 0.6 ˚C in with PCM condition. The daily indoor air temperature peak is negligibly slumped; however, the daily indoor air temperature is more than phase change temperature.

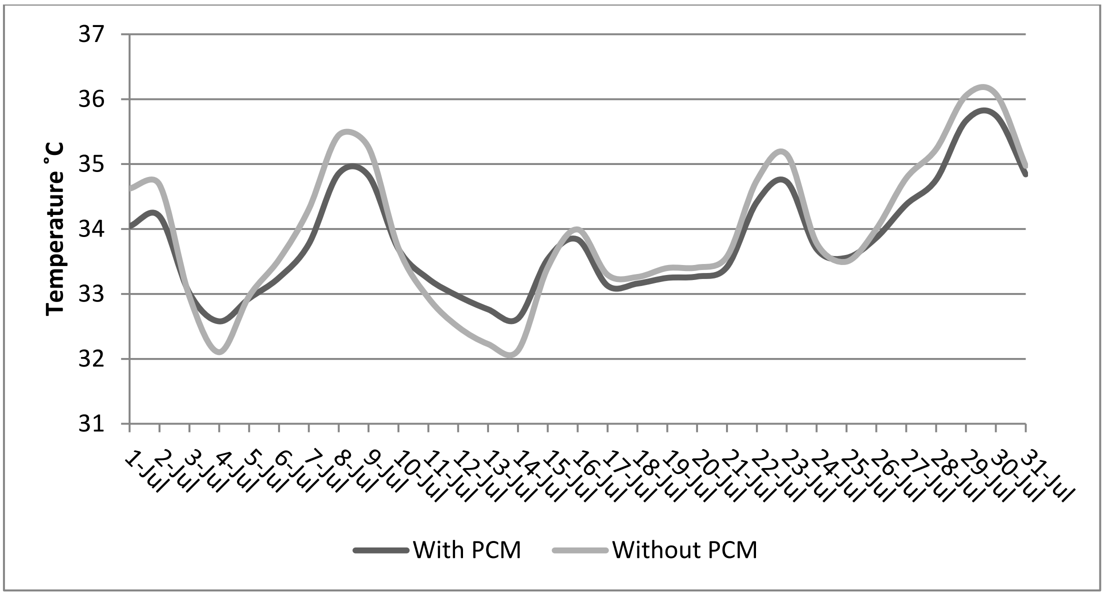

Figure 6.3: Daily mean indoor air temperature in July

In Figure 6.4, the daily indoor air temperature in August is illustrated for both conditions (with and without PCM). The maximum daily indoor air temperature when the lining layer is not active is around 33 ˚C which is occurred on 24th and the maximum one is 36.5 ˚C which is happened on the 13th. Since the daily indoor air temperature is always more than phase change temperature and does not have any fluctuations around it, the phase change material cannot be active. In other words, the phase change material is kept in liquid phase thus the absorbed heat in it is not allowed to release. The peak reduction and temperature fluctuation decrease is not significant in August.

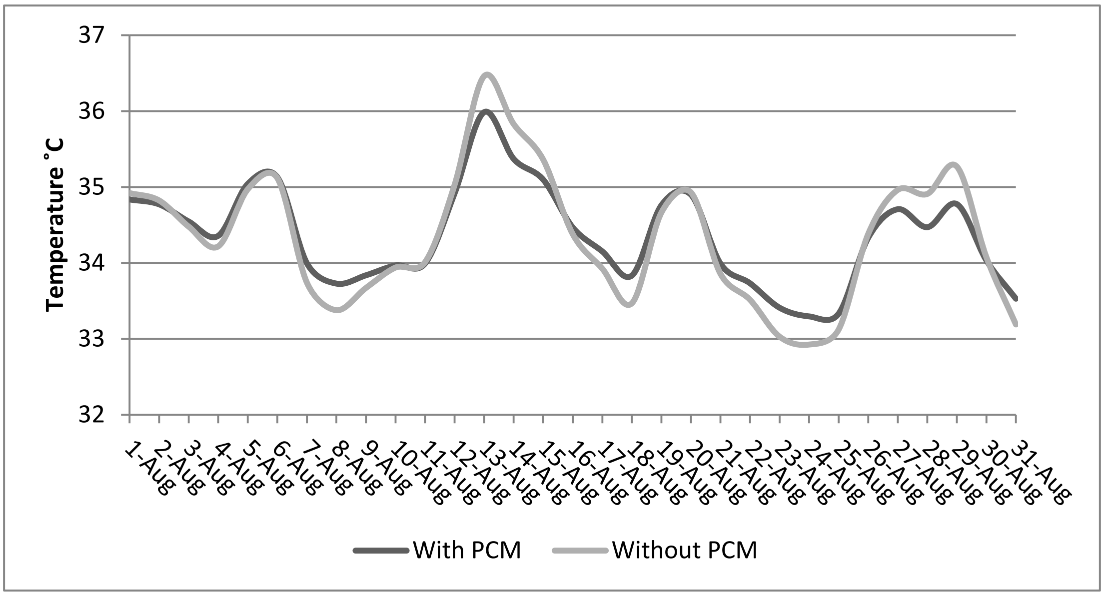

Figure 6.4: Daily mean indoor air temperature in August

The daily indoor air temperature is gently dropped from 34 ˚C to 31 ˚C during September which shown in Figure 6.5. The maximum of daily indoor air temperature peak decline is 0.65 ˚C which is occurred on 5th.

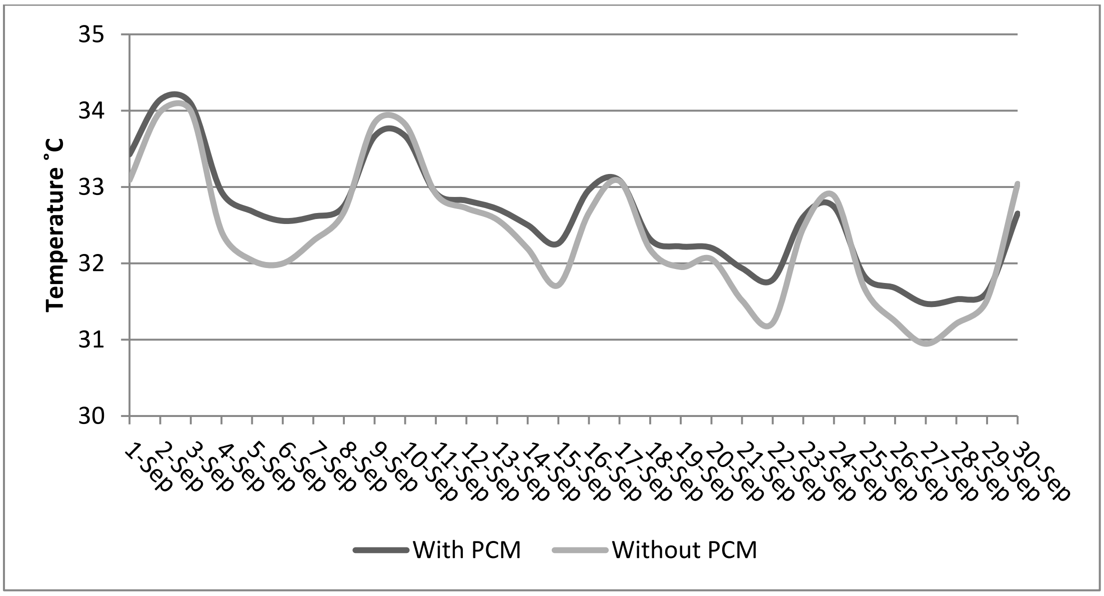

Figure 6.5: Daily mean indoor air temperature in September

According to Figure 6.6, the minimum and maximum daily indoor air temperature, in without PCM condition, are 26.4 ˚C and 31.2 ˚C occurring on 3rd and 20th of October respectably. Besides, the maximum daily indoor air temperature peak reduction is occurred on 3rd by 2.55 ˚C when the phase change ability of lining (PCM) layer is active. It should be mentioned that, this peak decline is occurred by increasing indoor temperature. Moreover, the maximum daily indoor air temperature reduction is happened on 31st by 0.5 ˚C. Figure 6.6 shows a noticeable downturn in daily indoor air temperature in with PCM condition in comparison to without PCM condition during October.

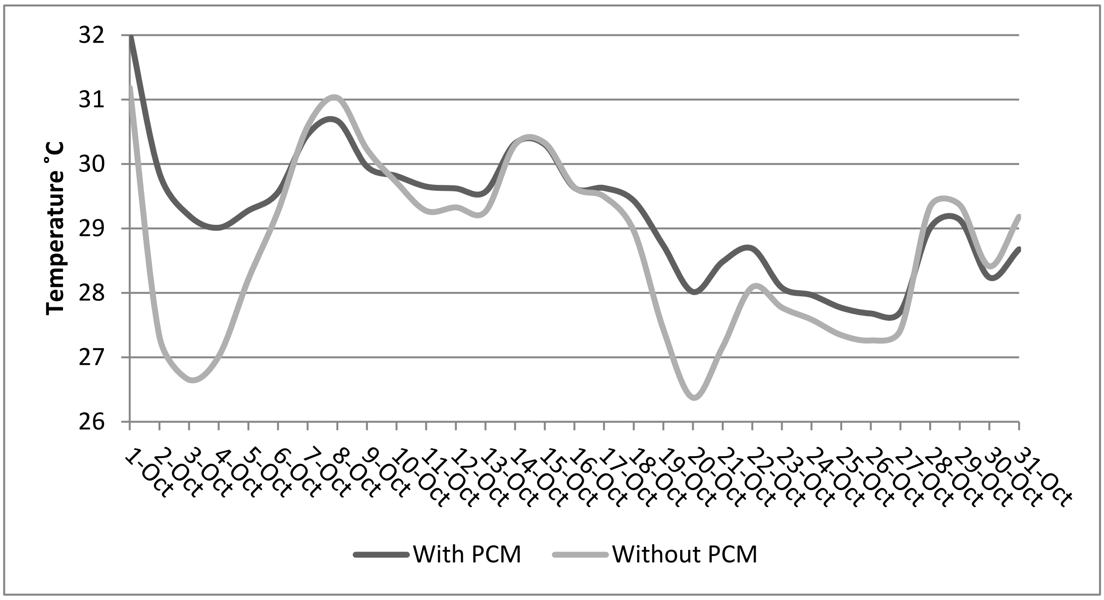

Figure 6.6: Daily mean indoor air temperature in October

According to daily indoor air temperature during June to October in both mentioned cases, the temperature fluctuation is reduced in all days. Although it has gradual decline in July and September, It sharply drops in June and October. In addition, the daily indoor air temperature is not considerably affected by application of phase change material in August; in other words, temperature fluctuation reduction has a slight trend.

6.3 Hourly Air Temperature

Hourly air temperatures of building indoor environment in two mentioned cases for three middle days (14th, 15th and 16th) of June to October are shown from Figure 6.7 to Figure 6.11 respectively. It is clearly observed that, applying phase change in lining (PCM) layers leads to decrease hourly indoor air temperature fluctuations.

Hourly indoor air temperature for middle days of June is illustrated in Figure 6.7. The lining layers start to absorb heat from the beginning hours of 14th for 28 hours. After that PCM freezing process is started and the absorbed heat is released to the environment from 05:00 to 14:00 on the 15th. On June 16th, melting process is begun again from 04:00 to 13:00. The lining layers work properly and the melting/freezing cycle is occurred respectively in order to good indoor air fluctuation around selected phase change temperature.

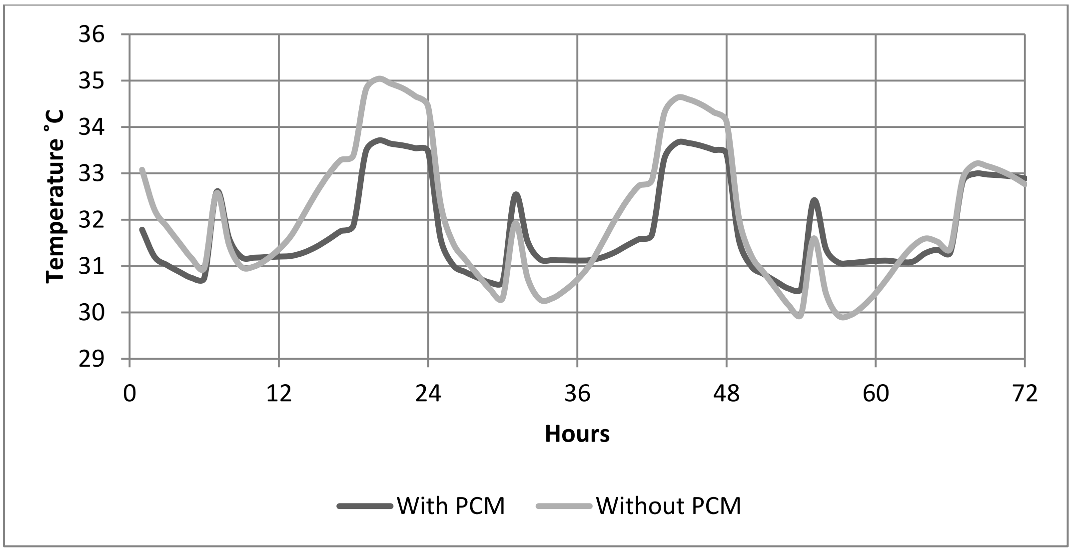

Figure 6.7: Hourly air temperature of 14th, 15th, 16th of June (0 is 01:00 of 14th and 72 is 24:00 of 16th)

According to Figure 6.8, the hourly indoor air temperature peak is decline slowly in comparison with same hours and days in June. The melting process is started at

16:00 on 14th when the freezing process is finished. Although the hourly indoor air temperature is increased in with PCM condition for 12 hours in the morning of 15th, it has a gentle downturn in next 12 hours in July 15th. Moreover, this cycle is quite repeated on the 16th. Considering the Figure 6.7 and Figure 6.8, hourly indoor air temperature peak reduction in July is not as much as its reduction in June; however, hourly indoor air temperature fluctuate well around 31 ˚C.

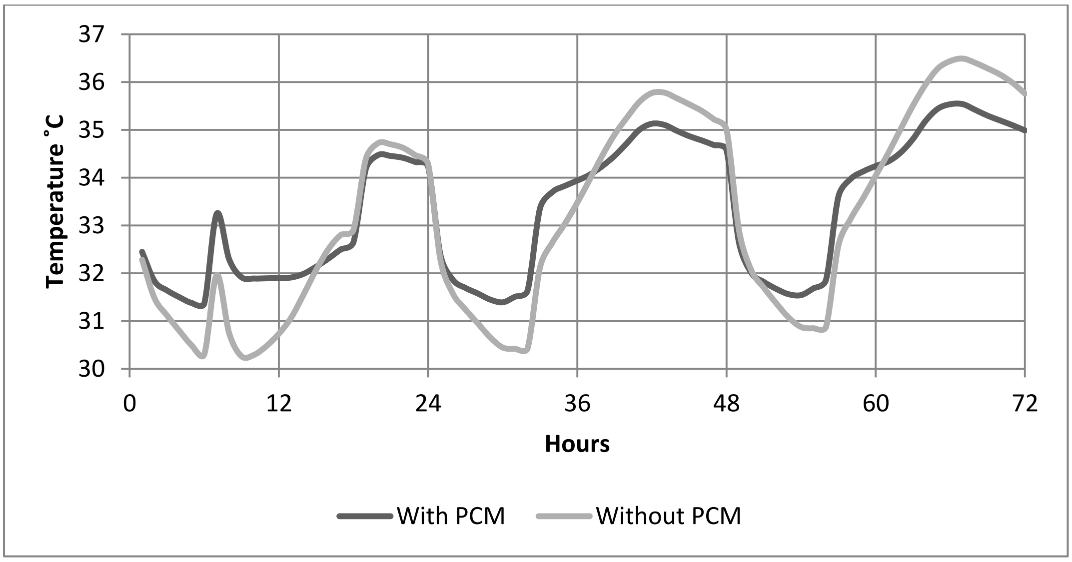

Figure 6.8: Hourly air temperature of 14th, 15th, 16th of July (0 is 01:00 of 14th and 72 is 24:00 of 16th)

Regarding the Figure 6.9, the hourly indoor air temperature is always more than 32 ˚C in all hours on August 14th, 15th and 16th. Thus the freezing process is not completely occurred during these days. In other words, lining layers are not able to release the absorbed heat to the environment because the environment temperature is always more than PCM melting point. Since it is revealed in Figure 6.9, the indoor air temperature peak has very slight reduction. The maximum reduction is happened on the 14th at 21:00 by 0.77 ˚C.

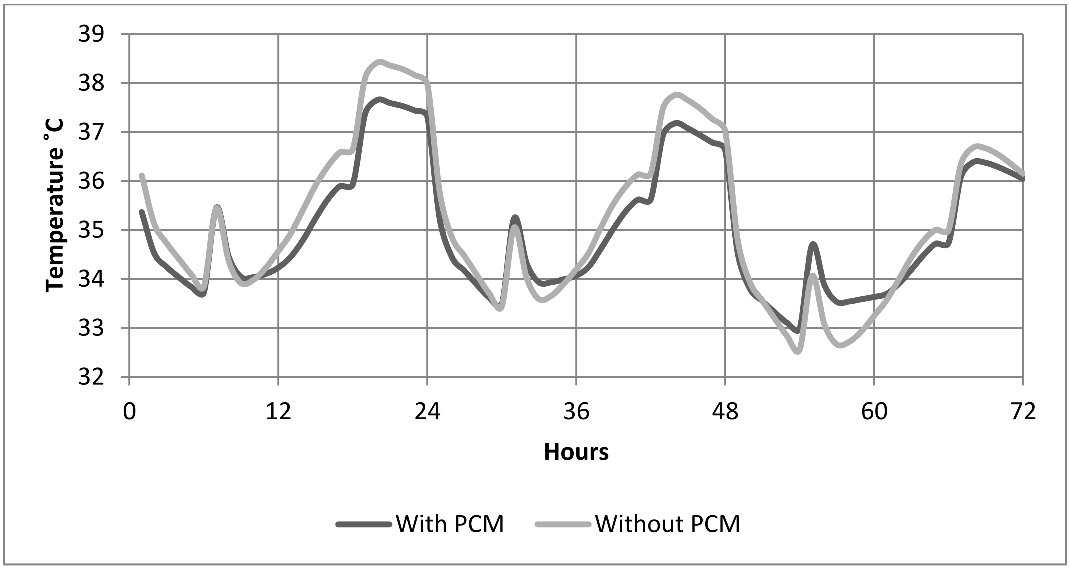

Figure 6.9: Hourly air temperature of 14th, 15th, 16th of August (0 is 01:00 of 14th and 72 is 24:00 of 16th)

According to Figure 6.10, the hourly indoor air temperature have a widely fluctuation from 29.5 ˚C to 34.8 ˚C, which is covered PCM phase change temperature, in these three days. The melting and freezing processes are clearly observed in the lining layer; however, the freezing process has more effect on the hourly indoor air temperature in comparison to melting process. The maximum peak reduction is occurred at 09:00 on the 13^{th} by 1.82 ˚C increasing in the indoor air temperature.

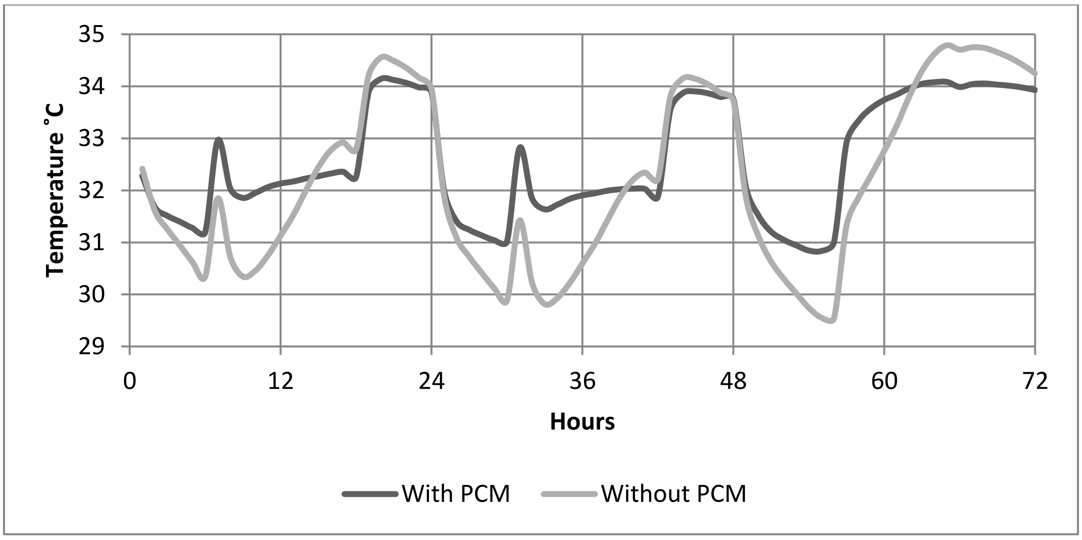

Figure 6.10: Hourly air temperature of 14th, 15th, 16th of September (0 is 01:00 of 14th and 72 is 24:00 of 16th)

As the Figure 6.11 reveals, the minimum and maximum of hourly indoor air temperature is 27˚C and 32.6 ˚C respectively and peak of indoor air temperature substantially slump especially in the morning (08:00 to 09:00) and the evening (17:00 to 20:00) of these three days. The maximum value of peak reduction is around 1.5 ˚C occurring at 8:00 on the 14th.

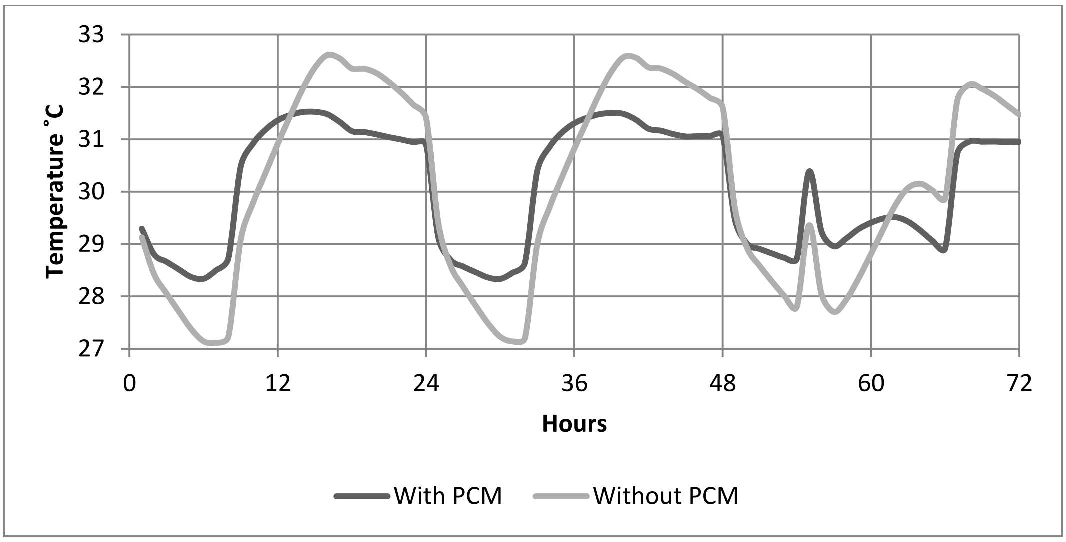

Figure 6.11: Hourly air temperature of 14th, 15th, 16th of October (0 is 01:00 of 14th and 72 is 24:00 of 16th)

6.4 Minimum and Maximum Temperature Difference

Minimum and maximum hourly decrease in mean indoor air temperature when the phase change ability is applied for lining layers are given in Table 6.1 for each month. The highest maximum and minimum hourly reduction are occurred in June due to acceptable temperature fluctuation around phase change temperature (31 ˚C) meanwhile the lowest hourly reduction is turned out in August because the indoor air temperature is always upper than phase change range in all hours, phase change material cannot work properly.

Table 6.1: minimum and maximum hourly temperature reduction for each month

Month	Minimum hourly decrease (˚C)	Maximum hourly decrease (˚C)
June	0.0061	2.3889
July	0.0034	1.1844
August	0.0011	0.9806
September	0.0053	1.4750
October	0.0018	1.6915

During discharge process, phase change material release the heat, which is absorbed in charging process, to the environment thus the indoor environment temperature is risen up. In other words, mean indoor air temperature increases due to the release heat caused by phase change material freezing process. The minimum and maximum increases in mean indoor air temperature when the phase change material is used are given in Table 6.2 for each month separately. The values of criteria in each column are almost same for different months except the maximum hourly increase in October which is sharply boom. Regarding the Figure 6.1, the indoor air temperature is suddenly decreased to around 27 ˚C in the first week of October. Due to this reduction, freezing process is started with high performance and tries to keep the indoor temperature around 29 ˚C. This is the reason of big differences in maximum hourly increase in October in comparison with other months.

Table 6.2: minimum and maximum hourly temperature increase for each month

Month	Minimum hourly increase (˚C)	Maximum hourly increase (˚C)
June	0.0003	1.7986
July	0.0022	1.7949
August	0.0010	1.4328
September	0.0056	1.9675
October	0.0084	3.5649

6.5 Life Cycle Cost Analysis

Life cycle cost analyzing is a method in evaluating the design alternatives economically with different investment, maintenance costs and operation costs.

This method is applied when a project needs high initial investment costs to identify the economic feasibility.

The quantity of life cycle cost is equal the sum of the present values of the total costs over project’s life cycle including investment and capital costs, installation and construction costs, energy costs, salvage costs, maintenance costs, operation costs and demolition costs. By present worth method, all present and future costs are converted to a single point in the investment time (Atikol U. , 2013).

Regarding to analysis the life cycle cost various parameters should investigated which are defined in the following (Atikol U. , 2013).

- The analysis period is the longest time which the life cycle cost should be evaluated over it. Rubitherm Company guaranteed minimum life of 50 years for the used material in this study.

- Initial investment costs of this technique are around 20,000 USD for modeled building in this study.

- Interest rate is the time value of money which is considered 6% in this study.

- Residual value is describes the future value of a good in terms of percentage of depreciation of its initial value. Since these materials are not recyclable after lifetime, zero is considered for this parameter.

- Annual saving is the value of energy which is saved by application of new method. since the application of phase change materials is not consumed any energy, the energy consumption of air conditioning method can be used as annual saving which is considered 2000 USD.

- Saving to investment ratio (SIR) is used to determine whether the potential saving of a project justifies the initial investment. It takes the total energy savings over the lifetime of the improvement (Present Value) divided by the upfront cost of the investment.

- Internal rate of return (IRR) is used to measure and compare the profitability of investments. It is an indicator of the efficiency. It is calculated by assuming the net present value equal to zero.

- Simple payback period is the number of years it takes for the energy saving from an improvement to equal the upfront cost. In other words, it intuitively measures how long something takes to "pay for itself." All else being equal, shorter payback periods are preferable to longer payback periods.

- Present value is the value of the sum of money at the present time that, with compound interest, will have a specified value at a certain time in the future. Equation 6.1 is used to calculate the present value.

$$PV = \frac{FV}{(1+d)^n} \qquad \text{Equation 6.1}$$

Where:

PV is the present value;

FV is the value in the future;

d is interest rate; and n is the number of years.

Ordinary air conditioning unit has 500 USD maintenance cost in each four years meanwhile the phase change materials has 2000 USD maintenance cost in each 10 years. Life cycle cost analysis is carried out by present value method (Atikol U. , 2013) to find the economic feasibility of phase change material application in Cypriot building and the results are given in Table 6.3.

Table 6.3: Life cycle cost analysis result

Net Present Value (NPV)	2978 USD
Saving to Investment Ratio	1.1
Internal Rate of Return (IRR)	8%
Simple Payback (Years)	10

Chapter 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

To investigate the widely used or the most typical Cypriot building, building statistical report was evaluated in terms of type, material, the total floor area and the number of floors. It was found that, Residential buildings play an important role in construction industry due to their highest percentage share among other buildings in both terms of number and total floor area. Although, the number of duplex type dominates the residential buildings, apartment type dominates them in term of total floor area by only 2% difference from duplex one. A two story duplex house with 101 to 200 square meters total floor area constructed with reinforced concrete and brick was chosen as a prototypical building in Northern Cyprus.

To select the proper energy simulation software, four energy simulation software were examined based on their capabilities to model and simulate the phase change materials, Energy Plus software was chosen to carry out the dynamic thermal simulation in this study. As Larnaca's weather data is the only weather data in Energy Plus software database for Cyprus, it was used in the simulation.

To find the suitable phase change material in Cyprus climate, four types of Rubitherm Company productions with different melting temperature was assessed and the RT31 was selected to simulate as lining layer in modeled building. It was also found that, 1 kg of RT31 can store 18000J/K heat; however, 6 kg normal weight concrete is needed to store the same heat.

To determine the effect of phase change material on indoor air temperature fluctuation, the dynamic thermal simulation is carried out and the results were studied in term of daily indoor air temperature from July to October and hourly indoor air temperature for three middle days of mentioned months. It is found that, the lining layers affected the daily indoor air temperature by peak reduction. Although this effect was not considerable in August, the peak reduction in other months had a steep trend especially in June and October. Based on the hourly indoor air temperature figures, the temperature peak reduction trend were occurred continuously, nevertheless, this trend is marginal on the 14th, 15th and 16th August as same as daily indoor air temperature. As it was mentioned in previous chapters, the phase change materials absorb the heat during charging process and release the heat during discharging process. In other words, the indoor air temperature goes up and down in discharging and charging process respectively. The highest value of maximum hourly indoor air temperature decrease was around 2.4 ˚C occurring in June due to sufficient indoor air temperature fluctuation around phase change temperature when the phase change ability is not applied. In the meantime, the highest value of maximum hourly indoor air temperature increase was almost 3.5 ˚C happening in October when the indoor air temperature had an enormous reduction for a week.

Regarding to life cycle cost analysis which is carried out to find the economy feasibility, Net present value of this method is a little bit less than 3000 USD with 10 years payback period. Since there are not any legislation about charging for Co_2 emission in Cyprus, it is not included in life cycle cost analysis. It should be mentioned that if the Co_2 emission penalty included in life cycle cost analysis, the amount of net present value is definitely increased meanwhile the payback period is decreased.

Finally, the author believes that, combination of different phase change materials with various melting temperature can increase the performance of the lining layer to control the indoor air temperature fluctuations.

7.2 Recommendations

Regarding to the current research which was based on assess the effect of phase change materials on indoor air temperature fluctuation, a list of recommendations for further research is mentioned as follow:

- Considering the effect of phase change materials on energy consumption of HVAC systems.

- Taking into account different buildings in terms of type, construction materials and total floor area.

- Performing life cycle cost analysis.

- Considering the different type of phase change material which are available for building application

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