Measuring Thermal Mass in Sustainable Concrete Mixes

By

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ABSTRACT

Nowadays, the popularity of sustainable concrete construction is increasing every passing year. The purpose of the construction industry is to increase the life of the residence by lowering CO_2 emissions and to increase the use of natural resources. Examination of thermal mass can be used to prevent or minimize temperature swings in the building and can be used to eliminate the need for energy consumption. Thermal mass reduces the risk of overheating in the summer and provides passive heating in the winter. Thermal mass is currently evaluated with "admittance" that is the ability of the element to exchange heat with the environment and is based on specific heat capacity, thermal conductivity and density. The aim of this study is to evaluate the effect of thermal properties namely, density, specific heat capacity and thermal conductivity on thermal mass of concrete. In order to evaluate the effect of such thermal properties, different types of cement materials (PFA, GGBS, and SF) and various types of aggregates (NA and RCA) are used. Additionally, water-cement ratio is investigated. Once thermal properties are found, thermal dynamic properties are calculated theoretically for each sample. These calculations lead an understanding on the effects of different types of cement materials, recycled coarse aggregate and water-cement ratio of the concrete mixes on the thermal admittance and hence thermal mass.

The laboratory tests results were analysed that PFA content concrete mixes were decreased the thermal conductivity more than other type of cements content mixes (such as SF and GGBS).30% PFA content in concrete mix has greater reduction thermal conductivity of the concrete mix. On the other hand, 15 % SF was decreased the thermal conductivity equal percentage (6.5%) with 55% GGBS content concrete mix. The laboratory results are shown that 10 and 20% SF content concrete has greater specific heat capacity than 10 and 20% PFA content concrete. 65% GGBS content concrete mix has greatest specific heat capacity of the concrete mix than all of the mixes. When 30% natural aggregate is replaced by recycled

coarse aggregate, the concrete mixes have more lightly. It means that the concrete mixes are less dense than NA concrete mixes. From the test results, the recycled coarse aggregate are affected thermal properties of concrete mixes more than the different types of cements content concrete mixes. RCA content concrete mixes have greater specific heat capacity value than NA content concrete mixes. However, GGBS content was greater than SF and PFA content in the concrete. The lowest decrease in the specific heat capacity is obtained as 3.9 % by using 100 % PC with 30 % RCA content concrete mix (C5). Whereas, when the w/c ratio minimized such as in the GGBS concrete mix (C2), the specific heat capacity is decreased by 14.8 % that results in the highest decrease in specific heat capacity in all the mixes. The results are defined that when minimizing water – cement ratio is applied in the concrete; the thermal diffusivity of the concrete is improved.

Thermal admittance value is affected by thermal conductivity, density and the specific heat capacity of the concrete mix. When GGBS is used in concrete mix; it increases the thermal admittance more than all groups. PFA content in concrete mixes have the lowest thermal admittance value than all mixes. Silica Fume concretes has similar value of thermal admittance with Portland cement concrete mixes. RCA content in concrete mixes have the lowest thermal admittance values than other natural aggregate content in concrete mixes. Thermal admittance does not need to have high or low thermal conductivity of concrete mix. The importance is to have a moderate thermal conductivity. The results are provided that thermal admittance is increased with high specific heat capacity, high density and moderate thermal conductivity of the concrete mixes. Those factors are vital for improving thermal admittance of concrete mix.

DECLARATION

This thesis and the research to which it means are the results of my own attempts. Any opinions, information, picture or text resulting from the work of others (whether published or unpublished) are fully defined as such in the research and attributed to their originator in the thesis. This research has not been submitted in whole or in part for any other academic degree or professional qualification. I completely agree that Kingston University has the right to submit my work to plagiarism detection service for originality checks.

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LIST OF PUBLICATIONS

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ABREVIATIONS

BS - British Standard

BRE - Building Research Establishment

C&D - Construction and demolition

CCA – Climate Change Agreements

CIA - Concrete Industry Alliance

CSD - Commission on Sustainable Development

EN - European Normative

EU - European Union

EC_2 - Eurocode 2

ECO_2 - Embodied CO_2

EE - Embodied Energy

FA – Fly Ash

GGBS - Ground Granulated Blast furnace Slag

NA - Natural Aggregate

PC - Portland cement

PCA - Portland cement Association

PFA - Pulverised Fuel Ash

RCA – Recycled Coarse Aggregate

RH - Relative Humidity

SF – Silica Fume

SSD - Saturated Surface Dry

UNEP - United Nations Environment Programme

LIST OF SYMBOLS

A= area of sample (m^2)

C= specific heat capacity

C_A= specific heat capacity of air

C_C= specific heat capacity of concrete

C_S= specific heat capacity of stainless steel bucket

C_W= specific heat capacity of water

D= exposed area of sample (m^2)

ε= thermal diffusivity (J/ m^2 ^{0}C)

L= thickness (m)

Lmn= periodic Thermal resistance (W/K)

l= specific latent heat of the water (226×10^4)

M= mass of material (Kg)

M_A = mass of air

M_C=mass of concrete

M_S=mass of stainless steel bucket

M_W= mass of water

M_1=the mass of the saturated & surface

M_2=the mass of the pykonometer containing the sample

M_3=the mass of the pyknometer filled with water only in grams

M_4=the oven dried mass of the aggregate in the grams

T= transmissivity

1= Period of the variations (s)

p= reflectivity

P= time period for one cycle (s)

PFA= Pulverised Fly Ash

p_W= density of water (Kg/m^3)

p= density

r= thermal resistivity (m ^{o}C/m)

R= thermal resistance (m^2 ^{o}C/m)

R_{sa}= Outside surface resistance (m^{2}K/W)

R_{sc}= Thermal resistance of Celotex

R_{si}= Inside surface resistance (m^{2}K/W)

R_p= Resistance of Plywood

T= time (s)

T_1= initial temperature (^{o}C)

T_2= final temperature (^{o}C)

^{T}= transmitivitivity

q= heat flux (w/m^2)

Q= specific heat capacity

Q_1=the heat transferred from hot to cold side of the equipment through the specimen

Q_3= the heat loss from hot side to the environment

Q_4= the flanking loss

Y_{mm}= Thermal admittance [W/ (m^2.K)]

Y_{mn}= Periodic thermal transmittance [W/ (m^2.K)]

Z= Heat transfer matrix environment to environment

Z_{mn}= Element of the heat transfer matrix

λ= thermal conductivity (W/m.K)

α= absorptivity

α= thermal diffusivity [(m/sec)*10^{-7}]

f= Decrement factor

δ = Periodic penetration depth of a heat wave in a material

ϕ= Heat flow rate (W)

ξ= Ratio of the thickness of the layer to the penetration depth

κ= Areal heat capacity [J/ (m^2.K)]

Λ= thermal conductivity

Θ= Temperature (^{o}C)

Ω= Angular frequency: $\omega\frac{2\pi}{T}$ (rad/s)

Φ, Ψ= Phase differences (rad)

Q= Density of heat flow rate (W/m^2)

ΔT_A= temperature different of air

ΔT_C= temperature different of concrete

ΔT_S= temperature different of stainless steel bucket

ΔT_W= temperature different of water.

1 Background

Sustainable construction is becoming more popular as this sector corresponds to the world changing needs. One of the key requirements in meeting challenges of sustainability within the built environment is to optimize the energy efficiency of buildings during their lifespan. Considering that the concrete is the construction material having the greatest common use, such material should have low embodied CO_2 together with consumption of various cementitious by-products like PFA, GGBS and furthermore, recycled aggregates that causes decrease in operational CO_2 with the intrinsic property called "thermal mass" that reduces the risk of overheating in the summer and provides passive heating in the winter. The purpose of those variations is to increase the life of the residence by lowering CO_2 emissions and to increase the use of natural resources. Construction industry has already performed numeral effective actions which were provided important steps to obtain sustainable construction. Hence, this will then encourage decreasing both embodied and total energy usage for the construction products. Examination of thermal mass can be used to prevent or minimize temperature swings in the building and can also be used to eliminate the need for energy consuming for air conditioning systems.

1.1 Research Aims & Objectives

The main aim of this research was to accurately evaluate thermal mass of novel concrete mix elements and building systems designed for achieving further sustainability within the construction.

The specific objectives of the work were to:

- Review published literature to establish current status of thermal mass in the building elements, especially in the concrete and related concepts applied.

- Investigate and compare thermal properties of concrete with different types of cements (prepared using cement replacements materials) and recycled coarse aggregate.
- Asses the influence of water-cement ratios on the thermal properties of concrete.
- Evaluation of the admittance value of the concrete hence thermal mass of concrete is calculated.

1.2 Scope of the Research

Research undertaken was devised to assist in minimizing the energy consumption of the buildings. Thus. provide solution for the sustainable concrete construction through ensuring the building materials positive effect on the thermal mass by measuring the thermal properties of concrete.

During the course of this study. the energy consumption in the buildings was minimized by applying the building concrete materials. Different types of cements used in the research were produced by blending Portland cement (PC) GGBS. Silica Fume. PFA. meeting the BS EN 197-1(2011) whilst recycled coarse aggregate. RCA is used in the concrete mixes. In this research. materials were chosen to develop more sustainable concrete by reducing the required energy consumption and also obtaining the optimal thermal comfort within the buildings.

Thermal mass of the concrete components is very vital but there are limited resources available on thermal properties (specific heat capacity. density and thermal conductivity) of concrete materials (cements and aggregates). Such as using BS EN 197-1 cementious materials and specially applying the recycled coarse aggregate on thermal properties of concrete. This is the reason that the cement replacement materials. recycled coarse aggregate and minimizing water cement ratio are examined to investigate the effect of the thermal properties such as thermal conductivity, specific heat capacity and density of the concrete in this research. The evaluation of thermal mass is done by calculating the thermal admittance value of the concrete. The admittance value is helped to compare materials on the concrete.

1.3 Thesis Layout

This introductory Chapter provides background information to the subject area researched, aims and objectives of work, and briefly outline the thesis layout.

A desk study was carried out review previously related investigations in the subject area researched. These include thermal mass, effect of concrete constitute, cement content, and through this current state of thermal mass was established and are given in Chapter 2.

A brief description on the research programme and experimental details are included in Chapter 3. This includes details of the materials, aggregate, concrete, specific heat capacity and thermal conductivity testing, specimen preparations and test procedures used in the study.

In Chapter 4, thermal properties of concrete mixes tested are presented and this cover the effects of different types of cements, recycled coarse aggregate and water cement ratio. Appropriate tests relating to thermal namely; thermal conductivity, density and specific heat capacity of the concrete are carried out and results are reported given that moisture content of the mixes are kept at constant value by using the dry conditions of all materials before casting.

In chapter 5, the excel spreadsheet was developed for calculation of thermal dynamic properties of different types of concretes by applying the thermal properties data (thermal conductivity, density and specific heat capacity). For this, factors which affect the thermal storage are taken under examinations that include thermal admittance, decrement factor, and thermal transmittance. The main aspect of this chapter was to clearly demonstrate the effects of types of cement materials, recycled coarse aggregate and water- cement ratio of the concrete mixes on the thermal admittance factor of the concrete mixes.

The conclusions drawn from the research findings, together with the recommendations for further study are given in Chapter 6.

Details about the references used throughout the research can be found in Chapter 7, whilst Chapter 8 includes Appendices providing background on Excel file calculations, raw data on thermal dynamic results, and copy of a published Journal paper.

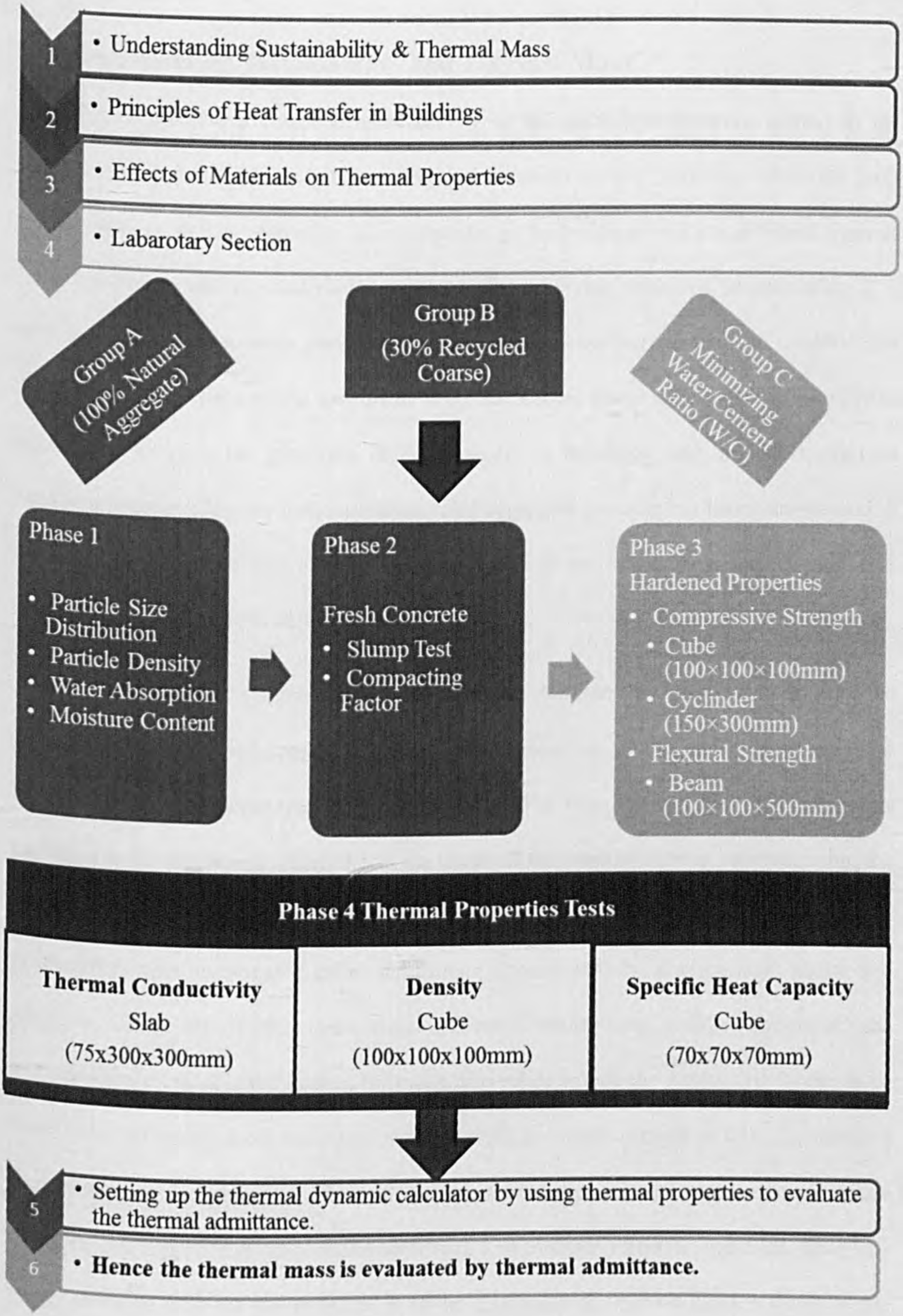


Figure 1-1 Outline of the research

2 Understanding Sustainability and Thermal Mass

This chapter presents a comprehensive review of the published literature related to the thermal mass and its influence of key practical situation on key activities within the built environment, as well as principles of heat transfer in the buildings and use different types of cement materials and recycled coarse aggregate for achieving enhanced sustainability. It is been divided into three main parts; the first part focuses on thermal mass to establish the current state in the light of the worldwide drive for a more sustainable construction. Whilst second part looks at the principles of heat transfer in buildings, and the information on thermal properties of binary cement and recycled aggregate concrete has been summarised in the third part. Through this attempt has been made to provide a clear understanding of thermal mass and its role in sustainable built.

"Our Common Future" (Bruntlandt, 1987) report was published by United Nations after the increasing popularity on harms of economic improvements on health, natural resources and the environment has been realized in 1980s. In this way, sustainable development is explained as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntlandt, 1987). The concept of sustainability was investigated under three main drivers namely; environment, social and economic. Even all of the three areas of sustainability are equally important; the environmental element is the interest for many researches around the world, mainly due to its likely wider influence on the society so reported work also concentrated on this. The research also concerns on decreasing the effect of concrete construction. Global warming is one of the consequences caused due to greenhouse effect. Greenhouse effect is occurred when the energy absorbed from the sun is locked in to the atmosphere by carbon dioxide which is one of the greenhouse gases.

Around 20 to 50 percent of the building's energy consumption is used for space heating and subject to the type of the building as well as third of the carbon emission of the buildings (The Concrete Centre, 2012). Certain standards are set by Building Regulations to ensure that minimum level of appropriate performance is met in construction of the buildings. Such Building Regulations consist of looking at health, safety, energy performance and how convenience of the obligations in constructing the building. However, these standards can only be applied in new buildings. Even there is no condition to improve the current buildings; certain modifications can generate the desire for the current buildings to fulfil Building Regulations (English Heritage, 2012). Part L of these Building Regulations covers management of fuel and power. Even, if the Building Regulations only expresses general necessities, they are assisting by Approved Documents that situated practice guidance according to such necessities. The Approved Document (i.e. defined as Part L) considers energy efficiency in four different subdivisions namely; new dwellings (L1A), work to existing dwellings (L1B), new buildings that are not dwellings (L2A) and existing buildings that are not dwellings (L2B) (English Heritage, 2012). The new regulations and standards are introduced to decrease the heat loss and outflow of air by improving levels of insulations. When heat loss is reduced by using low energy designs, the capability of buildings in terms of thermal mass is improved and hence this cause further decrease in the amount of energy needed to heat the environment. Nowadays, since more insulated air tight and low energy buildings are preferred to be used, understanding the concept of thermal mass is vital. Currently, there is a lack of knowledge in this field and this is why regulations are kept updated to increase understanding and awareness of thermal mass (The Concrete Centre, 2011).

Specifically in summer climates, when thermal mass is used together with reasonable ventilation and shading systems, it can be used to adjust the weather conditions inside the buildings, preventing both overheating and having a cooling load. Previously, the effect of thermal mass on buildings was neglected. This was because there were abundant amount of cheap energy sources and beside of this, there wasn't an issue on climate change. However, nowadays, the energy sources are limited and the climates change challenges are faced. Therefore, thermal mass is important for buildings and to assess the influence of thermal mass on buildings again, the researchers first have to understand the basic principles of thermal mass (The Concrete Centre, 2011).

2.1 Sustainability & Sustainable Concrete Construction

Even the concept of sustainability dates back to 1960s, the applications in this area to improve the sustainability concept began in 1980s (Monika Freyman, 2012). Brundtland Commission (1987) described sustainable development as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Evaluation of this concept is a major challenge for engineers. The main aim of engineers in this concept is to provide sustainable explanations. Such resolutions are needed to be produced by using qualitative ideals instead of traditional quantitative values. Problems are explained by using complexity science and the importance is to interpret these challenges by using Newtonian science (Fenner et al., 2006). If engineers are working together with other areas in a collaborative manner, then education and practice in engineering will be developed. Furthermore, this development will improve the way that engineers look at the problems in sustainability and will result in a more holistic design approaches. Currently, the greatest problem in sustainability is the harm of the ozone layer resulting from increasing the global warming (Costas Georgopoulos and Andrew Minson, 2014).

2.1.1 Embodied Energy

Cement and concrete institute. (2011) defined the Embodied Energy (EE) as "the energy consumed for raw material extraction, transportation, manufacture, assembly, installation, disassembly and deconstruction for any product system over the duration of a product's life". Embodied energy and embodied carbon are closely related to each other. Embodied carbon can be described as embodied energy by using different types of emission factors. Embodied energy is made from two parts, one containing direct energy and the other containing indirect energy. Direct energy is described as the type of energy that is used to carry building materials to the site after that construct the building. Whereas indirect energy is described as the energy used to obtain, manage and produce the products needed for construction as well as energy used while carrying those products between these activities.

Cement and concrete institute, (2011) was stated that the embodied energy is a measure of non-renewable energy per unit of building product, section or technique. The unit of embodied energy is stated as mega Joules (MJ) or giga Joules (GJ) per unit weight where the weight is in kg or tonne or giga Joules (GJ) per unit area where the area is in square metres.

2.1.2 Embodied CO_2

Embodied CO_2 is defined as total amount of CO_2 generated in the processes of removing, carrying and producing raw materials. When the final product is obtained, embodied energy is stated as the amount of CO_2 per unit weight where the weight is in tonnes and CO_2 is measured in kg. Alternative unit to express embodied CO_2 is as total amount of CO_2 per unit volume where the volume is in m^3.

In the unit used to express ECO_2, the amount of carbon dioxide is determined by using different emission factors. These emission factors occurred either during the building's life cycle considering from the initial design to refurbishment or alternative place where emission happened is during destruction of the building. The reason for measuring these emissions is to create carbon life-cycle for buildings. In this way, carbon life-cycle can be used in lowering carbon dioxide in buildings. Lemay (2008) recommended that the amount of ECO_2

is subject to the quantity of cement used in the mix. When concrete is compared with different building materials, it is found that the amount of ECO_2 in concrete is lower than the other materials. The figures of this ECO_2 found in concrete are reported as 95kg for C28/35 unreinforced or 110kg for C28/35 reinforced CO_2 per tonne (Costas Georgopoulos and Andrew Minson, 2014).

United Kingdom Quality Ash Association (UKQAA), (2010) reported the amount of ECO_2 included per tonne of the main materials of the reinforced concrete. Indicative values reported in Table 2.1 is taken from "cradle-to-factory-gate" excluding the energy needed for carrying the materials from the manufactured area to the concrete plants. GGBS is a material used in the production of iron whereas PFA is a product used in generating power plants. Therefore, both GGBS and PFA can be called as by-products. Therefore, since such by-products are manufactured and land filled, the influence they create an environment due to the production of iron and electricity is not taken into consideration. On the other hand, the effect is taken into account during the development procedure from granulated slag to GGBS. Beside of this, in order to use PFA, additional further procedure is not needed. Thus, it can be stated that PFA creates less environmental hazard then others.

Table 2-1 Embodied CO2 after UKQAA (2010)

Materials	**Embodied CO_2 Kg/tonne**
Portland Cement CEM I	913
GGBS	67
PFA	4
Limestone	75

Even all three sections of the sustainable development namely; environment, economic and social are equally important, from the construction aspect, environment is the one which has the highest influence. Cement is important constituent material in the concrete and due to several factors including the constraints on the accessibility of natural minerals, which are used as sources in the production of cement and emission of CO_2, which is realised during the production of cement, part of the cement can be substituted by other by-products namely; PFA, GGBS and silica fume. Managing such by-products eliminates the requirement of landfill.

In the concrete industry sector, The Concrete Centre (2010) suggested that the Portland cement covers majority of the total energy used in the production of concrete such as 74%. Therefore, both cement sector and ground granulated blast furnace slag sectors are promised to control climate change agreements (CCA). Both of these sectors have made CCA with the government, so that the industries in such sectors have to undertake programs to reduce their energy usage. In the case that such sectors fail to undertake programs to reduce energy, industries should pay financial penalties to the government.

Since the cement sector consists of the majority part in the manufacturing of the concrete, a care should be taken in this area and CCA helped to decrease the energy usage in the manufacturing of cement by increasing the CCA performance by 44.8% within 10 years (i.e. from 1990 to 2010). At the end of this period, industries in cement sector have achieved and even went beyond of the target CCA performance requested which was 30%. When the same time period is considered, the ground granulated blast furnace slag sector has also increased its CCA performance by developing grinding and hence decrease the energy usage by 16%.

Since UK buildings account 50 per cent of total UK CO_2 emissions on daily basis, it is very important to exceed the concept of embodied CO_2 emissions of construction materials in energy proficiency and focus on effective emissions of buildings for a long term. Significant amount of energy can be saved by considering the intrinsic thermal mass over the lifespan of the building. In this way, both heating and cooling conditions are reduced (The Concrete Centre, 2011).

2.2 The Focus on Thermal Mass

Thermal mass is defined as the capability of a building material to store heat energy. In the building with high thermal mass, firstly, heat is absorbed when the building is exposed to sun or daylight, then the absorbed heat is stored in a thermal storage and afterwards, the heat from the storage is used to maintain the temperature inside the building by realizing the heat from thermal storage when the temperature inside the building is dropped. A material having high specific heat capacity, high density and moderate thermal conductivity is classified to be a useful material that can be used as a thermal mass material. The reason of preferring;

- A high **specific heat capacity** is to maximise the amount of heat that can be stored in every Kg.
- High **density** is needed for the same reason as well, so that when the material is heavy, it can absorb more heat.
- **Moderate Thermal conductivity** because this will allow the rate of the heat flow to be approximately in both heating and cooling cycles of the building.

Thermal mass affects the building in two ways. Firstly, it balanced the interior temperature by taking the average of peak temperatures during the day and night. Secondly, it maintains the interior temperature to be kept at constant temperature; therefore it postpones the occurrence of peak temperature in the building. Thermal mass delayed this process more in heavy weight buildings than lightweight buildings. As well as this, thermal mass have made the heavy weight building to achieve lower peak temperature than light weight building. This behaviour is called thermal inertia.

Yannas and Maldonado (1995) explained thermal inertia as the capability of the building to store and realize the heat in total. As thermal inertia increases for a building, the rate of changing the inside temperature decreases. This change can be in both ways, either increasing the indoor temperature or decreasing the indoor temperature. By using this ability, thermal inertia can decrease the rate of heat flow to the indoor environment. As well as this, thermal inertia can be used in winter periods to keep the heat inside the building. Thermal inertia enables the heat that is absorbed and stored to be realized at a slower rate to the indoor environment when the heat is needed at the interior of the building.

Construction materials such as brick, stone, concrete are classified to be heavyweight materials. The advantage of such materials is their feature of joining both high storage capacity and moderate thermal conductivity specifications.

On the other hand, materials such as wood also have high storage capacity but do not have moderate thermal conductivity. Instead, wood has low thermal conductivity. This means that the rate of heat flow during the absorption and while realizing the heat is restricted. Having high rate of heat flow is equally bad as having low rate of heat flow. Therefore materials such as steel which has high thermal conductivity are not preferred. The reason is when the heat is absorbed and realized rapidly, the heat flow cannot be coordinated to the natural heat flow of the building.

Popularity in analysing thermal mass in buildings have been increased due to effect that it creates on decreasing space conditioning energy of buildings, specifically reducing the amount of energy used in cooling of buildings. There are two main reasons why thermal mass is more important in cooling energy rather than heating energy. First is the effect of climate changes, since the global warming is occurring in everywhere, it is more important to maintain the cool weather rather than hot weather. Second is the construction of new buildings which should be carried out without damaging the environment such as made with zero carbon and using less fossil fuel than before (Roberts, 2008).

A study is conducted in the UK to examine the effect of climate changes on functioning energy and carbon dioxide emission. The effect is investigated on both lightweight and heavyweight types of houses. The main aim of the study was to look at the effect of thermal mass on the balance between embodied and operational CO_2. As well as this, the effect of climate change on the same balance is evaluated. A single house is selected and four different measures of thermal mass is used to compare the effect of each. Different measures of thermal mass are ranged from timber framed with brick veneer house which is a type of light-weight construction to a block walls and hollow-core suspended floors which are the type of heavy-weight construction. (Hacker, De Saulles, Minson and Holmes, 2008)

When the house is newly built, the residence was passively cooled in summer. However, when the temperature exceeds the threshold value, air conditioning is introduced to prevent overheating. When thermal mass involved in the building, better heat control is achieved and overheating in summer can be controlled for longer periods. Hence, having thermal mass in buildings postponed the inclusion of air conditioning in the lifecycle of the building. Energy needed for functioning of the building and energy needed for cooling are also found to be decreased relative to increase in thermal mass. This is because thermal mass has an advantageous effect on the energy stored by the structure of the building. When heavy weight houses are compared with light weight houses, it can be concluded that heavy weight houses have up to 15% higher initial embodied CO_2 then light weight houses. At the beginning of the lifecycle, this difference is balanced due to the savings in functioning CO_2 emissions. Total savings in functioning CO_2 emission over the total lifecycle of the building is found to be around 17% in heavy-weight construction.

It is confirmed with several studies that increase in thermal mass prevents having extreme temperature conditions inside the buildings. Considerable amount of research have been conducted in this area that suggests that when the building has high mass, this eliminates the extreme variations caused in indoor temperature and maintain more stable temperature (Balaras, 1996; Barnard, et al., 2001; Tompson, 2006).

2.2.1 Influence of Thermal Mass on Cooling Energy Consumption

When warmer climates are taken account in Europe, the advantages of thermal mass is clearly demonstrated. Nowadays, the interest is to look at other regions where the climate changes are occurring in the direction towards overheating. Since using thermal mass decrease the need for cooling, applying their thermal mass to commercial buildings is another interest raised. When the weather is warm, the heat absorbed by heavyweight materials such as concrete walls and floors prevent the unnecessary temperature rises and by this way, overheating is kept under control. As a result of the effect of thermal mass, if the building is naturally ventilated, thermal mass ensures that maximum comfort is reached. However, if the building is air-conditioned, thermal mass ensures that peak cooling load is reduced and delayed. The structure of the building permits large amount of heat to be absorbed given a little increase in the surface temperature. This feature of heavy weight materials is important in the sense that low surface temperatures can be used to create cooling effect given that the residents are accepted to stand for a slightly higher air temperatures.

If the cool night air is permitted to circulate in the building, this will then cause the heat that is stored in the thermal storage during the day to be removed during the night. In the UK, since the air temperature at night is approximately 10 degrees less than the air temperature at day time, the heat stored at thermal storage is realized at night and hence the cycle of heating and cooling operated well. The variation of the temperature during the day time usually more than 5 degrees, therefore night cooling in the UK is moderately dependent on the differences between the temperature readings during the day. Over the 21st century, the effect of global warming decease the change in the temperature during the day. This means that temperature during the day is forecasted to be the same or a little different thought the day. On the other hand, the effect of global warming increased the temperature range that a particular day can have. Towards the end of the 21st century, even increase in temperatures results in this night cooling system not to be as effective as before, the combined effect of thermal mass and night cooling system together is effective. When thermal mass and night cooling systems are considered together, it can help buildings to be familiarized with climate changes.

2.2.1.1 Summer Day

During the summer day, when the weather is hot, outside temperature is very high and the building is absorbing the heat from the sun during the day, therefore windows are kept close to prevent the heat and hot air to come inside the building. Different forms of shading are used to prevent the projection on the south elevation from the highest angles of the sun. As well as this, radiant and convection cooling is obtained by thermal mass where the heat is absorbed and stored at walls and floors by the thermal storage. This will maintain the internal temperature and prevent the overheating.

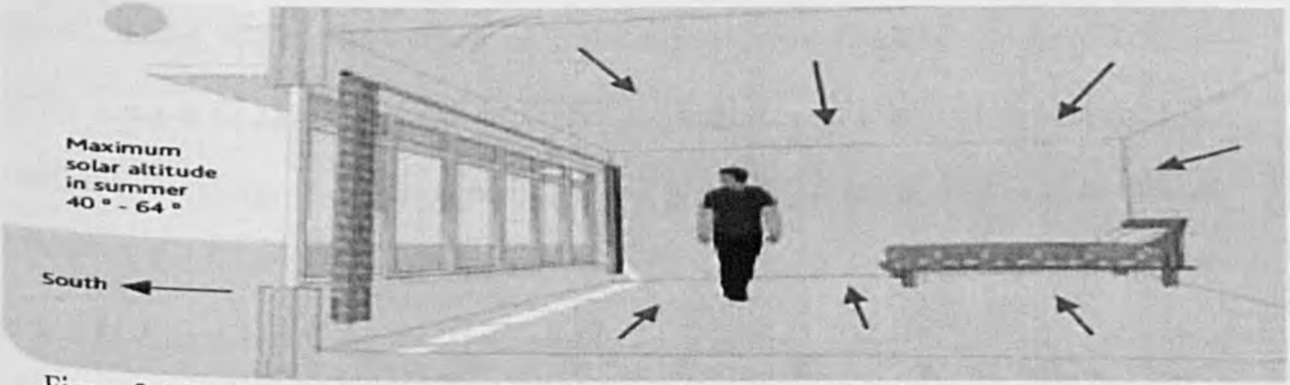


Figure 2-1 During the day of summer [Thermal Mass Explain 2012 from The Concrete Centre]

2.2.1.2 Summer Night

During the night time at summer, windows are kept open, so that the cooler air is passed inside the house and natural ventilation is achieved. This will make the structure of the building to cool and if the next day is expected to be hot again, windows are closed in the morning and the cycle is repeated over and over again.

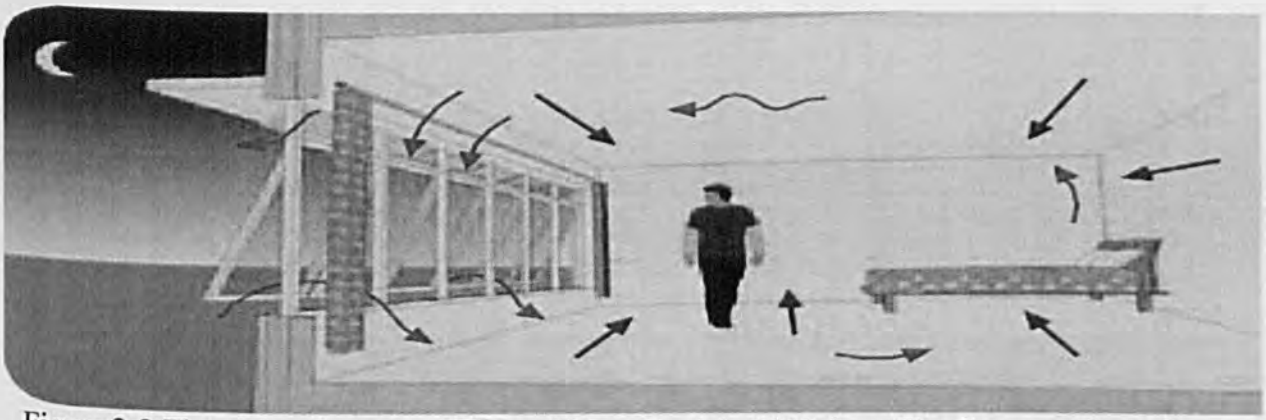


Figure 2-2 The night of summer [Thermal Mass Explain 2012 from The Concrete Centre]

Even if the thermal mass is found to affect the performance of conditioning energy (Yang & Li, 2008), a greater effect is observed on decreasing cooling energy consumption, specifically this effect can be seen at offices when thermal mass is combined with night ventilation (Balaras, 1996; Barnard, et al., 2001; Thompson, 2006; Yang & Li, 2008).

The difference between the effects of thermal mass on different climates can be seen from the study that reported 18% reduction in the energy usage in commercial buildings in hot and humid climates whereas 40% reduction in the energy usage in milder climates (Balaras, 1996). Yang & Li (2008) reported that when thermal mass is combined with night time ventilation, the energy usage at maximum heat and cooling loads can be reduced from 18% to 50% given that the difference between the highest temperatures obtained at day and night is around 15 degrees in a typical day of the warm climate in Hong Kong.

Various researchers have suggested that thermal mass is more effective when there is a difference between the temperatures throughout the day. In such cases when there is a difference in outdoor temperature during the day, night time ventilation can be used to take out the heat stored during the day due to thermal mass. Studies conducted by these authors also indicated that when there is no continuous stay in the residence, this improves the benefit of thermal mass because heat stored in thermal storage is thrown away at hollow times. Hollow times are usually the periods when the internal gain of heat energy is minimized because there is no need to provide comfort (Balaras, 1996; Barnard, et al., 2001; and Yang & Li, 2008).

2.2.2 Influence of thermal mass on heating energy consumption

Increase in fuel costs together with harder conditions on performance means that the desire to use passive techniques is higher than usual to heat homes and offices. Comfortable low energy solutions are obtained by considering design, orientation, glazing and thermal mass together to apply such passive techniques. When thermal mass is applied in passive heating designs, the capability of thermal mass enables thermal mass to decrease fuel consumption. By this way, in winter period, heat absorbed from south facing windows are maximised and when this is combined with heat obtained from cooking, light, maximum benefit is achieved from thermal mass. During night time, as the temperature decrease, the heat stored by using solar passive energy techniques are used to maintain the temperature of the building and to eliminate the need for extra heating. By this way, it is estimated that 10% of the fuel can be saved and when more advanced solar techniques are used such as sunspaces, this figure can go up to 30%.

2.2.2.1 Winter Day

During the day in winter period, if thermal mass is used in a building, this can result the absorption of heat from the south facing windows by floor and walls of the wilding. Whereas, in the evening time when the effect of sun is dropped, the temperature is started to decrease which will affect the heat flow making the heating flow to be reversed and passed back into the room.

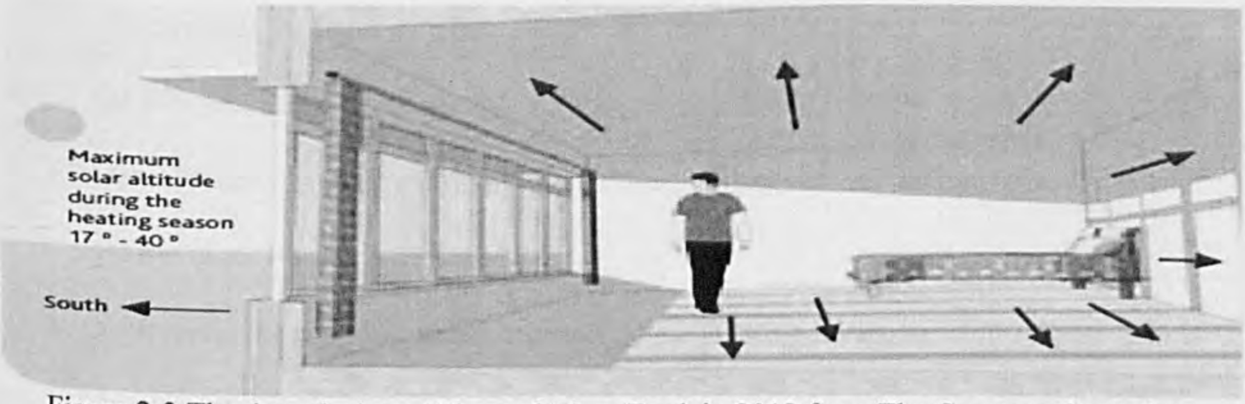


Figure 2-3 The day of winter [Thermal Mass Explain 2012 from The Concrete Centre]

2.2.2.2 Winter Night

During the winter period, at night times, heat loss is eliminated by keeping the windows and curtains close all the time. In such situations, when the heat loss is minimised and the heat is realized from the thermal storage, this can result to minimize the need to use extra heating. At the next morning, since most of the heat from the thermal storage is realized during the night, residents may need to use heating until new heat is stored in the thermal mass later in the day.

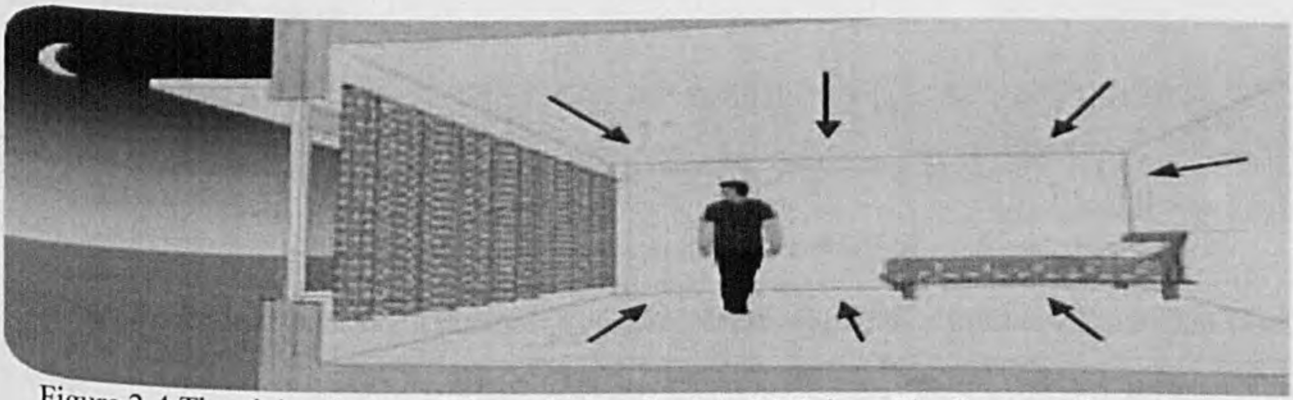


Figure 2-4 The night of winter [Thermal Mass Explain 2012 from The Concrete Centre]

2.2.3 Benefits of Designing with Thermal Mass

The advantage of thermal mass can be taken if the outer design of the building and orientation are considered carefully. If the requirements of the building are met with concern, advance passive techniques can result great benefits, including (European Concrete Platform ASBL, April 2007);

- Observing an increase in fabric energy efficiency and reduction in carbon usage over the lifecycle of the building.
- Developments in day lighting of the building, enhancing ventilation process, so that a greater quality of air is achieved.
- Postponing the time lag and decrement factor to decrease the amount of heat gained during summer.
- Providing comfort at summer time as well by eliminating the risk of overheating.
- Obtaining estimation for proofing when the effects of climate changes are taken into account.
- Cutting down the need for advance and expensive techniques to decrease the amount of carbon dioxide.
- Added value for the properties and increase the sale prices.

2.2.4 Thermal Comfort

Thermal comfort is defined as the feeling of satisfaction when the body's internal temperature matches with the environmental temperature. According to BS EN ISO 7730-2005, thermal comfort is expressed as '...that condition of mind which expresses satisfaction with the thermal environment.' This means that the person under this situation will not feel too hot or too cold. For instance, if a person is walking up the stairs while wearing a coat, that person may feel too hot and similarly, another person at the same environment in a seated position wearing a t-shirt might feel too cold. This means that the concept of thermal comfort is different from person to person. According to Health and Safety Executive, an environment is classified as 'reasonably comfortable' when at least 80% of the people existing in the environment are happy about their thermal comforts. Therefore, evaluation of thermal comfort is made by examining the occupants at the environment to observe their satisfaction level about their thermal comfort. Hence analysis of thermal comfort is complex and difficult.

Analysis of thermal comfort provides important information to combine the properties of thermal efficiency with the design of the buildings that is needed. This will then help to create right thermal comfort levels for the residents. Increase in knowledge of thermal comfort, can help to provide effective and efficient designs of the buildings (Andris Auliciems and Steven V. Szokolay, 2007).

2.2.5 Thermal Bridging

The term called thermal bridge is used to explain the heat loss or gain when the heat is transferred between the building materials. When there is no or little insulation in the building, heat loss or gain will be observed by conduction through the clear parts of the cover and hence the concept of thermal bridge in unnecessary to be considered (CIBSE, 2006). Therefore, thermal bridging was not considered in the past even in calculations. However, in the recent years, improvements in building regulations result in increasing the popularity of taking thermal bridging into account. If the building is well insulated, thermal bridging became a significant factor that should be considered in assessing the overall performance of the building.

The biggest challenge came into when bridging materials such as steel beam is used at or close to the surface of the cover. By this way, heat can be conducted through the material from one side to other. Conduction of heat can be minimized or prevented if the design is made in a way, so that the effect of thermal bridge will not be greater than 10-15% of the total heat loss resulted from conduction (S M Doran & Gorgolewski, 2002; Way & Kendick, 2008). When materials are used in a building, conductive materials should be insulated to avoid the direct contact with the external air from surrounding environment.

2.2.6 Thermal Mass and Legislation

In 2005, the UK, the Energy Saving Trust report stated that building regulations did not focus on the main concern regarding on overheating in urban houses (Energy Save Trust, 2005). After 2005, it is started at Part L of the building regulations to consider overheating for buildings only. Standard Assessment Procedure (SAP) assumed low level of thermal mass regardless of the type of the material used in constructing the building. This value can be used to suggest overheating. However, the estimate does not consider the rate of heat flow.

This assumption involving in Part L and Part F of the building regulations is changed to consider thermal mass (Department for Communities and Local Government, 2009). The new regulation is launched in 2010. According to new regulations, Part L, the passive designs of buildings are taken into account to generate code for sustainable homes (CFSH) ratings. This change in regulations will motivate people to apply passive measurements such as thermal mass in the construction of houses.

Agreements with current government, policies sate that by 2016, the construction of all new houses should be made with zero carbon. In order to achieve this goal, the design at the underneath is needed to be changed such as improving fabric performance.

Towards the target for 2016, amendments on Part L of the building regulations in 2010 and 2013 have made main actions on the way to zero carbon (Department for Communities and Local Government, 2010). These also helped to make improvements on airtightness, insulation and in use of zero carbon technology. Achievements specified in Part L of the building regulations are studied from the concrete and masonry housing point of view. The performance of different fabric and services options are highlighted on using SAP 2009 modelling. When considering fabric performance of housing, medium and heavy weight construction plays an important role in thermal mass. This is why Government's new Fabric

Energy Efficiency Standard [FEES] for zero carbon homes included the importance of fabric on heavy weight construction performance.

Table 2.2 shows how Part L of the building regulations restricts the emissions from new houses. The way of stating the conditions needed on performance will be changed in 2016 and will be reported as kg CO_2/m^2/year instead of percentage development compared to previous standard. This will go along with the required fabric performance target that is given in FEES and expressed in terms of Kwh/m^2/year. New Homes and Community Agency [HCA] design standards are established by government in November 2010 (NHBC, December 2010). By this way, reasonable housing can use HCA land or fund to complete code for sustainable Homes Level 3. The condition for code for sustainable homes level 3 is to achieve 25% decrease in emission (Thermal Performance Part L1A, 2010).

Table 2-2 Part L performance requirement [Thermal Performance: Part L1A from The Concrete Centre]

Year	Percentage change
2010	25 % less than Part L 2006 *
2011	25 % less than Part L 2006 *
2012	25 % less than Part L 2006 *
2013	44 % less than Part L 2006 *
2014	44 % less than Part L 2006 *
2015	44 % less than Part L 2006 *
2016 (Subject to public consultation in 2011)	$\leq$ 10Kg **CO_2** / m^2 /year (detached house)** $\leq$ 11Kg **CO_2** / m^2 /year (detached house)** $\leq$ 14Kg **CO_2** / m^2 /year (detached house)**

(*) In addition to measures taken to address party wall heat loss (where applicable)

(**) Plus allowable solutions to achieve zero carbon performance

Emission factor is the Table 2.3 that shows the amount of carbon dioxide obtained in kg per KWh of energy from a range of fuels. Emission factors have changed in SAP 2009 to update the standards using the up to date data. The results show that emission factors are increased in all types of fuels mainly electricity reflecting increase of 23%.

Table 2-3 Revised CO2 emission factors. (Source: Table 12, SAP 2005 and Table 12, SAP 2009)

Fuel	SAP 2005 (CO_2Kg/kWh)	SAP 2009 (CO_2Kg/kWh)	Change
Main gas	0.194	0.198	+2%
Heating Oil	0.265	0.274	+3%
Wood pellets	0.025	0.028	+12%
Grid supplied electricity	0.422	0.517	+23%

Opposing to the assumptions made before, it can be stated that due to air circulation in the cavity and party cavity walls can be a cause of heat loss (J. Wingfield, D. Miles-Shenton and M. Bell, May 2009). If this air flow is not limited, it can result to large amounts of heat loss. This difficulty can be overcome by blocking the cavity and as wells as this, using effective sealing at the outer part of cavity. After these protections, U-value shown in Table 2.4 can be assumed.

Table 2-4 U-values for party walls (as detailed in Part L) [Thermal Performance: Part L1A from The Concrete Centre]

Party wall construction	U-value (W/ m^2K)
Solid	0.0
Unfilled cavity with no edge sealing	0.5
Unfilled cavity with edge sealing	0.2
Fully filled cavity with edge sealing	0.0

The restriction of heat at the party wall is 0.2 as shown in Table 2.5. This means that, in this case the control of sealing is minimum. The Building Control Bodies are the ones who determine how effective the sealing is.

Table 2-5 Backstop U-values in Part L: 2010 [Thermal Performance: Part L1A from The Concrete Centre]

Element	Part L 2006 (W/ m^2K)	Part L 2010 (W/ m^2K)
External walls	0.35	0.3
Party walls	N/A	0.2
Floor	0.25	0.25
Roof	0.25	0.2
Windows	2.2	2.0

2.3 Principles of Heat Transfer in Buildings

This chapter presents some concepts of energy transfer in a building as well as the influence of the mass on it. It covers the flow of energy through the building's envelope and the storage of energy in the mass for later utilization. While taking account overheating in houses, the factors that cause overheating should be considered. In this chapter, the conception of energy transfer in buildings is considered.

When there is a thermal storage inside the building, this allows great quantities of heat to be collected and released gradually per unit volume. By this way, interior temperature will be kept under control. In broad definition, any material which has the ability to absorb, store and release the heat can be defined as thermal mass. Therefore, in order to measure the thermal mass, as well as the fundamental features of the material namely; **thermal conductivity**, **specific heat capacity** and **density**, heat transfer mechanism of the material should be considered.

Heat balance is obtained when the heat is gained due to solar radiation and released as a result of convection and radiation. After this heat balance, the procedure of heat transfer is started to be observed during the day time. Heat gained from external walls over the time and the temperature raises depending on the material used. Boundary conditions are also affecting the amount of heat gained from external walls. The gained heat is then transferred through the walls to the inside surface. However, the opposite procedure takes places during the night time where the outside temperature is lower and additionally, there is no supply of solar radiation. In this way, the temperature at the walls gets lower but again the amount of decrease in temperature depends on the thermal properties of the material used and boundary conditions.

The heat balance is achieved when heat is transferred from the condition where the temperature is high to the condition where the temperature is low. Therefore, having a higher speed of wind increases the convective heat loss. As well as this, having a greater air movements inside the wall increases heat loss and results in intemperance of the heat that is collected. This means that, by the aid of the structure of the walls, increasing the thermal mass of the building will result in decreasing the rate of heat transfer procedure.

2.3.1 Thermo physical Properties of Materials

The speed of conduction of energy is based on the material itself, density of the material, ability of the material to absorb the energy and ability of the material to transfer the energy. Thus, the main features of a material in thermal analysis should consider **density**, **specific heat capacity** and **thermal conductivity**.

- **Density (ρ)** is the mass of the material occupied per unit volume (kg/m).
- **Specific heat (c)** is the amount of energy needed to generate a temperature difference in a mass of material (J/kg°C).
- **Thermal conductivity (λ):** is the capacity of the material to conduct heat at a unit thickness of material with both surfaces at a unit temperature difference (W/m°C).

Change of the temperature of the material and/or the change in the moisture content of the material cause thermal properties such as density, specific heat capacity and thermal conductivity to be depend on time. Several authors have reported lists containing building materials and their thermodynamic features. The list by Energy Simulation in Building Design (Clarke, 2001) is represented at Table 2.6 where materials are split into different groups. It can be concluded that these properties can vary based on the sample, test procedure and accuracy of the performed test

Table 2-6 Thermophysical properties of common construction materials (Clarke, 2001)

Material	Thermal Conductivity (J/ m°C)	Density (Kg/ m³)	Specific Heat Capacity (J/ Kg°C)
Block – Masonry medium weight	0.6	1350	840
Brick – aerated	0.3	1000	840
Brick – inner leaf	0.62	1700	840
Brick – outer leaf	0.96	2000	650
Brick – reinforced	1.1	1920	840
Cement (regular)	0.72	1860	840
Cement fibreboard	0.082	350	1300
Cement screed	1.4	2100	650
Ceramic tiles	1.20	2000	850
Concrete – heavyweight	1.3	2000	840
Concrete – lightweight	0.2	620	840
Concrete – medium weight	0.32	1060	840
Earth (common)	1.28	1460	880
Expanded polystyrene (EPS)	0.035	23	1470
Gypsum Plasterboard	0.16	800	840
Hardwood	0.05	90	2810
PVC (regular)	0.16	1380	1000
Sand	1.74	2240	840
Softwood	0.17	550	1880
Steel	45	7800	480
Water (liquid at 20°C)	0.58	1000	4200

Thermal conductivity of the building is the feature that describes how simply the heat is transferred from the cover of the building. Temperature is the factor affecting the thermal conductivity and in anisotropic materials, as well as temperature, direction is an additional factor affecting the thermal conductivity. However, the size of the effect can be small over a substantial range of temperatures.

The reciprocal of thermal conductivity is known as thermal resistivity. **Thermal resistivity** is a measure of how much a material is opposed to conduct heat. Thus, a negative association exists between conductivity and resistivity of the material. The reciprocal to conductivity, is thermal resistivity which is how much a material resists conducting heat as shown in equation below:

$r=\frac{1}{\lambda}$ Where: r= resistivity (m°C/W), λ= thermal conductivity (W/m°C) (1)

Conductivity and resistivity are both based on factors such as 1 degrees temperature change between the two surfaces through 1 second time period when a sample of 1m material is used having 1m thickness. However, the effect of changing the thickness of the layer of the material on conductivity and resistivity is not considered. Therefore, when the same material is taken into account, even using thin or thick layer of the material result in same conductivity, the actual amount of heat conducted by the sample will be different due to the distance where the heat has to be transformed.

Generally, when materials used for insulation purposes considered against materials having high thermal conductivity, these materials will have lower specific heat capacity and even much lower thermal conductivity. As well as this, gathering of heat do not happen in these materials and by this way, they have the capability of decreasing unwanted heat transfers. In thermal insulation, air can be used as a good insulator if it is trapped in the right way in numerous very small fibres so that the air with poor conductivity will not support convection and will prevent radiation. Any material having the similar properties of poor conductivity with no reinforce of convection and radiation is classified as being a good insulator. The heat transfer procedure in thermal mass can be described in four stages;

At the first stage, heat is absorbed by the surface of the material when a radiation of heat is received from a body such as sun. Then, at the second stage, the conduction of heat is occurred from a warmer surface to the cooler areas such as the inner sides of the material. At the third stage, heat is radiated back to the space if the surface of the material is warmer than the environment where the material exists. This makes the material to start cooling down again. Hence at the final step, heat is conducted from the warmer inner sides of the material to the surface of the material.

The following part, two types of heat transfer calculations in buildings namely; **steady-state** and **dynamic heat transfer** calculations are explained stating the difference between the two calculations. This section also explains how the thickness of the material is taken into consideration when calculating heat transfer.

In a **steady-state condition**, heat flux is moved towards a constant value by retaining the same temperature at both sides of the wall over a long period of time. By this way, heat flows from a higher temperature to lower temperature across a distance in buildings. this distance is the thickness of the wall.

$q= - \lambda\ [T_1-T_2]/L$ (2)

Where:
q = heat flux (W/m^2)
λ= conductivity (W/m^oC)
T_1 = initial temperature (^oC)
T_2 = final temperature (^oC)
L = thickness (m)

As can be seen from the equation, thickness of the wall affects the heat flux. Therefore, in order to evaluate thermal mass in buildings, the thickness of the wall should be considered. From the equation 2.6 (which calculates the Thermal Resistance [R] value), it can be stated that thermal resistance which is known as R value depends on resistivity and thickness of the material. For that reason, as the layer of the material gets thicker, the resistance of the material gets higher. If the material consists of multi layers, appropriate resistance is estimated by adding the R value of each layer and taking the average to find the overall R value.

Thermal resistance or R-value $R=r*L$ (3)

Where:
R= resistance ($m^2\ ^oC/W$)
r= resistivity (m^oC/W)
L= thickness (m)

Thermal conductance which is also known as thermal transmittance or U-value can be calculated by replacing thermal resistivity in the calculation of thermal resistance by "1/ thermal conductivity".

The Conductance of a material can be determined, known as a **U-Value** or **Thermal Transmittance** (BSi, 2003; CIBSE, 2006). The U-Value Value of the building envelope is the major factor in the determination of the steady-state heat losses and gains.

Thermal conductance, transmittance or U-Value; $U=\lambda/L=1/R$ (4)

Where:
U= conductance ($W/m^2\,{}^oC$)
R= resistance ($m^2\,{}^oC/W$)
λ= conductivity (W/m^oC)
L= thickness (m)

Conductance and Resistance in Fourier's law $q=U\Delta T$ or $q=\Delta T/R$ (5)

Where:
q = heat flux (W/m^2)
U = conductance or U-Value ($W/m^2\,{}^oC$)
R-value ($m^2\,{}^oC/W$)
ΔT = temperature difference (${}^oC$)

In addition, for a multi-layered wall the equation can be written as (Clarke, 2001: p. 8; BSi, 2003):

Heat flux through a multi-layered wall in steady-state $q=\Delta T/[R_1+R_2+R_3....+R_n]$ (5)

Where:
q = heat flux (W/m^2)
ΔT = temperature difference (${}^oC$)
R = resistance or R-value ($m^2\,{}^oC/W$)

When the density of the material is multiplied by the specific heat capacity of the same material, the resultant value will represent **Volumetric Heat Capacity (VHC)** of the material. When the temperature is considered to be a situation insist on the wall, VHC of the material is multiplied by the thickness of the wall to evaluate the capability of the wall to store energy per unit surface area. **Thermal diffusivity** is evaluated by taking the ratio of the ability of the wall to store heat energy relative to the ability of the wall to conduct heat energy.

Ability to store energy divided by ability to conduct heat; $\boldsymbol{\rho cL/[\lambda/L]=\rho cL^2/\lambda=L^2/D}$ (6)

Thermal diffusivity $\boldsymbol{D=\lambda/\rho c}$ (7)

Thermal effusivity $\varepsilon = [\lambda\ \rho c]^{1/2}$ (8)

Where;
c= specific heat capacity of material (kJ/kg.^{o}C)
ρ= density of material (kg/m^3)
L= thickness of material (m)
λ = Thermal Conductivity (W/m^{o}C)
D= Thermal Diffusivity (m^2/s)
ε= Thermal Effusivity (j/m^{2o}c)

As can be demonstrated from the above equations, thermal diffusivity suggest the rate at which heat is transferred through the middle of the wall and therefore, thermal diffusivity is an important concept on investigation of thermal mass of the material. In the material with high thermal diffusivity, heat at the surface of the wall is transferred quicker than a material having low thermal diffusivity (Clarke, 2001). By this way, a material with high thermal diffusivity is also reacting to temperature differences quicker than a material with low thermal diffusivity (Kalogirou, Florides et al., 2002).

The **Thermal Effusivity** is also known as Thermal Inertia and it is the value estimated by taking the square root of the quantity obtained from multiplying thermal conductivity, density and capacity of the material. Thus, it is used to show the ability of the material to interchange energy with its environment. It describes the performance of the thermal transfer when two materials are contacted together. When the material has high thermal effusivity, this means that the material can be able to react more promptly to absorb the heat from the surface (Kalogirou, Florides et al., 2002). To sum up, diffusivity considers the heat transfer from the centre of the material whereas effusivity considers the heat transfer from the surface of the material.

Even thermal diffusivity and thermal effusivity are used to describe the thermal mass of the material, considering only those two properties are not entirely enough. Therefore, as well as taking account these factors, **time lag** and **decrement factor** are concepts that needs to be concerned about.

Primarily, in the case when both sides of the wall have the same temperature, incident rise in the external side will result in heat flux to be delayed and hence being different from the heat flux estimated by using steady state equations. The time difference where delayed of heat flux has occurred is known as time lag and it is equal to $L^2/6D$. When the process of heat transfer will follow an exponential distribution and will be approaching towards $L^2/6D$. However, due to the nature of the distribution, it will never be $L^2/6D$ exactly. Even theoretically, time lag is approaching to infinity, in practice; this time lag is needed to be determined, so that the lag will be kept same. The time lag where the lag is kept same is the time constant. Time constant is achieved when the 36.8% of the total heat is transferred (Childs, Courville et al., 1983).

In order to calculate this heat flux in steady state equations, the wall's R-value is used as a parameter and thermal mass of the wall is not considered. Therefore, it can be stated that total heat flow through the wall does not affected by thermal mass. However, thermal mass does affect the time lag that determines how long the heat is transferred to the internal surface.

In situations where there is no time lag to attain the steady state condition while a change in the temperature is obtained, then there will be difference between the actual peak heat flow and the heat flow predicted from the steady state equation. This reduction of heat flow is called **Decrement factor**. For instance, in single layered homogenous wall, increase in L^2/D will cause an increase in decrement factor as well. (Childs, Courville et al., 1983)

Even, if time lag took place then steady state condition hardly. Seldomly it is found in buildings. Thus, in order to forecast the effect of thermal mass, the researchers should carry out dynamic calculations.

The approach called **Response Factor Method** developed by Brisken and Reque in 1956 is used in building analysis in order to overwhelm the problem of estimating the heat flux at a point in the cycle. This approach uses the principle of superposition. By this way, individual temperature pulses at various heights are added to reconstruct the cycle (Davies, 2004).

There are two sub types of response factor method namely: **Time-domain** and **Frequency-domain response** function. Both types of response factor methods are based on transient heat domain transfer and intra-zone energy zone flows. Both of these methods are well known in history going back to 1970s and are used to decide the thermal performance of buildings (Davies, 2004).

Numerous methods are existing for the evaluation of dynamic performance of the building. The modest method depends on a method called **Admittance Method** is based on a variation of the frequency domain method which is generated by the United Kingdom Chartered Institute of Building Services Engineers (CIBSE). This method is formed by adapting the freg domain method. Therefore, CIBSE admittance method is also a type of cyclic model. In this method, the underline assumption about the intervals of the data points is different. Cycles are assumed to be harmonic based on 24 hours of intervals.

As well as this, other assumptions include using material's **admittance**, **time lag** and **decrement factor** to describe the dynamic outcome. By this way, the model generated is used to create prompt evaluations about the maximum summer time temperatures, determining the required cooling loads and deciding the obligations of preheat. On the other hand, the simplicity of the model resists the model to be used in the forecasting of summertime overheating. The main reason of this limitation is that the model cannot evaluate the mass accurately. (CIBSE 2006)

Thermal admittance is a measure that describes the amount of heat that move across a material. In steady state condition, admittance is the same as **U-value** in walls. However, when the condition is time dependent, admittance is different from U-value. Since thermal admittance is changing based on the thermal mass of inner layers of the materials, it can be used as a sign to thermal mass. Admittance tends to be high if the thermal mass of the material is high and vice versa. If the structure of the material is multi-layered. admittance is evaluated by considering the layers close to internal surface and hence it can be seen as a dynamic U-value calculated based on internal space only.

Milbank (1974) conducted a research to investigate the thermal response obtained from buildings as a result of cyclic energy inputs. This thermal response is examined by the aid of admittance method in the study carried out by Milbank. As a result achieved from his study, Milbank concluded that the admittance method used is mainly manual and in the evaluation of thermal response, this method request to provide a balance for diverge range of needs for calculations.

After simple calculations are carried out, temperature distribution obtained from conduction process through the building element is investigated. This investigation suggest that, usually, temperature distribution is either under a condition where the change of temperature over time and over the variation of energy is steady-cyclic meaning that the variation occurred in temperature can be repeatable over a certain time or temperature distribution can be under the condition where the change in temperature and energy is different in an irregular manner from one day to another.

Admittance method can provide a solution to steady-cyclic cases. However, in cases where the change is unpredictable, solution is complex. Hence, different methods such as response factor should be used. Heavy materials such as concrete, brick or stone can store large proportion of cyclic energy due to having large capacity at the internal surfaces. Therefore, such materials have high admittance values which then results in small amount of temperature swing in the room. The unit for admittance (Y) is $W/ m^2 K$ and the values of admittance for some constructions components are reported in CIBSE Guide section A3.

The total admittance of a room can be evaluated by the total of the products of all room surface areas (A) and their corresponding admittance values (Y), symbolized by the succeeding expression:

ΣAY (9)

The units will be, then, given by W/ K.

According to Balcomb (1983), the admittance can be evaluated by:

$$Y = \sqrt{\frac{2\pi\lambda\rho c}{p}} \quad (10)$$

Where P represents a period of 24-hour cycle.

Generally, in materials having high density, high thermal conductivity is observed. Hence, such materials are classified to be good for heat storage. Furthermore, in steady-steady conditions, the value of admittance agrees with U-value. However, the meaning of admittance and U-value is different as explained in Petherbridge (1974): "Whereas thermal transmittance is the reciprocal of thermal resistance under steady state conditions (i.e. U = 1/R), admittance is the reciprocal of impedance under the corresponding cyclic conditions."

The concrete centre stated thermal admittance can be seen as a measure of thermal mass. However, it is well stated that it can be misleading if it is not used by intense care. When thermal admittance is compared with estimations obtained from more advanced modelling techniques, since these techniques uses the real climate data, using thermal admittance instead can result in biased results around 50% of underestimation of the actual peak cooling capacity (Saulles, 2009).

Calculation procedures of thermal admittance are described in CIBSE Guide A and British Standards 13786:2007 (BSI, 2007). The complete list of values of thermal transmittance, thermal admittance, decrement factor and surface factor are delivered in the CIBSE Guide A. By this way, thermal properties of these materials and their use in buildings are described in these guidelines. For instance, traditional bricks have admittance around 3W/m^{2}K and timber frame has an admittance of 0.75W/m^{2}K. Thermal dynamic properties including admittance, conductance and decrement factor values of commonly used walls in construction industry is illustrated in Table 2.7.

Table 2-7 Admittance, conductance and decrement factor of some common wall constructions (CIBSE, 2006)

Construction	Admittance (W/ m^{2}K)	Conductance (W/ m^{2}K)	Decrement factor
Dense concrete wall (19mm render, 50mm mineral wool insulation between battens, 200mm dense concrete block, 13mm dense plaster)	5.32	0.70	0.16
Solid brick with insulation (19mm render, 50mm EPS insulation, 200mm solid brick, 13mm dense plaster)	4.23	0.54	0.12
Brick and block cavity wall (105mm brick, 50mm EPS insulation, 100mm lightweight aggregate concrete block, 13mm dense plaster)	2.98	0.52	0.42
Precast concrete panel wall (80mm dense concrete, 50mm EPS insulation, 100mm dense concrete, 12.5mm plaster board)	2.61	0.56	0.17
Timber frame wall (105mm brick, 50mm airspace, 19mm plywood sheathing, 95mm mineral wool insulation between studs, 12.5mm plasterboard)	0.75	0.39	0.58

Heat flux predicted by both types of calculations namely; state steady calculations and dynamic calculations are followed a sine curve over time. However, in state steady calculations, the heat flux is also affected by changes occurred at external temperature. For this reason, time is delayed and the actual heat flux is resulted out of the phase. Although mass does not affect the mean heat flux at steady state condition, mass can affect the time lag by requiring more time for heat to be transferred to inner space when the mass of the material is high.

For the reasons explained so far, it can be concluded that taking thermal mass into account results in decrease in the change of heat flux through the wall. On the other hand, the capability of thermal mass enables arranging of maximum and minimum temperatures by altering the heat flux through the wall.

Childs, Courville and Bales, 1983 are generated an estimation to evaluate the parameter of heat flux amplitude ratio. This parameter is based on greatest heat flux and time lag.

Parameter of heat flux amplitude ratio; $[(L^2) / (\alpha /P)]^{1/2}$ (11)

Where:
L= thickness of material (m)
α= thermal diffusivity (m^2/s)
P= time period for one cycle (s)

Parameter showing the dependency between some wall properties and the heat flux amplitude ratio as proposed by Childs, Courville and Bales (1983)

$[(R\rho cL) / P]^{1/2}$ or $[(\rho cL) / (UP)]^{1/2}$ (12)

Where:
R= resistance (m^2 °C/W)
U= conductance (W/m^2 °C)
ρ= density of material (kg/m3)
c= Specific heat capacity of material (kJ/kg°C)
L= thickness of material (m)
P= time period for one cycle (s)

Total heat flux is formed from two components. The heat flux at the first component is calculated by using steady state equations where the heat flux is only dependent on U-value and not on the thermal mass. On the other hand, at the second component where the heat flux is changing, the heat flux is affected from thermal mass and hence calculated by using dynamic heat flux equations. Overall, the total heat flux over a cycle is affected from U-value only and not from thermal mass whereas the peak heat flux and time lag is affected from both U-value and thermal mass.

The relationship between the properties of the wall and the heat flux amplitude ratio is expressed in Equation 2.13. From this equation, it can be stated that the product of pcL is negatively proportional to U-value. This means that when an increase of one unit in the product of pcL is compared with a decrease of one unit in U-value, the effect will be the same on the heat flux amplitude ratio. Although both ways result in the same influence on the heat flux amplitude ratio, a decrease in the U-value will trim down the maximum heat flux while an increase in the product of ρcL will not have this effect. Thus, when the effects of U-value and thermal mass on the maximum heat flux are compared, it is concluded that U-value has a greater influence then thermal mass.

Negative relationship between the product of ρc and thermal diffusivity is stated. This means that when a material has a low value of product of ρc, this material will have high thermal diffusivity. However, at the same time, a low value of the product of ρc will not result in higher capacity to keep heat of the material. Hence, in order to look at the speed of the heat's penetration in the wall, a better measure should be considered. A better indicator that is the product of λρc is considered which is known as **Thermal Penetration** [J/m^{2}°C]. In real cases, temperature of the inner surface increases after the heat is absorbed by the surface and followed by a decrease to maintain the temperature at the original state. This process is explained that, the transformation of heat energy is following a wave curve with decreasing amplitude over time. Thus, the concept of thermal penetration is vital to be considered.

It can also be defined that the material should be subject to radiant or convective heat energy until the maximum energy storage limit is obtained. The reason for this is to gain the greatest advantage from building's thermal mass. After the energy storage limit is achieved, the heat energy recuperated from the inner space of the material or released to the environment. The ideal temperature to apply this process is in totally passive form is when large diurnal temperature differences are observed. If the temperature difference between night and day times is very large, then the stored heat is released by using night time ventilation.

During the transformation of heat energy through the wall; Time lag should be taken into account in daily cases because having a large time lag limit can be made difficult to apply thermal mass. In cases when the time lag is more than 12 hours, transformation of heat energy to the inner space continues while there is no space to take more heat energy in. For this reason, thermal mass overwhelm with the heat. This can be unfavourable in winter period since the continuous heat intake result in requiring longer time periods to heat the space. On the other hand, over heating is not observed since a very small amount of excess heat is released to cause air temperature to rise. This means that the energy balance of the whole building should be taken into consideration very carefully.

2.4 Use of Different Types of Cements and Recycled Coarse Aggregate in the Building Concrete

In this section, different types of construction materials such as GGBS, PFA, SF and also RCA were explained. Different types of cements and Recycled coarse aggregate are used with some parameters and conditions such as types of aggregate, water cement ratio [W/C], moisture content and temperature to determine the effects of Thermal Mass on concrete. The following review summarises findings of some researches such as Steiger and Hurd (1978), Ramazan Demirboga (2003) and X.Fu, D.D. L Chung (1997), which are used to illustrate how these parameters affect the effectiveness of thermal mass of the concrete mixes.

2.4.1 Use of Different Types of Cements

The establishment of Portland cement went back to 19th century and at today's world, this cement material became the vital part of the concrete. As well as this, there are some other materials known as supplementary cementitious materials, mineral admixtures or additions that are used instead of proportion of Portland cement in concrete mixes. Binary cements are the mixtures containing only one type of supplementary cementitious beside of Portland cement whereas blended cements are the mixtures containing one or more type of supplementary cementitious beside of Portland cement. Blended cements are also known as composite cements or combination cements.

Pozzolanas can be either natural materials obtained from resources such as volcanish ash and pumice or can be artificial materials obtained from resources such as PFA, silica fume and blastfurnace slug which they have been widely applied as supplementary cementitious materials. Pozzolanas can be classified as cementitious material if and only if they are presented in latent form. Otherwise, if pozzolanas are used in alternative forms, they will have no or little cementitious value. By this way, if pozzolanas are used without converted, they do not add any strength to the concrete when mixtures with water. However, when pozzolanas are converted to finely divided form, then they can add strength to the concrete by reacting with calcium hydroxide when there is an existence of moisture.

Nowadays, finely divided pozzolanas are used to replace Portland cement due to the economic reasons. Since, Portland cement is expensive, if part of the Portland cement can be replaced by other materials such as pozzolanas, then the cost of the production of the concrete will be reduced. Beside of this reason, the amount of energy required to process Portland cement is very high and hence, the damage caused to the environment is huge.

There are two main reasons for this huge environmental damage. One is due to the consumption of large amounts of natural raw materials that produces lots of greenhouse gases and the other is removal of industrial waste materials such as PFA, silica fume or ground granulated blast furnace. Whereas, pozzolanas are widely and readily available without requiring large amount of energy for processing. Therefore, pozzolanas are used in the manufacturing of concrete and can be used to achieve greater performance concrete if the right amounts are used in concrete mixes.

2.4.1.1 Pulverised Fly Ash (PFA)

United Kingdom Quality Ash Association (UKQAA) (2004) described PFA as a by-product that is solid and can be achieved at power stations. PFA is produced when electrostatic and mechanical means from flue gasses of furnaces are discharged with pulverised bituminous coal. This process is carried out by exhaust gases and as a result of this process, fly ash is produced as fine particles.

In order to generate electricity at power stations, coal is used as a fuel. When this coal is fired, steam is produced from coal, and then this steam is used in a turbine to create electricity. During the process of fire to obtain steam from coal, by-product called fly ash is achieved. In the UK, the main combustion method used is pulverised coal combustion. Therefore, fly ash can also be called as pulverised fuel ash.

In this combustion type, firstly, the coal that is crushed into very finite particles is burnt, and then these burnt particles are moved to the boiler furnace with the aid of air. After that, the finite coal particles burnt in 3-4 seconds in the boiler furnace to result in ash. These ash particles are then moved to the furnace part via flue gases. While this processes of movement carried out, the ash particles are started to cool down.

By this way, those ash particles are formed a solid substance that are carried by combustion gases. Finally, fly ash content is released from flue gases using electro-statically precipitators. Fly ash obtained from this process can be used either directly in concrete mixes or can be sorted if it is mixed with water up to 18% to form conditional form of fly ash. Transportation is also easier if the fly ash is in the conditional form.

The properties of ash are different if the ash is obtained from pulverised fuel combustion or it is obtained from other types of combustion. The reason of coal grinding process in the production of PFA is to give PFA fine particles of a reasonable consistent size. Beside of this, usage of combustion in high temperature is to discharge and abolish the hydrocarbons and the ash before the formation of PFA as a solid substance.

This production procedure is followed over the years. However, environmental concerns increase on reduction of gaseous emissions at power stations. The developments to reduce the gas emissions have not affected the way that PFA is generated. Only a small increase on loss on ignition (LOI) is observed. The developments to decrease the gas emissions include using low NO_x burners, flue gas de-sulfuration and developed combustion efficiency. PFA has been applied for a wide range of applications in construction. For instance, due to technical, economic and environmental reasons, PFA is extensively to be used in concrete in the UK concrete industry.

BS EN 450-1 (2012) explained that fly ash is a fine powder containing spherical, glassy particles and generated from firing pulverised coal. Pulverised coal can contain co-combustion materials in this process. When the pulverised coal is burnt alone or together with co-combustion materials, this process enables the fly ash to have pozzolanic properties and to contain mainly SiO_2 and Al_2O_3.

Hydration of cement is formed from hydrated calcium silicate and calcium hydroxide. The key constituent in this mix is SiO2. CSH is formed when glassy amorphous forms of silica, alumina and iron that are found in PFA are mixed together and joined with calcium hydroxide and other soluble alkalis such as potassium. When all PFA is mixed with other materials, pozzolanic properties of PFA cannot be observed straight after. This is due to chemical reaction of glassy material on PFA only starts to form when the pH of water goes above 13.2. By this way, alkalinity of water is increased and hence, hydration of Portland cement started to form. This reaction is more rapid at the surface of the material where the particles act as nuclei. However, when the pH is increased to the appropriate level, reaction of PFA particles started and hence more particles started to diffuse away. This results in decrease in capillary porosity and therefore finer pore structure. Since reaction of molecules in PFA is occurring slowly, prolonged wet curing is needed and therefore, curing is more effective on PFA concrete compared against PC concrete.

2.4.1.2 Ground Granulated Blast furnace Slag (GGBS)

GGBS is a type of by-product and this product is achieved when the iron is produced in the blast furnace. Since GGBS is widely available in enormous quantities, it is appropriate to use in ready-mix concretes, in the manufacturing of site batched concrete and in precast production. Ironore, coke and limestone are mixed in the right proportion in blast furnace at 2000 degrees. At this process, iron ore is converted to iron and then, it drops to the bottom of the blast furnace. The slag is then reduced in large volume of water quickly. The procedure of slaking improves properties of cementitious materials and generate granules. These granules are similar to coarse sand particles. GGBS is then formed as a result the process of grounding to fine power of dried granulated slag. GGBS is a white-coloured material with the bulk density being 1200 kg/m^3. Jones (2011) suggested that GGBS was first produced in Germany in 1865 and nowadays, more than 200 million tonnes of GGBS material are used per year around the world.

According to BS EN 197-1 (2011) when the melted slag is cooled speedily, granulated blast furnace slag is generated. While around two third of the proportion of Granulated furnace slag contains calcium oxide, magnesium oxide and silicon dioxide together, the other one third contains aluminium oxide with other small compounds. The ratio of sum of calcium oxide and magnesium oxide relative to silicon dioxide should be greater than one. GGBS is then created by finely crushing this granulated blast furnace slag.

2.4.1.3 Silica Fume

Microsilica or condensed silica fume are alternative names to silica fume. Silica fume is also a by-product that is produced from silicon and ferrosilicon in electric furnaces. Silicon and ferrosilicon are mixes obtained from high puity quartz and coal. These materials are used in variety of places such as in the manufacturing of aluminium, steel, computer chips and silicones.

During the blending of silicon and ferrosilicon, high quartz is reduced in the electric furnaces and hence the outflow of SiO gas is used to produce silica fume. The SiO gas that has leaked combined with oxygen in the air and the resultant molecules condense to form a fine particle which is called silicon dioxide (SiO_2). This molecule models the largest part of the smoke or fume from furnace. The thinness of silica fume causes silica fume to have low bulk density (200-300 kg/m^3) and hence this increase the difficulty and cost of handling of silica fume (ACI 234 R Guide, 2006).

Therefore, silica fume is either provided in densified form or in the form of slurry (EN 13263-1). Densified silica fume is formed from micropellets that are agglomerates of the distinct particles which are generated from aeration. By this way, the bulk density of densified silica fume is around 500-700 kg/m^3 which is greater than undensified silica fume. On the other hand, slurry contains same proportion of water and silica fume by mass. The bulk density of silica fume in the form of slurry is normally between 1300 to 1400 kg/m^3 (ACI 234 R Guide, 2006).

Silica fume particles are generally very small being less than 1 μm in 95% of particles. According to ACI 234 R Guide (2006) for the applying of Silica Fume in Concrete, it is estimated that when 15% of the cement is replaced with silica fume material, around 2000000 particles of silica fume are present for each grain of Portland cement. Physical and chemical properties of silica fume in concrete are mainly occurred depending on particle size and having high silicon dioxide content (>85%) of silica fume.

When silica fume contains high amorphous silicon dioxide SiO_2, the chemical properties of silica fume will include very reactive pozzolan materials. When the Portland cement starts to react, the discharge of calcium hydroxide is obtained. CSH is then formed when this calcium hydroxide reacts with silica fume. CSH develops the hardened properties of the silica fume concretes.

When silica fume reacts with calcium hydroxide, silica fume dissolves in few minutes and immediately after the water is saturated with calcium hydroxide, on top of the silica fume particles CSH is started to form. This process has a high speed. For instance, if silica fume consist of 10% of the total mass of the concrete material, this means that around one half of the silica fume reacts in 1 day, whereas two thirds reacts in 3 days and the rest of the silica fume is observed to react slowly such as three quarters reacting in 90 days.

2.4.2 Use of Recycled Coarse Aggregate

The most important constituent in a concrete when volume is concerned is aggregates and therefore these aggregates have substantial influences on engineering properties as well as having major consequences on the final cost of concrete mixtures. Furthermore, increase in demand in construction industry have resulted in reduction in available natural resources to be used in construction if such buildings. For instance, the amount of natural resources used in construction industry is greater than 165 million tonnes per year. On the other hand, around 109 million tonnes of demolition are created per year in the UK. Out of this figure of excesses from destruction, 60 million tonnes are generated from concrete. This value also shows that the main material used in the construction of buildings is still concrete and additionally, the feature of the concrete to absorb natural mineral resources have increased the significance of recycling rubble concrete. Using recycling rubble concrete maintain natural resources and replacing proportion of the aggregate by the destroyed concrete disregard the requirement of disposal. The greater the proportion of aggregates replaced by recycled materials, the more sustainable the concrete is. As well as this, such usage can also minimize the discharge of the amount of carbon-dioxide and reduces the energy consumption in the production of concrete. As a conclusion, since extracting of virgin aggregates causes vast damage to environment and beside of this need huge amount of energy in the process of extraction and crushing, the popularity of using recycled aggregates obtained from demolished constructions instead of natural aggregates have been increasing. (Mukesh Limbachiya, 2012).

Primary and recycled crushers and screens from such demolishes are used to decrease the size of the remained concretes to have maximum 0.4m size. At this process, hydraulic shears might be used to cut the steel reinforcement. If it is required. After that, the material is pressed in a primary jar grinder. This is done in order to generate rubbles that are maximum 75mm in size. The rubbles obtained are then carried down under an electromagnet. The purpose of this is to get rid of any remain reinforcement that are gathered in to the recycled material. Finally, after all these procedures, rubbles that are remaining displayed via sequence of appropriate monitors.

At the primary display, materials that are fine as like dirt and gypsum are detached and stored, so that they can be recycled to be used for alternative purposes. After that, the material which does not contain any dirt is distracted on a conveyor belt in order to be removed manually. Furthermore, in order to decrease the size of the cleaned concrete remainder, remain concrete is transported to the secondary cone presser. This will allow to control the size of remain concrete at maximum 20mm. The next step is to take away the final materials by the aid of air separation unit. Finally, the material is then displayed into different size proportions such as; 20-10 mm, 10-5mm, and <5mm. The main purpose of this separation of the final material to various size fractions is to provide a clean and properly graded RCA.

The information about using the maximum amount of recycled aggregate in a concrete is started to be recognized by both national and international standard bodies. For instance, at 1st June 2005, BS 882 (Specification for aggregates from natural sources of concrete) is changed with EN 12620-1 (aggregate for concrete).

While, obligations that are needed for the excellence and categorization of aggregates used in concrete are expressed in BS 882, EN 12620 described the possessions of aggregates and filler aggregates that is used in concrete which are achieved from natural, manufactured or recycled materials and mixtures of all of the aggregate types used in the manufacturing of concrete.

Consumption of recycled aggregate in concrete are described in BS 8500-2 in clause 4.3. At this standard, two different groups of recycled aggregates are classified namely:

- Recycled Concrete Aggregate (RCA) which mainly contains crushed concrete and
- Recycled Aggregate (RA) that consist greater amount of masonry

RA can only be used in concretes which have a maximum strength of C16/20. These classes of concretes contain concretes that have same properties of cube strength of 20 N/mm^2. RA is also limited to be used on only slightly coverage situations. Whereas, RCA can be used in concretes having maximum strength of C40/50 only in the mildest exposure conditions. These classes of concretes contain concretes that have the same properties of cube strength of 50 N/mm^2. RCA can also be used in broader range of coverage situations compared against RA. Usually, if the concrete is exposed to conditions such as sea water or de-icing salts or severe freezing or thawing or in extremely aggressive ground, then RCA is not authorised to be used in such concretes.

2.4.3 Effects of Different Types of Cements and Recycled Coarse aggregate on The Thermal Properties of Concrete

2.4.3.1 Effects of different types of Cements on Thermal Properties of Concrete

D.D.L. Chung (2002) state that replacing cement by silica fume is found to reduce the density of the concrete. If the silica fume added is raw material, then this increases the specific heat capacity of the concrete. Y.Xu. D.D.L. Chung (2002) suggest that when silica fume is included in cement, this results in decrease in thermal diffusivity as well as increase in specific heat capacity and further decrease the thermal conductivity.

The thermal conductivity of water is 25% more than the thermal conductivity of air. For this reason, when the small holes in the air are replaced with water or moisture, this results in increasing thermal conductivity. Steiger and Hurd (1978) suggested that water absorption causes the weight of the concrete to increase by 1% per unit weight and hence results in 5% rise in thermal conductivity. Higher the cement content exists in the concrete, the higher the thermal conductivity resulted. At the same time, thermal conductivity of the concrete gets higher if the aggregate used in concrete have higher thermal conductivity. For instance, if SF is used as an aggregate, this reduces the thermal conductivity but increased the specific heat capacity of the concrete.

For instance, it is reported that thermal conductivity of crystalline silica is around 15 times greater than thermal conductivity of amorphous. Therefore, concrete containing crystalline silica have less thermal conductivity than concretes containing amorphous. If amorphous silica is used as a compound in the generation of the concrete, it can be used to reduce the thermal conductivity. The main purpose of using admixtures such as SF in making the concrete is to lower the speed of hydration, develop the mechanical properties of the concrete, reduce the reactivity of alkali aggregate and decrease the permeability of concrete.

However, the impact of each admixture on thermal conductivity is different and should be investigated separately. Ramazan Demirboga (2003) found out that SF is the factor to have caused a decline in thermal conductivity. When the Portland cement is replaced by SF, the higher the percentage of cement replaced, the lower the thermal conductivity achieved. This is because replacing cement by SF reduces the density of the concrete content. Hence reduction of density of the concrete causes a decline in thermal conductivity.

Such decrease is also reported to suggest that there is an association between density and thermal conductivity where the thermal conductivity increases as the density gets larger. Usually Portland cement is replaced by SF or at 10, 20 or 30%. It can also be stated that the highest decline of thermal conductivity is achieved at highest rate when the Portland cement is replaced by SF at 30%. (Gul *et al.*, Akman Tasdemir *et al.* Lu-Shu *et al.*)

X.Fu, D.D. L Chung (1997) state that when 15% of Portland cement is replaced by SF, it can decrease in thermal conductivity up to 46%. Addition of further SF content improves the decline of thermal conductivity. The differences in the percentage reductions can be explained by being exposed to different testing conditions and moisture contents.

2.4.3.2 Effects of Types of Aggregate on Thermal Properties of Concrete

Kook-Han Kim et al (2002) clarified that when the volume of all parameters are kept same, exposing the specimen to different temperatures such as 20, 40 and 60 degrees, resulted increase in the volume of fraction of aggregates from 0 to 0.71. During this process, moisture content is either wet or completely dry. When the volume of fraction of aggregates increases, after a certain point, the temperature where the same is exposed or the moisture content of the specimen does not make any difference in terms of effect in thermal conductivity. At such cases, linear increase is obtained in thermal conductivity. Therefore, concretes containing large amounts of aggregates have higher thermal conductivity.

Kook-Han Kim et al (2002) described an alternative method of measuring thermal conductivity by separating fine aggregate fractions from the total aggregates. This study is carried out on four sets of materials where the results are reported for each set. It is concluded from the results that only slight increase is observed by using larger amount of aggregate fractions. This is explained by the fact that fine aggregate has a greater thermal conductivity relative to the coarse aggregate. When the fine aggregate is added to the concrete mix, this can cause the aggregate in the mix to be distributed evenly and this can be the alternative reason. This research is shown how the aggregates are affected the thermal conductivity. This is the reason that thermal conductivity is one of the main factor of the thermal mass of the concrete.

Yunsheng Xu and D.D.L Chung (2000) compared the inclusion of sand against silica fume and conclude that lower values of specific heat capacity and greater values of thermal conductivity can be obtained when sand is used instead of silica fume. Sand has larger particle size compared to silica fume. Therefore, sand has lower interface area relative to silica fume and hence the diffusion through the border is easier for silica fume than sand.

Properties of sand; having low specific heat capacity and high thermal conductivity can be due to small interface area because slippage at the interface effects the specific heat and as well as this, this interface corresponds as a thermal barrier. When SF is added in the cement content, this increases the specific heat capacity of the specimen by 7%. On the other hand, including sand in the cement mix reduces the specific heat capacity by 13%. Beside of this, SF and sand had reverse effects on thermal conductivity as well.

For instance, addition of SF reduces thermal conductivity by 38% and inclusion of sand increases the thermal conductivity by 22%. The opposite effect of SF and sand is primarily based on having smaller interface area for sand and vice versa for silica fume. When the properties of sand are compared with silica fume, high reactivity of silica fume can be seen as a factor that generates the difference in the effect of adding sand or silica fume together.

However, relativity should not be a main property in consideration because relativity improves the interface, making the interface to be stronger and hence resulting reduction of specific heat capacity. This contrasts with the observed influences. When sand is included in the mix to replace proportion of cement, both the reason for reduction of heat capacity and increase in thermal conductivity are explained to be having greater homogeneity in sand particles compared against within cement paste. The highest factor that affects the thermal conductivity is the type of the aggregates.

K.J.Mun (2006) reported the thermal conductivity to be between 0.593-0.7333 W/m.K in their study. In lightweight aggregate with the highest mixing ratio of sludge, production of internally calorific organic materials and gas creates increase in maximum porosity levels and hence this causes decline in thermal conductivity. Thus, lowest thermal conductivity is achieved in lightweight concrete with highest mixing ratio of the sludge. However, if only the crushed stones are used in the mix, then the thermal conductivity is reported between 1.50-1.60 W/m.K. The benefit of using lightweight aggregates such as sewage sludge over the ordinary concrete is the capability of lightweight aggregate to make the insulation effect stronger than ordinary concrete. The specific heat capacity of the concrete is defined as the quantitative heat energy stored in that concrete. The amount of heat stored in the concrete is based on the mass of the material and also the characteristics of the material. Even if the thermal conductivity of two materials are same such as fine aggregate and coarse aggregate, the amount of heat stored is different. Since fine aggregate has lower mass and size, specific heat capacity is lower in fine aggregate when assessed against coarse aggregate. If the value of specific heat capacity is multiplied by density, then volume heat capacity (VHC) is obtained.

2.4.3.3 Effects of Water Cement Ratio on Thermal Properties of Concrete

The water cement ratio is important for thermal properties of the concrete. Since water/cement ratio directly affects thermal performance of the concrete. low water cement ratio resulted for the concrete to be denser. For instance. Kook-Hand Kim et al (2002) suggest the reason for thermal performance being affected by W/C ratio as the quantity of the aggregates in the concrete mix. According to Kook-Hand Kim et al (2002). the amount of aggregates should be added to the concrete mix based on the amount of cement in the mix. When the amount of cement is increased and hence low W/C ratio is obtained. the thermal conductivity of the concrete increases. This is due to the feature of the cement that is having higher thermal conductivity value then water. On the other hand. decreasing the amount of water. decreases the specific heat capacity of concrete and the reason for this is water having a greater specific heat capacity value than cement. The other researchers Renga Rao Krishnamoorthy and Juvinia Augustine Zujip (2013) found that thermal increase in thermal conductivity is obtained when reduce water cement ratio is used and this is explained due to cement having greater thermal conductivity compared to water.

2.4.3.4 Effects of Moisture Content on Thermal Properties of Concrete

Kook-Han Kim et al (2002) suggested that when all materials in the cement paste are considered. the main affecting factor is found to be moisture state. Thermal conductivity is decreased hugely when the moisture state is changed from saturated to fully dry. The reason for this huge variation is when the concrete is fully saturated. air voids filled with water and that makes the thermal conductivity to be greater than the thermal conductivity of the air. It is also important to forecast the moisture content all over the concrete.

When the thermal conductivity of water is compared with thermal conductivity of air. it can be concluded that since thermal conductivity of water is 25 times greater than thermal conductivity of air, the thermal conductivity is resulted as higher values in saturated condition than dry condition. Steiger and Hurd (1978) stated that water absorption increases the one unit weight of the concrete by 1% and hence thermal conductivity of the sample increased by 5%. M.I. Khan (2001) explained that when rocks are compared, higher speed of increase in thermal conductivity is achieved for the ones having high absorption proportions with maximum saturation state relative to the ones at the dry state.

For instance, siltstone having the absorption of 1.99% proved that thermal conductivity is increased around 48% more when it is at maximum saturation condition, the increase in thermal conductivity will be small relative to dry condition. For instance, basalt and quartzite have absorption rates 0.4% and 0.3% respectively. The difference in the increase in thermal conductivity they create at maximum saturation is 0.65% and 0.60% respectively relative to dry condition.

Table 2-8 Physical properties of Portland cement and types of aggregate (M.I. Khan, 2001)

Material	Specific Gravity	Absorption (%)
Ordinary Portland cement	3.15	-
Sand type I	2.69	5.20
Sand type II	2.70	4.70
Basalt	2.70	0.30
Limestone	2.69	0.80
Siltstone	2.66	1.83
Quartize	2.67	0.25

Table 2-9 Thermal conductivity of the rocks in dry and saturated states (M.I. Khan, 2001)

Type of concrete	Thermal conductivity (W/mK)	
	Dry	Fully Saturated
Basalt	4.03	4.30
Limestone	3.15	3.49
Siltstone	3.52	5.22
Quartize	8.58	8.63

The rate of increase in thermal conductivity increases as the moisture content increases. However, this rate of increase happens up to a point which is about 4.5% of moisture content by weight. After this point, the speed of increase in thermal conductivity started to decrease. When the increase in thermal conductivity is compared between the change of aggregate from the dry condition to 50% saturated condition and the change of aggregate from 50% saturated state to fully saturated state, it is reported that the thermal conductivity increases more while changed from dry to 50% saturate. Whereas the change from 50% saturated to fully saturated is found to be not significant (M.I. Khan, 2001).

2.4.3.5 Effects of Temperature on Thermal Properties of Concrete

Kook-Han Kim et al (2002) studied the impact of temperature on thermal conductivity of the concrete and samples of cleaned cement paste. From their study, it is concluded that there is a negative relationship between the temperature and thermal conductivity in both concrete samples and cement paste samples. This means that the higher the temperature of the sample, the lower the thermal conductivity of the specimen. Same conclusion is also reported by Morabito (1989). As well as considering specimen at temperatures above the room temperature is also important. For instance, in the cases of curing or recoding, moisture content of the sample will be lower due to the specimen losing water. Therefore, the density of the sample decreases in such situations than heating the sample.

When the temperature is low, the specific heat capacity increases as the moisture content rises. This pattern of increase in specific heat capacity continues until around 500 degrees and beyond this temperature, the specific heat capacity started to decrease until around 1000 degrees. Thermal diffusivity is defined by thermal properties of the concrete. For instance, aggregates that show an increase in thermal diffusivity are basalt, rhyolite, granite, limestone, dolerite and quartzite. Elements that affect the thermal conductivity of the concrete are found to have similar impact on thermal diffusivity of the concrete.

2.5 Summary of main findings

- The aim of the sustainability is to prevent the damages occurred in the environment. In terms of construction, concrete is found to be the most sustainable material. The reason for this is the ability of concrete to have less change to the environment when compared against steel. The embodied energy consists of 3% of the total energy in construction of the house where the lifecycle of the building is estimated to be around 100 years. On the other hand, embodied energy in commercial buildings is found to be between 5% to 15% of the total energy (The Concrete Centre, 2010). Cement is the important constituent material in the construction of concrete and to generate one tone of Portland cement, 4GJ of energy is needed. During the manufacturing, the process realize around 0.89% to 1.1% tone of carbon dioxide. Due to downsides of producing cement such as high energy requirement and lack in availability of minerals, cement is needed to be mixed with other materials such as silica fume, GBS and PFA. These products are called by products. In the UK, concrete industry have made agreements with Concrete Industry Sustainable Construction Strategy (CISCS) and the concept of the CISCS state that "By 2012, the UK concrete industry will be recognised as the leader in sustainable construction, by taking a dynamic role in delivering a sustainable built environment in a manner that is profitable, socially responsible and functions within environmental limits".
- In the buildings, thermal mass prevents the huge variations in the temperature inside the building in either heating or cooling direction. The ability of thermal mass to act as a buffer avoids the extreme conditions of maximum and minimum temperatures inside the building. By this way, the demand on extra heating or cooling is minimized and hence lowers the fuel consumption. Beside of this, carbon dioxide emission is reduced as well. To get the maximum benefit of thermal mass, the surface of the

material should be exposed to heat to permit heat transfer. The thicker the walls of internal environment, the greater the benefit obtained from thermal mass. Thermal mass generates energy savings based on climatic location and energy efficiency of the specific building. If the interest is to use higher energy saving systems, several factors such as the performance of the building materials, design and the effect of climate changes should be considered. In order to meet all the requirements, the whole building is needed to be designed in such a way to maximise the overall performance. The main parameter is materials of the building including the structure should be carefully considered. These issues arise specifically for the thermal mass in concrete and these issues are important challenges that are needed to be addressed.

- The approach of thermal mass is started to be used from the earliest days to provide fresh and more comfortable environment. Overheating in summer is a growing problem and using thermal mass can overwhelm this challenge by saving the energy. Every material has a different speed in conducting and storing this heat energy which is already absorbed. This speed is based on the properties of the material namely: conductivity, density and specific heat capacity. When thermal mass absorbs the additional heat from the space, this will decrease the temperature at the space and reduce the temperature difference between interior and exterior environments. By this way, change in heat flux while transferring though the wall is reduced. Hence, this will then move the time at which the minimum and maximum heat fluxes are observed. Subsequently, resulting a lower interior temperature difference move the time at which the peak temperature is achieved and this can also supply saving of energy for a HVAC system. The time delay can be described as time lag known in thermal mass. Thicker materials with having higher resistivity will be longer to conduct heat flux. Decrease in cyclical temperature at the interior surface when compared with exterior surface was described by decrement factor. Relationship between thermal mass and all other factors was complex. Therefore, it can be analysed in dynamic simulation software.

- Ramazan Demirboga and Rustem Gul (2002) stated that Low density of Light Weight Aggregate Concrete results in decrease in thermal conductivity of the concrete. When the SF content was increased in the dry condition of Lightweight Aggregate Concrete, this results in reducing unit weight of Lightweight Aggregate Concrete and hence the thermal conductivity. SF was the main component that results in the maximum decline of thermal conductivity. Yunshang Xu, D.D.L Chung (2000) explained that inclusion of sand was resulted a reduction in the specific heat capacity and also rise in the thermal conductivity of the concrete. This effect of sand was found to be the reverse effect resulted in inclusion of silica fume. Rise in thermal conductivity was observed to be higher when sand was added if the cement paste has already consisted silica fume. However, decline in thermal conductivity was achieved to be decreased when silica fume is added if the cement paste already consists of sand. The impacts mentioned here are related to the small area of the border among the sand and cement. This area among silica fume and cement was used as a large area to have the decreasing effect of thermal conductivity and to increase specific heat capacity of the concrete. Renga Rao Krishnamoorthy and Juvinia Augustine Zujip (2013) suggested that water cement ratio was a factor which influences thermal conductivity of the concrete. According to the results obtained, thermal conductivity was found to be increased when water cement ratio was decreased. The reason for this impact was the increase in aggregate content of the sample when the moisture was included in the cement paste.

3 Research Programme and Experimental Details

3.1 Introduction

This chapter briefly outlines the experimental programme devised to meet the research objectives. This chapter is divided into two main sections; the first section covers the phases of the programme of work, whilst description on experimental work including materials used, mix proportions, preparation of specimens and testing procedures used are covered in the second section.

3.2 Overall Research Programme

The research programme is divided into three main phases; Phase 1, 2, 3 and 4 are shown in Figure 3.1. There are four briefly described below. The main part of the research programme looks at the thermal properties of concrete such as thermal conductivity, specific heat capacity and density.

Phase 1: Aggregate Characterisation

The physical properties of aggregates tests were done. Such as particle size distribution (BS EN 933-2 (1996) and BS EN 933 Part 1 (1997)), particle density (BS EN 1097-6(2000), BS EN 932-1(1997), water absorption (BS EN 932-2(1999)), and moisture content (BS 812: Part 109) tests were determined.

Phase 2: Fresh Properties

The main aim was to measure the workability for the concrete mixes using Slump (EN 12350-2 (2009)) and compacting factor (BS 1881: Part 103) tests were done.

Phase 3: Hardened Properties

The hardened properties included compressive strength (EN 12390-3 (2009)) such as cube (100x100x100mm), cylinder (150x300mm) and flexural strength (EN 12390-5 (2009)) such as beam (100x100x500mm) were tested at 7 and 28 day.

Phase 4: Thermal Properties

The thermal properties were main research applications which it is included thermal conductivity (BS EN ISO 8990:1996 and BS EN 1934: 1998) such as slab (75x300x300mm), specific heat capacity such as cube (70x70x70mm) and density (BS EN 12390-7, 1097-6) such as cube (100x100x100mm) were tested at 28 day.

Figure 3-1 The Research Programme

3.3 Mix Proportions

Throughout the research experiments, the CEMI concrete mixes were designed following steps described in BRE mix design procedure (Building Research Establishment, 1997). Concrete mixes were proportioned using different proportion of PFA, GGBS, SF and RCA, as replacement of PC and coarse aggregate respectively. In total, 28 concrete mixes were cast in three different groups namely: Group A, B, C. The 28-day characteristic strength concrete mixes in Group A and B were designed as class C40, whilst design characteristic strength of Group C was class C50. These concrete strength were selected as they commonly adopted in the practice for commercial, residential and multi-storey buildings concrete structure (floors, walls and columns) constructions.

All of the concrete mixes in Group A were designed by containing only 100% natural aggregate content with CEMI cement. On the other hand, all Group B concrete mixes were proportioned using 30% RCA as direct replacement of natural aggregate. In Group C concrete mixes were designed to have minimizing water-cement ratio. The main aim is to understand the effect on thermal properties when minimized the water in the concrete mixes. In this group, from the 8 mixes, 4 mixes are designed to have 100% natural aggregate content as like in Group A and the other 4 mixes are designed to have 70% natural aggregate plus 30% RCA content as like in Group B. Table 3.1 is shown the mix proportion of all group mixes.

According to British Standard, the percentages of different types of cements were used in the concrete mixes. For instance, PFA is up to 30 %, GGBS is up to 65% and SF is up to 20% replaced in the concrete mixes. However, British Standard gives permission to use up to 15 % added silica fume in the concrete. The main reason of using 20% silica fume content is to understand the effects on thermal properties more clearly. On the other hand, RCA was applied 30% in the concrete mixes. However, British Standard allows using 20% in the concrete. The main aim for this is applying RCA material more in the building structures confirming to EN 132631-1 by mass combined in the concrete mixer as per BS 850.

Table 3-1 Mix proportion of all group mixes

Mix No.	Description	Constituent Materials Kg/m^3									
		Coarse Aggregate			Types of Cements				Water (Kg)	FA/CA	W/C
		FA	NA	RCA		PFA	GGBS	PC			
A1	100%PC + 100%NA	586	1240	-	195	-	-	345	195	0.57	0.57
A2	45%GGBS+ 100%NA	586	1240	-	195	-	155	190	195	0.57	0.57
A3	55%GGBS+100%NA	586	1240	-	195	-	190	155	195	0.57	0.57
A4	65%GGBS+100%NA	586	1240	-	195	-	225	120	195	0.57	0.57
A5	10%PFA+100%NA	586	1235	-	185	32	-	315	185	0.53	0.53
A6	20%PFA+100%NA	580	1222	-	185	60	-	295	185	0.49	0.49
A7	30%PFA+100%NA	575	1190	-	185	82	-	272	185	0.45	0.45
A8	10%SF+100%NA	586	1240	-	195	-	-	310	195	0.57	0.57
A9	15%SF+100%NA	586	1240	-	195	-	-	293	195	0.57	0.57
A10	20%SF+100%NA	586	1240	-	195	-	-	275	195	0.57	0.57
B1	100%PC + 70%NA+30%RCA	597	850	365	204	-	-	345	204	0.59	0.59
B2	55%PC+45%GGBS + 70%NA+30%RCA	597	850	365	204	-	155	190	204	0.59	0.59
B3	45%PC+55%GGBS + 70%NA+30%RCA	597	850	365	204	-	190	155	204	0.59	0.59
B4	35%PC+65%GGBS + 70%NA+30%RCA	597	850	365	204	-	225	120	204	0.59	0.59
B5	90%PC+10%PFA + 70%NA+30%RCA	597	850	365	194	32	-	315	194	0.55	0.55
B6	80%PC+20%PFA + 70%NA+30%RCA	593	845	360	189	60	-	295	189	0.51	0.51
B7	70%PC+30%PFA + 70%NA+30%RCA	587	835	358	184	82	-	272	184	0.47	0.47
B8	90%PC+10%SF + 70%NA+30%RCA	597	850	365	204	-	-	310	204	0.59	0.59
B9	85%PC+15%SF + 70%NA+30%RCA	597	850	365	204	-	-	293	204	0.59	0.59
B10	80%PC+20%SF + 70%NA+30%RCA	597	850	365	204	-	-	275	204	0.59	0.59
C1	100%PC + 100%NA	460	1150	-	195	-	-	557	195	0.35	0.35
C2	45%GGBS+ 100%NA	460	1150	-	195	-	306	251	195	0.35	0.35
C3	20%PFA+100%NA	451	1132	-	180	120	-	478	180	0.30	0.30
C4	20%SF+100%NA	460	1150	-	195	-	-	501	195	0.35	0.35
C5	100%PC + 70%NA+30%RCA	448	786	337	204	-	-	583	204	0.35	0.35
C6	55%PC+45%GGBS + 70%NA+30%RCA	448	786	337	204	-	262	321	204	0.35	0.35
C7	80%PC+20%PFA + 70%NA+30%RCA	440	772	331	190	126	-	502	190	0.30	0.30
C8	80%PC+20%SF + 70%NA+30%RCA	448	786	337	204	-	-	466	204	0.35	0.35

3.4 Experimental Details

3.4.1 Materials

3.4.1.1 Cement

Portland cement (PC) used in this research is selected based on BS EN 19701 (2011) and this cement is categorized as CEM-I. The quantity of the cement is bought in the amount that is required for the tests, so that long term storage is prevented. In this way, the possible contact of cement with humidity is minimized. Beside of this, bought cement is stored in a laboratory environment for the same reason. Tables 3.2 and 3.3 show the physical and chemic properties of Portland cement respectively. Lafarge is supplier of the Portland cement.

Table 3-1 Physical properties of Portland cement

Physical properties of Portland cement	
Surface Area	300-450 m^2/kg
Setting time initial	80-200 minutes
Apparent particle density	3080-3180 kg/m^3
Bulk Density Aerated	100-1300 kg/m^3
Settled	1300-1450 kg/m^3

Table 3-2 Chemical Properties of Portland cement

Chemical properties of Portland Cement	
Sulphate	3 %
Chloride	0.07 %
Alkali	0.8 %
Tricalcium silicate	53 %
Dicalcium Silicate	28.7 %
Tricalcium Aluminate	10 %
Tetracalcium Aluminofferite	8 %
CaO	65 %
SiO_2	20 %
Al_2O_3	5 %
MgO	1 %
Fe_2O_3	2 %

3.4.1.2 Pulverised Fly Ash (PFA)

PFA is used according to BS-EN 450-1 (2012). PFA is used as the second component in the concrete production in addition to cement. PFA used in this research that is the most common type of PFA used in the UK is classified as CEM IV according to BS EN 197-1 (2011). Tables 3.6 and 3.7 show the physical and chemical properties of PFA respectively. CEMEX is the supplier of PFA material.

Table 3-3 Physical properties of Pulverised Fuel Ash

Physical properties of Pulverised Fuel Ash	
Odour	Virtually None
Particle Density (Specific Gravity)	1.8 to 2.4
Solubility in water	Less than 2 %
Bulk Density (g/cm^3)	1.1 to 1.7
Alkalinity – Ph	9 to 12 when damp
Dielectric Constant	1.9 – 2.6

Table 3-4 Chemical properties of Pulverised Fuel Ash

Chemical properties of Pulverised Fuel Ash	
Component	Typical % by weight
SiO_2 (%)	59
Al_2O_3 (%)	21
Fe_2O_3 (%)	3.70
CaO (%)	6.90
MgO (%)	1.40
Na_2O (%)	3
K_2O (%)	0.90
TiO_2 (%)	0.9
SO_3 (%)	1
Cl	0.1

The PC/PFA cement was used in this research project was a combination of CEMI PC confirming to BS EN 197-1(2011) and up to 30% PFA confirming to EN 132631-1 by mass combined in the concrete mixer as per BS 8500.

3.4.1.3 Ground Granulated Blast furnace Slag (GGBS)

GGBS used in the research was based on BS EN 15167-1 (2006). GGBS can be easily found in the UK and classified as CEM III according to BS EN 197-1 (2011). Tables 3.4 and 3.5 show the physical and chemical properties of GGBS respectively. Hanson is the supplier of GGBS material.

Table 3-5 Physical properties of Ground Granulated Blast furnace Slag (GGBS)

Physical properties of Ground Granulated Blast furnace Slag (GGBS)	
Fineness (m^2/kg)	450 – 550
Bulk Density (kg/ m^3)	1000 – 1100 (loose)
Relative density (Specific gravity)	2.9
Colour	Offwhite

Table 3-6 Chemical properties of Ground Granulated Blast furnace Slag (GGBS)

Chemical properties of Ground Granulated Blast furnace Slag (GGBS)	
CaO	40 %
SiO_2	35 %
Al_2O_3	12 %
MgO	10 %
Fe_2O_3	0.2 %

The PC/GGBS cement was used in this research project was a combination of CEM III PC confirming to BS EN 197-1(2011) and up to 65% GGBS confirming to EN 132631-1 by mass combined in the concrete mixer as per BS 8500.

3.4.1.4 Silica Fume (SF)

In this research, silica fume is used based on EN 13263-1 in a slurry format. Slurry form of silica fume is liquid containing 50% water and 50% silica fume powder. This slurry is stored in close-fitting containers, so that the contamination among slurry ad air is prevented. In this way, worsening of silica fume over time is minimized. The supplier of the silica fume is

Elkem Materials Process Service B.V. from Netherlands. The physical and chemical properties of Silica Fume are shown in Table 3.7 and 3.8 respectively.

Table 3-7 Physical properties of Silica Fume

Physical Properties of Silica Fume	
Specific gravity	2.22
Fineness (>45μm, %)	3-5
Specific surface (m^2/g)	15 to 35
Bulk Density (kg/m^3)	1320 to 1440
Surface Area (m^2/kg)	13000 to 30000

Table 3-8 Chemical properties of Silica Fume

Chemical properties of Silica Fume	
SiO_2 (%)	92.9
Al_2O_3 (%)	0.69
Fe_2O_3 (%)	1.25
CaO (%)	1.73
MgO (%)	0.4
Na_2O (%)	1.19
K_2O (%)	1.22
TiO_2 (%)	<0.01
SO_3 (%)	0.3-0.7
Loss on Ignition (%)	3.5

The PC/SF cement (CEM II/ A-D) was used in this research project was a combination of CEMI PC confirming to BS EN 197-1 (2011) and up to 15 % SF confirming to EN 132631-1 by mass combined in the concrete mixer as per BS 8500. And also applying 20% SF in the concrete.

3.5 Types of Aggregates

Generally, the type of aggregate as defined by BS EN 12620:2002 +A1:2008 comes in the form of natural, manufactured or re-cycled.

3.5.1 Fine Aggregates

In this research. fine aggregate used in the concrete mixes are based on BN EN 12620-1(2009) where it consist of graded natural sand with maximum particle sizes of 5 mm according to BS 882:1992.

3.5.2 Natural Coarse Aggregate

Throughout the research experiments. Thames valley natural aggregate was used in concrete mixes with the maximum size of 20 mm according to BS 882:1992.

3.5.3 Recycled Coarse Aggregate

RCA is obtained from managing the remained. unwanted concretes and from the concretes that will be destroyed. The proportional size of RCA was used as 20-5 mm. The Day Company is producer. RCA is included of crushed concrete. hydrated cement paste and also is dirtied with minor quantities of masonry. lightweight materials. gypsum. metals. plastics. glasses and other substances obtained from various sites within Greater London. According to Annex B of BS 8500 Part 2 [2006]. RCA sample were stated in Table 3.9.

Table 3-9 Typical component materials present in RCA and comparing with BS8500-2 limit.

Components present	Proportions mass %	BS 8500-2 maximum mass %
RCA & unbound aggregates	77	100
Masonry	10	100
Asphalt	9	10
Fines	2.6	3
Light weight material	0.5	1
Foreign materials [Metal, plastic. glass, wood]	0.9	1

3.6 Water

The tap water was used for the production of concrete mixes throughout the work

3.7 Superplasticiser (SP)

Superplasticiser is used in order to achieve the required workability. This material is taken from Grace Construction Ltd and it is classified as ADVA 655. It conforms to the requirements of BS EN 934 Part-3 (2009) as stated by supplier. Grace Ltd.

3.8 Aggregate Characterisation 3.8

3.8.1.1 Particle Size Distribution 3.8.1

The test sieves applied in this research conformed to the requirements as specified in BS EN 933-2 (1996). The grading was identified as the cumulative percentage passing by weight through the sieves as explained in BS EN 933 Part 1 (1997). In order to perform sieve analysis, a filter containing small holes is used to split the dry aggregate. Initially, proportion of dry aggregate is taken where the weight of this sample is known. Then, the aggregate is separated by gradually unlocking the small holes on the filter specified above. After the aggregate is split, the weight remained at each filter is evaluated and the result obtained from each sieve is weigh against the total weight of the aggregate. Hence, particle size distribution can be stated as a proportion of total weight remained at each sieve. Such results are presented in a table or on a graph. Particle Size Distribution test includes separating the aggregate into various particle sizes. Particles are separated in descending order in size through the sequences of filtering processes. The size of the holes and the number of filters are chosen depending on the feature of the sample and the requested accuracy. The amount of particles remained on different filters are based on the initial weight of the aggregate. The particles retained at each filter are measured both individually and cumulatively.

Dispense either the washed and dried or directly dried sample of aggregate into the filtering column. This column contains several holes of filters attached together where these filters are positioned from top to bottom where the size of the holes is decreased in the same arrangement. Different filters are separated by the aid of a pan and a lid. Then, the column is vibrated either by using a man power or mechanical power. After that, filters are taken separately and each filter is vibrated manually to confirm that all of the material is been processed. At this point, before carrying on the process by using the same filter, all the material that passed to the next filter should be removed. There is a capacity of the filters that depends on the area of the filter and the size of the hole on the sieve. A portion is calculated by using the formula;

$$\frac{A \times \sqrt{d}}{200} \quad (13)$$

Where;
A = the area of the sieve (mm^2)
d= the aperture size of the sieve (mm)

Weight of the material remained after filtering from the sieve containing the largest hole is measured and defined as R1. After this process, step 5 is repeated for all filters resulting in R2, R3, R4, etc. values. Mass of the materials remained at each filtration process found at step 5 are documented at test data sheet. The mass of the materials remained at each filter is then evaluated as a portion of the total weight dry weight. Then, values from step 7 are used to calculate the cumulative portions If the difference between the cumulative mass of the material remained from all filters and the original dry weight is greater than 1%, then the process should be performed again. Calculate the cumulative percentage of the original dry mass passing each sieve down If the sum of the masses retained $R_1 + R_2 + \ldots$ differs more than 1% from the mass M, the test shall be repeated.

Figure 3-2 Sieving Apparatus

The results of fine aggregate with a maximum particle size of 5mm was applied to make concrete mixes in this research. The requirement of BS EN 12620 (2002) is conformed in Table 3.10 .

Table 3-10 Natural sand applied in this research and the requirements of BS EN 126

Sieve Size [mm]	8.0	5.6	4.0	2.0	1.0	0.5	0.25
BS EN 12620 limits for % passing	100	95-100	85-99	-	-	-	-
% Passing for sand	100	99	98	94	88	72	30

Also the results of the natural and recycled coarse aggregates are shown in Table 3.11. The requirement of BS EN 12620 (2002) is conformed by grading of the natural and recycled coarse aggregates.

Table 3-11 NA and RCA applied in this research and the requirements of BS EN 12620

Sieve Size [mm]	40.0	28.0	20.0	10.0	5.0	2.5
BS EN 12620 limits for % passing	100	98-100	90-99	25-75	0-15	0-5
% Passing for RCA	100	100	99	49	14	3.8
% Passing for NA	100	100	95	43	4	2

3.8.2 Aggregate Particle density and water absorption

Density of the particles and water absorption of the aggregates are controlled based on pyknometer method that is explained in BS EN 1097-6(2000). Beside of this, sampling is performed based on BS EN 932-1(1997) and reduction is carried based on BS EN 932-

2(1999). The excellence of concrete depends on the quality of the aggregate. Therefore, characteristics of the aggregate used in making the concrete have a significant impact on the condition of concrete. The feature of the aggregate that affects the concrete most is the water/cement ratio.

Mechanical power of the concrete is obtained from water that aids hydration of the concrete. However, using the correct dose of water is vital because using more water than needed can increase the porosity of the concrete. This results in reducing the mechanical performance and durability. On the other hand, using less water than needed can cause partial cement hydration which can then result in decreasing the fresh concrete's workability. Three different types of densities namely; apparent particle density (pa), particle density on an oven dried basis (prd) and particle density on a saturate and surface dried (pssd) are calculated by using the corresponding masses of the aggregate. After that, the following equations are used to evaluate water absorption figures in Mg/m^3.

Apparent Dentsity - $\rho a = \rho w \frac{M4}{M4 - (M2 - M3)}$ (14)

Oven Dried Density - $\rho rd = \frac{M4}{M1 - (M2 - M3)}$ (15)

Saturated Surface – Dry Density - $\rho ssd = \frac{M1}{M1 - (M2 - M3)}$ (16)

24 hours Water Absorption - $WA_{24} = \frac{100 \cdot (M1 - M4)}{M4}$ (17)

Where ρw, is the density of water at the test temperature in Mg/m^3

M_1= the mass of the saturated and surface dried aggregate in air in grams.

M_2= the mass of the pyknometer containing the sample of saturated aggregate and water in grams.

M_3= the mass of the pyknometer filled with water only in grams.

M_4= the oven dried mass of the aggregate in grams.

3.8.3 Coarse aggregates

The sample of the aggregate was sieved and washed by using 31.5mm and 4mm sieves. The reason for this process is to get rid of the particles that are very thin and very thick. After the filtration process, the sample is plunged in the water in a pyknometer. The water in the pyknometer should be around 22±3 degrees. The air taken in is detached by spinning and vibrating the pkynometer slowly at the fallen position.

Then, pyknometer retained in water for one whole day where the temperature of water is kept at 22±3 degrees. After a day, pyknometer is taken out from the water and again air inside the pyknometer is detached by using the same procedure described above. By this way, pyknometer is completely full up with water. The pyknometer is left at outside to dry and the dried weight is measured. This measure is called as M_2. Then, temperature of the water is reported. The variation in temperature of water recorded from changing M_2 to M_3 should not exceed 2 degrees.

When the water was removed from the aggregates, the drained aggregates are relocated in a dry tray and are left to attain surface dried aggregates. For the aggregates to be surface dried, aggregates should be positioned in the tray in such a way that aggregates are not more than one stone deep. As well as this condition, the tray should be placed on somewhere away from direct sunlight. Surface dried condition is obtained when all the visible water is evaporated but when the aggregates are still humid. Weights of such aggregates are measured and the mass is recorded as M_1. After measuring the damp weight, same aggregates are placed in over with 110±5 degrees temperature to obtain fully dried condition. Fully dried condition is achieved when the weight of the aggregates do not change. This fully dried mass is classified as M_4. Calculations using the above expressions are performed to obtain value for water absorption.

3.8.3.1 Fine aggregates

The sample of the aggregate was washed by using 4mm and 0.063mm sieves for the purpose of removing particles that are very thin and the particles thicker than 4mm. For the fine aggregates, initially the process explained for coarse aggregates is applied up to recording the measure for M_3. After this point, the drying procedure of the fine aggregate was different from the coarse aggregate. After the measure of M_3 is recorded, sample of wet aggregate was distributed equally like a constant layer in a tray. Then the tray was kept in a warm environment, so that the water at the surface can be vanished.

Aggregates are then blended continuously to make sure that all of the surfaces of the aggregates are dried and aggregates are not stick to each other. Aggregates are then stirred and left at the room temperature to cool down. Afterwards, the metal cone was used to determine whether the surfaces of the aggregates are dried or not. The metal cone has two sides; a side with large diameter and a side with small diameter. The cone was placed in a position that the side with the larger diameter is faced at the down in a tray. Sample of the aggregate was roughly placed inside the cone and tamper is used 25 times to fill the cone.

Then, mould is slowly raised and if the cone does breakdown, this means that the aggregate is dried. Otherwise, if the cone does not fall down, this means that the aggregate is not surface dried and drying process has to be performed again until the collapsing is obtained. The weight of the saturated, surface dried aggregate is measured and recorded as M_1.

After this measurement, the same aggregate is placed in an oven with the temperature of 105±5 degrees. From time to time, weight of the aggregate is measured and when the constant weight is achieved, this means that the aggregate is dried completely. The complete dried weight is recorded as M_4. Again, the same formulations are used to find several density types and the value for water absorption.

The results of particle densities and water absorption tests for sand, natural aggregate and recycled coarse aggregates applied in this research are shown in Table 3.12.

Table 3-12 Particle densities and water absorption results of the aggregates applied in this research identified in BS EN 1097 Part 6 (2002).

Material	24 hrs Water Absorption [%]	Oven Dried Particle Density [ρ_{rd}-Mg/m^3]	SSD-Particle Density [ρ_{ssd}Mg/m^3]	Apparent Particle Density [ρ_a-Mg/m^3]
Sand	0.70	2.58	2.60	2.65
RCA	3.35	2.40	2.44	2.61
NA	1.35	2.51	2.55	2.58

3.9 Moisture Content

According to BS EN 1097-5 (2008), moisture content which is defined as a proportion of the oven dry mass of the aggregates is estimated. In order to regulate the quantity of water in concrete before the production of mixes, the amount of water in each aggregate type namely; coarse aggregate and fine aggregate are decided by using the aggregates as stored in laboratory conditions. For the evaluation of the quantity of water in such aggregates, a sample of aggregates are taken from the storage and weighted. Then, these aggregates are placed in a tray and afterwards, this tray is maintained in the oven at 105 degrees. The aggregates are continued to keep in the oven until the mass of the aggregates are stabilised. Finally, the variation in the amount of mass is calculated and hence water content is decided. In the case when water content is greater than water absorption, the quantity of water content that will be decreased from the mix will be approximately the same as the variation calculated amongst water content and water absorption.

3.10 Concrete Mixing Procedure

Normally, aggregates were kept in the laboratory where the temperature is around 20 degrees and relative humidity is around 35%-55%. Concrete mix proportions are changed to ensure the process of water absorption of the aggregates. In order to generate a concrete mix, WinGET Crocker type concrete mixer is used. This mixer which is shown in Figure 3.3 has the capacity of 198 kg. The mixing process is performed in accordance to BS 1881-125. The procedure in this standard is described in 11 steps at the below;

Figure 3-3 Concrete mixer

The concrete mixing was conducted following steps described BS 1881- 125 (1986) was followed as outlined below;

1- The pan and the paddles of the mixer is slightly moistened

2- Then, both types of aggregates namely; coarse aggregate and fine aggregate are added and the content is stirred for 30 seconds.

3- Around half of the total water needed for the mix is put inside the mixer and stirred for 1 minute and then, mixing process continued manually.

4- After that, the mix is untouched around 8 minutes in order to permit the water absorption by aggregates.

5- The cement is distributed consistently around the aggregates and stirred for 1 minute. In the cases of silica fume mix, before adding the cement to the mix, silica fume is added to the mix and stirred for 1 minute. This allows the silica fume to blend with the mix separately from the cement.

6- After the mixing process, the paddles and the mix material are cleaned manually.

7- Then, the other half of the water is poured into the mix and stirred for additional 2 minutes. At the end, concrete mix is stirred manually to confirm the homogeneity.

8- The slump test is performed.

9- After the slump test, concrete is placed in the mixer and stirred again for 30 seconds.

10- Then, casting of the concretes is carried out.

11- Finally, the mixer is cleaned, so that all the concrete are taken way from paddles.

3.11 Curing Environment

This research is applied to Water Curing Environment. After casting concrete in the moulds, it was stored at a laboratory temperature of 20°C and was covered with plastic sheets. After 24 hours, concrete was demoulded and was immersed in the water chamber controlled at a temperature of 20 +/- 2°C. Concrete stored under curing environment is shown in Figure 3.4.

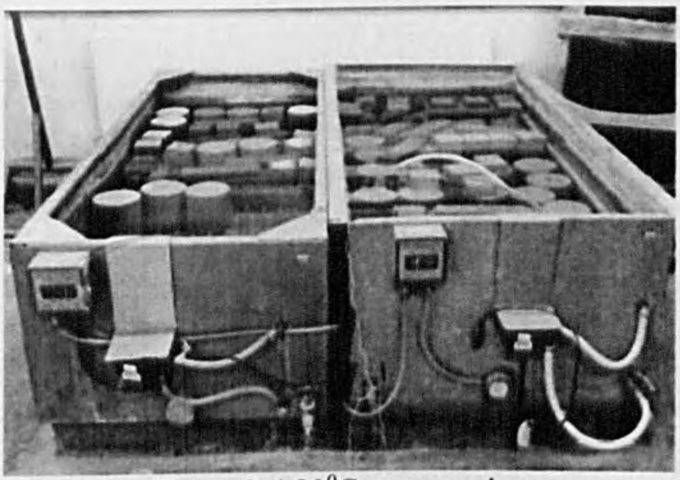


Figure 3-4 20^0C water curing

3.12 Concrete Fresh Properties

Workability of the concrete is measured by slump test and compacting factor test. These tests are performed on fresh concrete.

3.12.1 Slump test

Slump test is performed based on the EN 12350-2 (2009) standards. Generally, concrete mixes are aimed to have a value of 60-180mm from a slump test. It is found that the binary cement content affects the workability of the concrete. The slump test is performed on the fresh concrete directly after mixing procedure and after the slump test, extra superplasticiser is inserted if required in order to achieve the aimed value from the slump test. The Figure 3.5 shows how to perform a slump test. The main purpose of this test is to decide reliability of the fresh concrete. The strength of the fresh concrete, cohesiveness, managing and finalizing the concrete are all determined by checking the appearance of the fresh concrete. The appearance of the fresh concrete obtained from the cone of the slump test is checked to test the cohesiveness by using a slump cone. This slump cone is pushed five times by the aid of a tamping rod with a 16mm diameter that is located at the adjacent side. After one hour of placing the concrete to the form, the top surface of the concrete is altered manually to make it straight.

Figure 3-5 Slump test

Process of the slump test is carried out in 8 steps;

Initially the inner parts of the cast are carefully cleaned and a thin layer of oil is applied to the mould. Then, this mould is located in a place where the surface is smooth, horizontal, rigid and non-absorbent. The total height of the mould is approximately divided into four sections and each section is filled with fresh concrete mix to form four layers. By the aid of the tamping rod, each layer is pushed 25 times where the strokes are allocated equally throughout the cross-sectional area. Then, top layer of the concrete is pushed down and by the help of a trowel, concrete is smashed into the level. After that, the mould is directly taken out in a vertical direction. This processed is carried out slowly. A drop in the height of the concrete is observed and the variation among the height of the mould and the highest point of the concrete is measured. The variation measured in step 7 is defined to be the slump of the concrete. The unit of the slump is in mm and should be recorded throughout the test.

3.12.2 Compacting Factor

According to BS 1881: Part 103, the formula to evaluate compacting factor is (i.e., compacting factor = m_p/m_f). As can be seen from the Figure 3.6, firstly, the top hopper is totally loaded with the concrete. Then, the concrete filled is released in to the lower hop and then falls down into the cylindrical mould. Compacting factor is calculated by using the overloaded concrete. Compacting factor is determined by taking the ratio of concrete in the cylinder (m_p) relative to the concrete that is totally compressed in the cylinder (m_f). Concrete that is totally compressed in the cylinder is obtained as a result of filling the four layers and pushing the concrete down either by the aid of trowel or vibrating equipment.

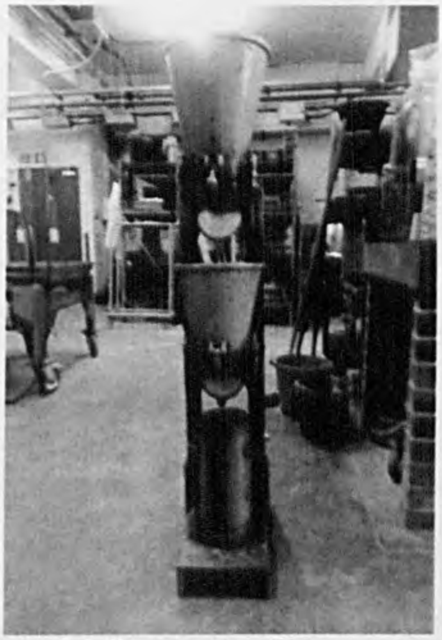


Figure 3-6 Compacting factor apparatus

Process of Compacting factor test is achieved in 6 steps; Process of Compacting factor test is achieved in 6 steps; the concrete specimen mix is filled in to the brim to the upper hopper. Then, the trap-door is opened. This makes the concrete to release down to the lower hopper. After that, trap-door of the lower hopper is unlocked. By this way, the concrete is allowed to fall into the cylinder. Flat, sharped edged equipment are used to remove the additional concrete left at the top of the cylinder. After that, the weight of the concrete cylinder is measured. This measure is defined to be the weight of the semi compacted concrete. The cylinder is then loaded with a fresh concrete and in order to achieve maximum compaction, vibration is applied to the concrete. The weight of the concrete in the cylinder is measured again and hence this measure is now called as weight of the totally compacted concrete.

$$\frac{\text{Weight of partially compacted concrete}}{\text{Weight of fully compacted concrete}}$$

Each mix from three different types of groups namely; Group A, Group B and Group C are investigated and the results are reported in the previous sections of this chapter. Furthermore, the results of the slump and compacting factor tests for all of the concrete mixes are reported in Chapter 4.

3.13 Concrete Hard Properties

3.13.1 Compressive strength

Compressive strength of the concrete is determined on cubes and cylinders. The concrete cubes have dimensions of 100mm and concrete cylinders have the dimensions of 150mm diameter and 300mm height. The samples are tested by using the procedure suggested in EN 12390-3 (2009). This speed is given to the concrete until the concrete breaks down. Both types of specimens namely; concrete cubes and cylinders are tested on 7 and 28 day.

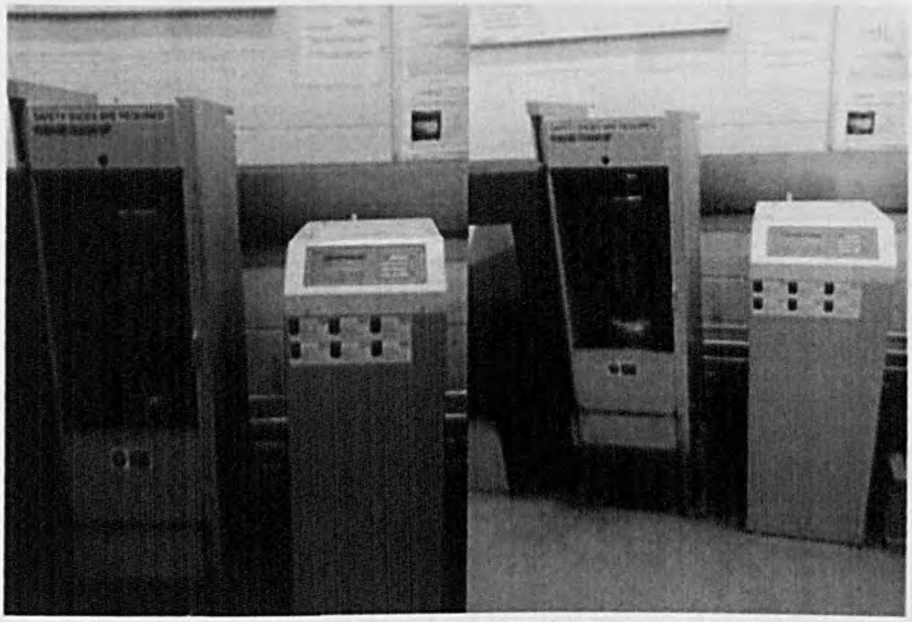


Figure 3-7 Compressive strength Test (Cube and cylinder)

Three samples from each type of specimen are tested for each mix. This means that three concrete cubes and three cylinder cubes are tested for compressive strength from each mix per testing day. These concretes are all tested by using the machine called "Avery Denison 2500 kN". The Figure 3.7 shows this machine and how the compressive strength tests are performed by using this machine.

The compressive strength tests are carried out on cubes and cylinders for both 7-day and 28-day concrete mixes. The results of the concrete mixes were shown in Chapter 4 respectively from group A, group B and group C.

3.13.2 Flexural Strength

In this research, flexural strength is applied on concretes which are 7 and 28 days. Flexural test is performed on beams after curing where the dimensions of the beams are 100×100×500mm. Again, three specimens from each mix are tested for flexural strength. Calculations of flexural strength are performed based on EN 12390-5 (2009) using the simple bending theory. Figure 3.8 shows the flexural strength test.

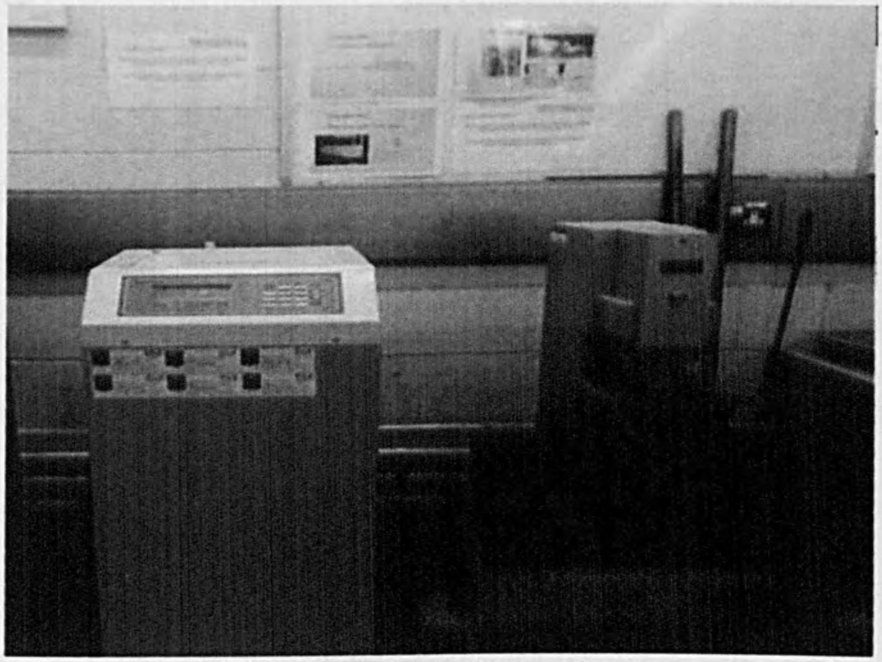


Figure 3-8 Flexural strength test

The flexural strength test is carried out on beams for both 7-day and 28-day concrete mixes. The results of the concrete mixes were defined in Chapter 4 respectively from group A, group B and group C.

3.14 Concrete Thermal Properties

3.14.1 Density of Hardened Concrete

Hardened concrete density is determined either by simple dimensional checks, followed by weighing and calculation, or by weight in air/water buoyancy methods [BS EN 12390-7, 1097-6]. The density of hardened concrete specimens such as cubes and cylinders can be quickly and accurately determined using a Buoyancy Balance. The buoyancy balance system developed by ELE consists of a rigid support frame, incorporating a water tank mounted on a platform. The water tank has internal dimensions of 380x240x280mm (l x w x h).

A mechanical lifting device is used to raise the water tank through the frame height immersing the specimen suspended below the balance. The balance supplied calculates the specific gravity of the sample automatically. The Density Test was carried out on 100x100x100 mm cubes after curing. Three samples were casted for each mix to be tested for Density of concrete at 28 day.

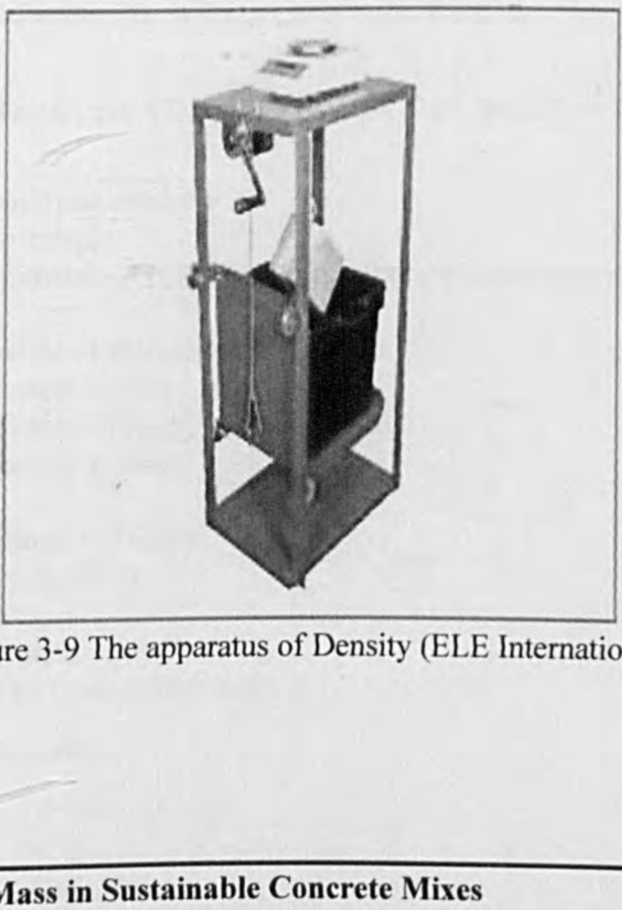


Figure 3-9 The apparatus of Density (ELE International)

3.14.2 Specific heat capacity

Thermal properties of concretes are examined in specific heat capacity, so that it can be determined how much mass is needed per unit for one unit increase in temperature of the sample. By this way, specific heat capacity can be used to explain association between heat and temperature variation. Specific heat capacity is found by performing an experimental procedure in an insulated box. This box consists one stainless steel bucket which is approximately about half of the bucket. This specific heat capacity equipment is developed by trained technicians from Kingston University.

First step of experimental procedure is to put heated 70x70x70mm cube of concrete in to the water. Records of temperature of the sample, water and air are kept constantly until all three elements have the same temperature. After that, observed values from three elements are used to evaluate the value for specific heat capacity by using the formula stated below;

$$Q = cm\,\Delta T \quad (18)$$

The specific heat capacity is found by using the following formula and known values for the specific heat capacity of water, the stainless steel bucket and air.

$$C_C\, m_C\, \Delta T_C = C_S\, m_S\, \Delta T_S + C_W\, m_W\, \Delta T_W + C_A\, m_A\, \Delta T_A + [M_w\, l] \quad (19)$$

C_c = Specific heat capacity of concrete
m_c = Mass of Concrete sample
ΔT_C = Temperature difference of concrete sample [before test temperature – after test temperature]
C_S= Specific heat capacity of Stainless steel bucket
m_S = Mass of Stainless steel bucket
ΔT_s = Temperature different of Stainless steel bucket
C_W = Specific heat capacity of water
m_W = Mass of water
ΔT_W = Temperature different of water
C_A = Specific heat capacity of air
m_A = Mass of air
ΔT_A = Temperature different of air
M_w = mass of water in air (evaporated water)
l = specific latent heat of water

Table 3-13 Known Specific Heat Capacities [ASHRAE Applications Handbook (SI)-2003; F. Tyler, 1970].

Known Specific Heat Capacities	
Material	**Specific heat capacity [$Jkg^{-1}K^{-1}$]**
Stainless Steel 18Cr/8Ni	502
Water at 20, 30, 40, & 50^{0}C	4181.6, 4178.2, 4178.3, 4180.4
Air at 20 to 100^{0}C [Dry]	1006

This table is shown the related specific heat capacity value by depends on the temperature

3.14.2.1 Preparation of Specimens

After casting of the required concrete sample in dimensions of 70x70mm, the sample was needed to be prepared. Before testing the specific heat capacity, when the sample is taken from the oven, it was left to cool down and then the dry mass of the concrete is measured. A sample is kept at room temperature and a hole was opened on the top of the concrete having 3-4mm diameter and 40mm depth towards the down of the cube. After 24 hours of the casting process, the sample was first demould and then curved. After curing procedure, the sample is dried in the oven for 18-24 hours at 105^{0}C ± 5^{0}C.

3.14.2.2 Test Procedure

The following steps should be attained one day before carrying out the test.

1. Oven is pre-heated at suitable temperature (i.e.100^{0}C) and the sample was placed in this pre-heated oven in order to reach a constant temperature.
2. Since the same stainless bucket was used for all specific heat capacity experiments, mass of the stainless steel bucket is constant and it was measured only once. Then, approximately half of the bucket was filled with water and the total mass of the stainless bucket with water was measured. After that, the mass of water can be

determined by subtracting the constant mass of stainless bucket from the total mass of bucket with water.

3. Bucket with half-filled water was placed inside the insulated box. Where the front of the insulated box was kept open in order to achieve constant temperature of bucket and water.

4. Connect the thermometer to the bucket with water to check the temperature.

After overnight stay, if the temperature is constant, the bucket with water was now prepared for testing. However, before the start of testing, weight of the bucket with water should be re-measured to aware of any variations in mass of water due to evaporation that might occur overnight.

If any changes in the mass of water were observed, new values should be used instead. Three thermometers were used in this experiment. One is placed in water which was inside the bucket in order to measure the temperature of water. The second one was placed in insulated box to measure the temperature of air and the last one was placed in the sample via a hole on the top of the sample which was taken from oven. Greater accuracy could be obtained in measurements by using a stop watch.

Before the sample was placed in the water, all three measurements of air, water and sample are recorded for the measurement time being equal to zero. Afterwards, records of all three measurements were kept at regular intervals. First measurement at time being equal to 1 was at 5th minute of the experiment. Variations in temperature of sample, air and water are evaluated under the assumption that both stainless steel bucket and water have the same temperature variation; the formula above could be used to find out the specific heat capacity of the concrete.

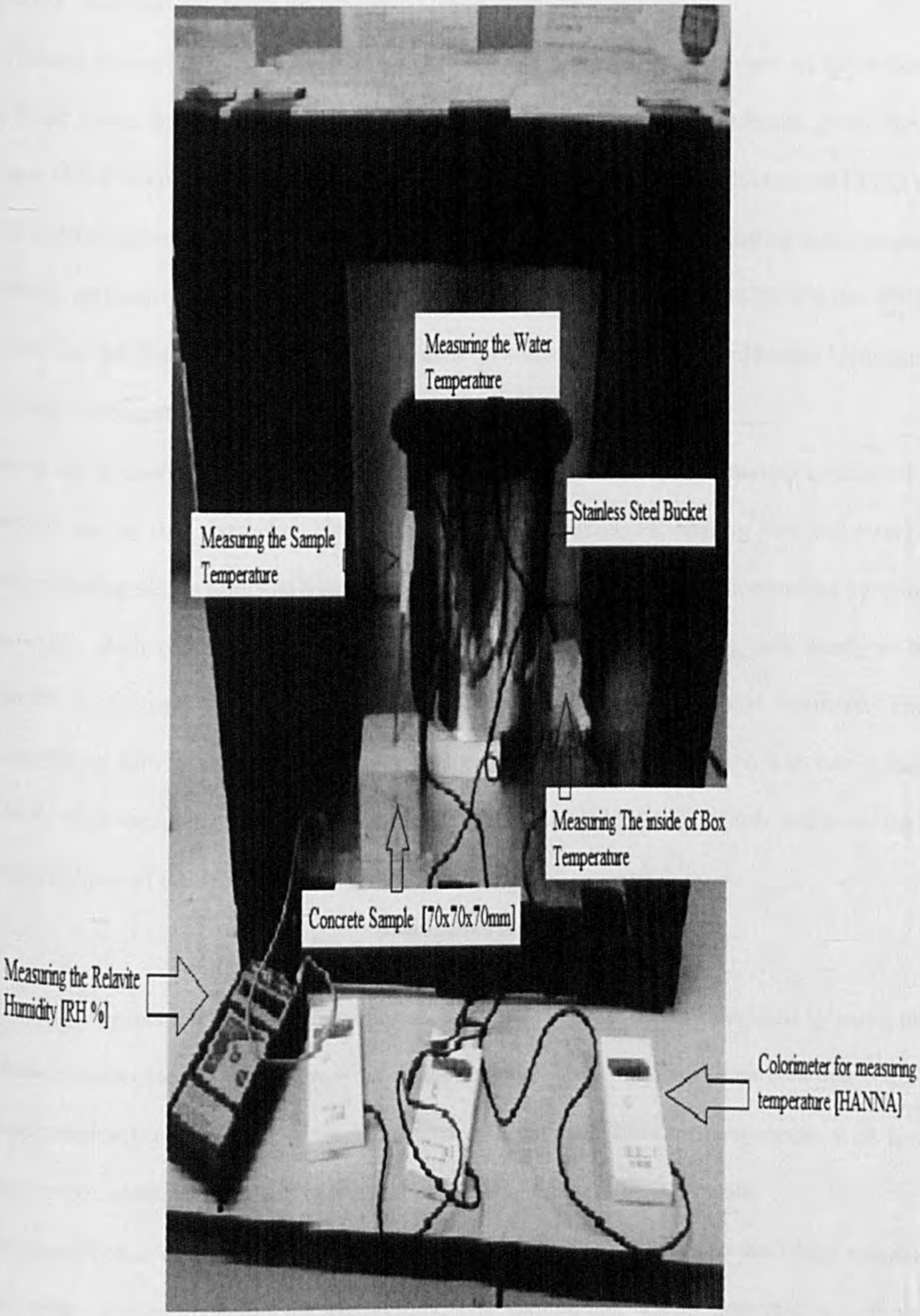


Figure 3-10 Specific heat capacity apparatus

3.14.3 Thermal conductivity

Thermal transmittance is represented by U-Value and it provides information on the amount of heat that is being conducted out by the substance. Greater U-Value indicates greater heat loss. In the recent years, the UK government established a standard which is called EPBD to be applied in construction of new buildings. The main aim of this standard is to develop energy performance standards and to reduce U-Value figures. According to BS EN ISO 8990: 1996 and BS EN 1934: 1998, a method called "hot-box" is developed by Dundee University in order to measure steady-state thermal transmission properties.

Kingston University laboratory technicians are trained to develop the thermal conductivity equipment for this research. This equipment contains two sides; heating side and cooling side. Heating side is achieved by using 40W light bulb and cooling side is achieved by using a fridge. Both cold box from cooling side and hot box from heating side needs to be insulated. As well as this, the box which includes the sample is also insulated. This experiment with two sides are designed on a trolley where both fridge and cold box is kept fixed, while designing the hot box and sample box in a way to move towards and away from the fixed part of the apparatus.

$$\Phi p = \frac{[40\text{xCounter Reading}]}{\text{Time between readings}} \quad (20)$$

By using the heating side of the equipment, total power input (ϕP) is calculated by using the measurement obtained from thermostat of hot box and timer counting. Timer counting is used to determine the proportion of the time needed to maintain constant temperature with heat source generated by 40W light bulb and a fan that is used to circulate the air.

Insulated box is open at both ends. At one open end, a fan is attached to the fridge whereas the other open end contains the sample box. This sample box has an open end as well and designed in a way that can be opened from top to place the sample inside the sample box. After the sample is placed, thermocouples are sealed at both sides of the box. Same amount of thermocouples are placed on heating side and cooling side separately. The sample that will be used in this study is accurate square shape slab with 300mm square area and 75mm thick. Temperature of the sample during the experiment is controlled by using a temperature controller at 240V/2A. The voltage and current used in the experiment is recorded by using 16 channel thermocouple data acquisition and a simple logger log system.

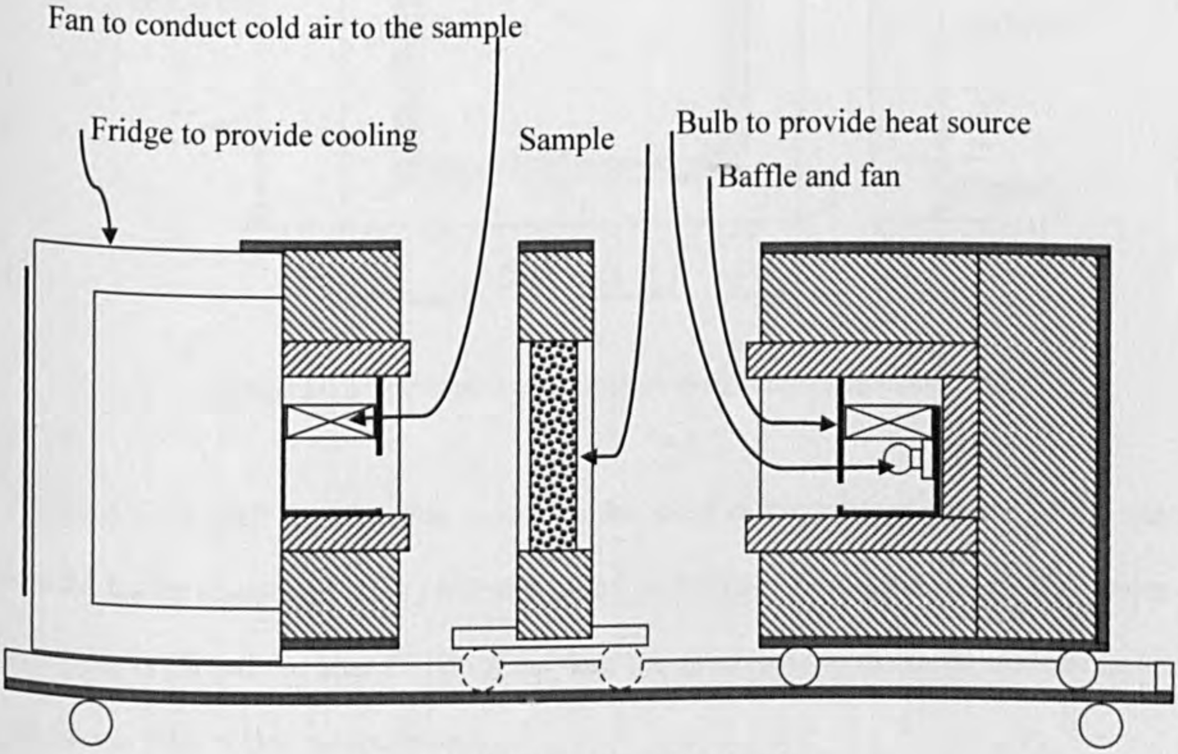


Figure 3-11 Schematic of the hot box

3.14.3.1 Preparation of Specimens

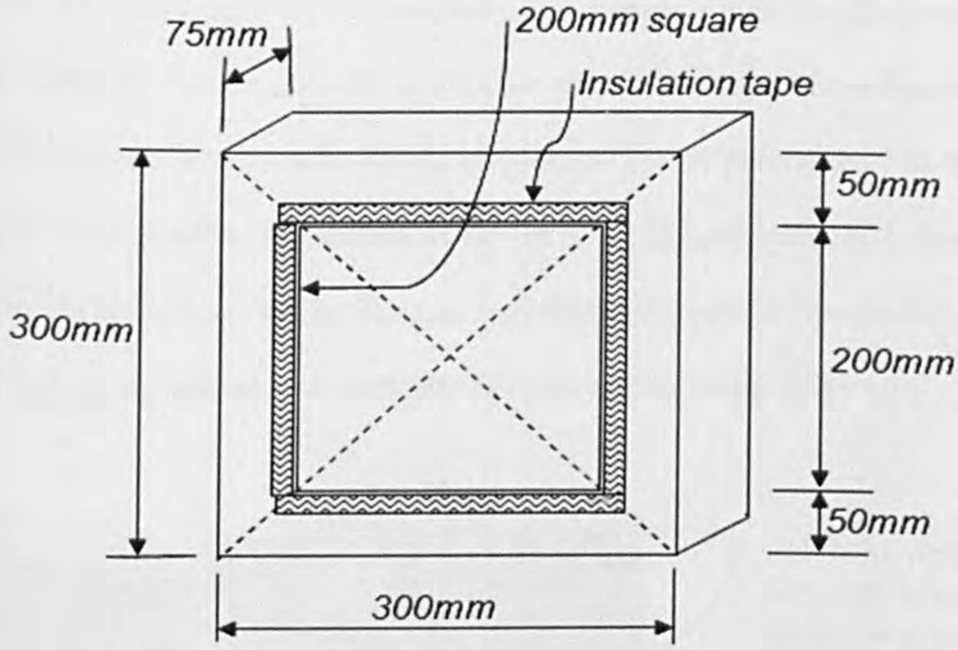


Figure 3-12 The concrete sample with insulation tape attached.

Figure 3.12 is used to show that wood moulds used in the casting process of the sample needed for the equipment. This process is based on BS EN 12390-1 standards. The process of remoulds is carried out after 24 hours and then the specimens were placed in water tanks for 28 days at 20oC ± 5oC temperature.

After 28 days, before performing the thermal transmittance test, samples are kept in a room with controlled temperature at 20°C (±2°C) and controlled RH with 55% (± 5) in order to achieve stable moisture content.

After that, the sample is needed to leave to dry at the operating temperature of the hot box. When the sample is ready for testing, before putting the sample in the apparatus, sample should be marked to have 200mm square on both sides and a record of thickness of the sample is kept from the Centre of this marked square. The points where the thermocouples will be placed is marked on the 200mm square.

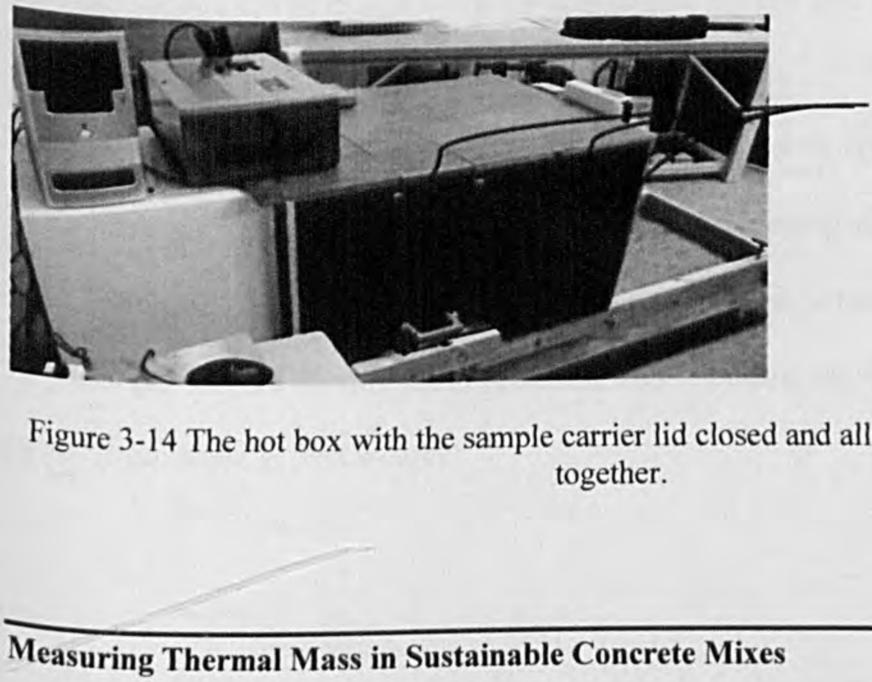
3.14.3.2 Apparatus for Testing

Firstly, hot box is separated into three sections, then sample is placed in the sample box and the lid of the sample carrier is closed. If there are any thermocouples from the sample tested before, all of these thermocouples should be removed before putting the new sample in a carrier box. After checking the security of the top of the sample carrier box, thermocouples are attached to the new sample by using an insulated sticky tape. At the cooling side of the equipment, it is vital to label each thermocouple with its position on the sample.

The bolts, here, engage into the holes on the handle, here, to secure the sample carrier lid.

Figure 3-13 Hot box components separated and the sample carrier open showing a sample in place.

Sample carrier box is pushed towards the cooling side and hot box is pushed towards the sample carrier. Then, the equipment is locked securely and thermocouples are attached to the acquisition unit.



Latches can be found in these positions on both the front and the back of the hot box

Figure 3-14 The hot box with the sample carrier lid closed and all three components sealed together.

The experiment is started and the figures from the channels are recorded. Temperature values of air and surface of the sample are recorded by using the software called Edam 5019 whereas the power provided to the hot box and voltage of the sample are recorded by using the software called simple logger II. The current is set to 100mV/A. Connection between PC and equipment is achieved by clicking the button of EDAM software. When the test tab is selected, temperatures from thermocouples can be seen on the PC screen. After validating that the software is working properly, both control panel and fridge can be switched on. The sample is then left for 4 or 5 hours, so that temperature values from thermocouples will be stable. After the figures are found to be stable enough, the power and temperature of the sample is recorded constantly at regular intervals for at least one hour. The results obtained can then be used to evaluate thermal conductivity.

The time needed to obtain constant temperature patterns from thermocouples will depend on the sample material and dimensions. Trial and error process is used to examine this time required to stable temperatures. On the other hand, type of the sample also affects the amount of data needed to obtain accurate results for thermal conductivity. The time is aimed to be at least 30 minutes in this study.

Firstly, these recorded data is used to calculate power which is represented as a fraction of time that voltage has been applied to the heater. The voltage data is exported to the Excel in order to perform the calculations.

If the fraction obtained from power calculation is multiplied by 40 which is the power rating of the heater used in this study and the 3.2W which is the power rating of fun is added to the value calculated. This figure at the end will provide the average heat flow and the unit will be in joules per second. Details about recording and exporting the data for the calculation of power is explained in next section.

3.14.3.3 Recording and down loading data from the simple logger

When the temperature figures from the thermocouples are obtained at constant level, voltage data is recorded by using the software as well as keeping the manual record of temperatures obtained from thermocouples at the EDAM window. The temperature figures are recorded manually in every 5 minutes. However, voltage data is obtained by selecting start recording real time data section from the top down menu under file in simple Logger II programme. Suitable file name is given to the recorded data when it is asked. In order to finish recording, select stop recording real time data from the same pathway. Recorded data is originally CSV file and this file is exported to excel spread sheet to perform calculations of thermal conductivity.

3.14.3.4 Calibration of Hot Box

The main aim of the "hot box" apparatus shown in Figure 3.15 is to examine heat transfer components of the sample when the temperature figures are achieved at constant level. Sections of the hot box equipment showing the heat components namely; Q_p, Q_1, Q_3 and Q_4 are examined in calibration of the equipment and shown at the figure below.

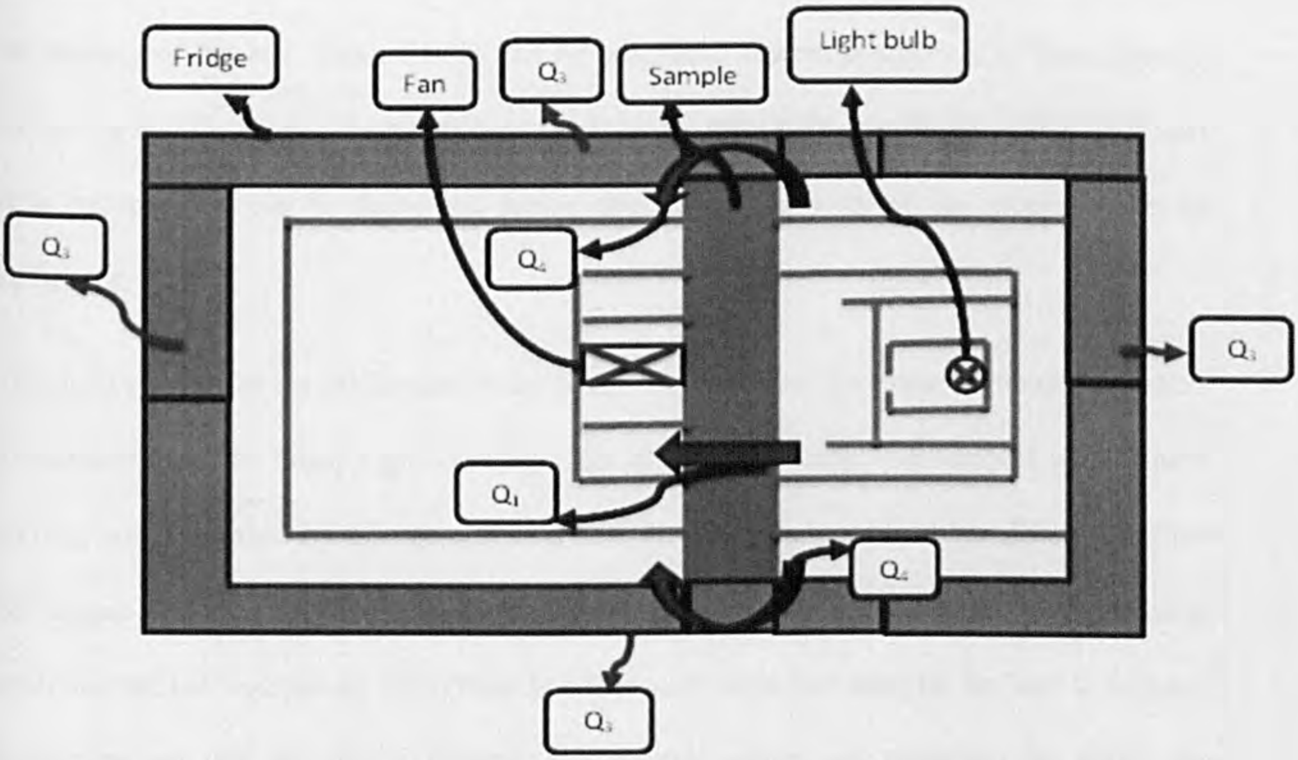


Figure 3-15 Heat flow through the hot box apparatus

Q_p represents the total heat input, Q_1 represents the heat transferred from hot side to cold side of the equipment through the specimen, Q_3 represents the heat loss from hot side of the equipment to the environment and Q_4 represents the flanking loss that is the heat lost through the gap between the specimen and the equipment during the experiment. Detailed information about each component can also be found in BS EN ISO 8990 and BS EN 1934.

Accuracy of the equipment depends on many factors such as equipment design, calibration, operation and sample properties (i.e. thickness, thermal resistance). In theory, when a sample with known thermal conductivity value is measured by using this equipment under the condition of keeping both inside and outside temperature same, coefficients of heat transfer are expected to be same on both surfaces. Furthermore, heat flow of air for both inside and outside are expressed to be same and therefore, a balance is expected to form on the top of the surface (I.e. $Q_4=Q_3=0$). However, in practice the expected situation does not occur even in homogenous samples. Coefficients of heat transfer matrix, surface temperature and air temperature are not resulted to be uniform especially the effect can be seen more towards to the borders of the box. From this, it can be concluded that in practice, it is impossible to reduce Q_4 and Q_3 to zero, therefore heat flow will be $Q_1=Q_p-Q_3-Q_4$. By using this total heat flow equation, Q_1 can be found and hence, thermal conductivity of the specimen can be calculated.

The main purpose of the calibration of the equipment is to find the linear regression equation to estimate Q_4. This linear regression equation is found by using five samples with known thermal conductivities. By this way, in total heat flow equation, only one unknown is left for calculation which is Q_1. The specimens with known thermal conductivities are examined using the hot box equipment. Therefore, as a first step, these five samples are sent to Dundee University, so that the actual thermal conductivity values are measured by using the calibrated equipment. Those samples that have been sent to Dundee University are used as reference samples and the corresponding thermal conductivity results are used as reference thermal conductivities. By using these reference values, flanking loss (Q_4) is calculated for each sample. Then, a linear equation is found to model the relationship between flanking loss (Q_4) and total heat loss (Q_p). Afterwards, this equation is used to estimate the flanking loss (Q_4) values for other samples.

General equation to estimate heat transfer is;

$$Q_p = Q_1 + Q_3 + Q_4 \quad (21)$$

If thermal conductivity is known, Q_1 can be calculated. Therefore, Q_1 can only be calculated accurately for the reference samples where the thermal conductivities are known. The formula to calculate Q_1 is;

$$Q_1 = A_1 + U_1 + \Delta T \quad (22)$$

Where A_1 is the area of the sample.

U_1 is the thermal transmittance of the specimen and

ΔT is the temperature difference between the hot side of the equipment and cold side of the equipment.

$U_1 = \frac{1}{R}$ and $R = \frac{1}{\lambda} \times d$ (23)

$d = 0.075m$ which is the thickness of the samples.

Q_p is calculated by using the formula;

$Q_p = (\Delta t \times 40) \div 3.2$ (24)

Where;

The proportion of time difference (Δt) is found by taking the ratio of the readings where the values are observed equal and greater than 1 relative to the total number of readings. Therefore, the equation used to calculate the proportion of time difference is;

$\Delta t = \frac{n \geq 1}{n}$ which represents the proportion of time that is calculated by using the values obtained from readings characterized by "n".

The value of Q_p can be calculated for every sample using the above equations.

The formula to calculate Q_3 is;

$Q_3 = A_3 \div U_3 \div \Delta T$ (25)

Where A_3 is the area of the hot box equipment, the area of hot box which is estimated to be around 0.8266 m^2.

U_3 is the thermal transmittance of the hot box equipment and

ΔT is the temperature difference between the hot side of the equipment and the room temperature.

$$U_3 = \frac{1}{R_{si} + R_{so} + R_c + R_p} \quad (26)$$

Q_3 can also be calculated for every sample.

Q_4 is unknown and needs to be estimated in order to leave only the Q_1 to be unknown.

The formula to estimate Q_4 is;

$$Q_4 = A_4 + U_4 + \Delta T \quad (27)$$

However. Q_4 cannot be estimated by using the above formula since the area A_4 and U_4 is undefined. Therefore. Q_1 is found for the reference samples and the corresponding Q_4 values are estimated by subtracting the sum of Q_3 and Q_1 from Q_p. Then. a linear relationship between Q_4 and Q_p is assumed since $Q_p = Q_1 + Q_3 + Q_4$. After that. a linear equation explaining this association is formulated by using five reference samples. The linear equation describing this association is found to be;

$$Q_4 = (0.9763 \times Q_p) - 6.2516 \quad (28)$$

Where 0.9763 is the parameter of Q_p that is estimated to describe the relationship between Q_4 and Q_p and -6.2516 is the intercept of this model equation.

Furthermore. this linear regression equation is used to estimate Q_4 for each sample and then Q_1 is estimated for each sample by subtracting the sum of Q_3 and Q_4 from Q_p. Once. Q_1 is estimated for each sample. this value of estimated Q_1 is used to estimate thermal conductivities of each sample. Formulas that are used to estimate thermal conductivities by using Q_1 are:

$$\lambda = \frac{Q_1}{A \times \Delta T} \times d \quad (29)$$

Where:

$$Q_1 = Q_p - Q_3 - Q_4 \quad (30)$$

$$Q_4 = (0.9763 \times Q_p) - 6.2516 \quad (31)$$

$A = Exposed\ area\ of\ the\ sample = 0.04m^2$

ΔT is the temperature difference between the hot side of the equipment and cold side of the equipment and $d = 0.075m$ which is the thickness of the samples. After this, λ is found for each sample using the above formula. This formula is from the Fourier heat flow equation on steady flow condition.

4 Fresh and Hardened Concrete

4.1 Introduction

Engineering performance of binary cement concrete, where Portland cement is partially replaced with various percentages of GGBS or PFA or SF has been evaluated in this chapter. Many factors such as the type of materials, amount of materials used in the concrete mixes, the features of these materials all have impact of the workability of the concrete. Detailed explanation on how to perform the workability tests are already explained in chapter 3. In this chapter, the results obtained from workability tests such as slump test and compacting factor tests are explained. In addition to this, features of fresh concretes having the same compressive and flexural strengths are considered. Concrete made was cured in water-tank (20^{0}C) described in Chapter 3. The compressive and flexural strength of concrete containing GGBS, PFA and SF was recorded at 7 and 28 days.

4.2 Fresh Concrete

4.2.1 Slump Test

Reference slump range for a concrete is between 60 to 180 mm. In this research, since low water/cement ratio is used, workability of the concrete is decreased. Therefore, additional superplasticiser called "ADVA 655" is used. This superplasticiser is provided from Grace Construction Ltd. By this way, reduced workability is increased to obtain the maximum workability value. This procedure is applied for Group C concrete mixes. Then, the values obtained as a result of slump test are recorded in Table 4.1respectively for different concrete mixes. From this table, it is concluded that al the slump values are resulted within the acceptable reference slump range. Both natural aggregate concrete mixes and recycled coarse aggregate mixes are found that RCA concrete mixes are decreased the slump more than NA concrete mixes.

In this research, it is found that when GGBS is added to the concrete mix, slump test results in greater values. In the GGBS concretes, the cementitious particles are distributed evenly, this eliminates the particles at the surface of the concrete to absorb water during the mixing process. Therefore, particles at the surface of the concrete which are smooth and dense take in small amount of water which will then increase the slump value. Hence, this shows that the workability of such concretes is increased due to the addition of GGBS content.

As like in addition of GGBS content, similar relationship is resulted in the workability of the concrete by the addition of PFA. The higher the PFA content, the higher the workability of the concrete. This is due to the reduction of water/cement ratio in the concrete mix when the PFA is included. When the amount of PFA is increased in the concrete mix, the effect of plasticising of the concrete is increased. This increase in plasticising effect is obtained as a result of spherical shape, smooth glassy nature of finer sized particles and the distribution particles in PFA.

On the other hand, when silica fume is included in the concrete mix, it results in decrease in slump value. Therefore, it can be concluded that silica fume resulted a lower slump value relative to the concrete mixes containing GGBS, PFA or PC. This result can be explained by an increase in water absorption due to the feature of silica fume which is containing particles having large surface area. Therefore, superplasticizers are used in such concrete mixes in order to achieve a slump value within the reference range, so that the workability can be kept equivalent to OPC concrete mixes.

Table 4-1 Slump and compacting factor values of Groups

GROUP A			GROUP B			GROUP C			
No.	Slump (mm)	Compacting Factor	No.	Slump (mm)	Compacting Factor	No.	Slump (mm)	Compacting Factor	Super plasticiser (ml/100Kg)
A1	180	0.98	B1	170	0.97	C1	105	0.97	-
A2	165	0.96	B2	150	0.97	C2	110	0.98	-
A3	170	0.94	B3	145	0.94	C3	100	0.98	-
A4	155	0.97	B4	150	0.98	C4	115	0.98	-

A5	165	0.92	B5	140	0.96	C5	100	0.96	-
A6	170	0.94	B6	165	0.97	C6	90	0.97	180
A7	180	0.94	B7	155	0.97	C7	90	0.98	205
A8	120	0.95	B8	110	0.98	C8	75	0.96	390
A9	110	0.97	B9	95	0.96	-	-	-	-
A10	100	0.96	B10	90	0.97	-	-	-	-

4.2.2 Compacting Factor

The reference ranges for compacting factor is the range of 0.92 to 0.98. The compacting factor results obtained from all mixes used in this research is reported in table 4.1. When different mixes are compered in terms of compacting factors, it can be concluded that unlike the slump test, there is a significant difference in compacting factor among the mixes. It can be seen from the tables that, for the concretes with low slump value, compacting factor is resulted to be large. The reason for this is explained due to the nature of the test where the compacting factor test is more precise to low workability compete against high workability.

The results indicate that compacting factor of PFA mixes are slightly less than PC mixes. However, this result cannot be used to state that PFA mixes are less workable than PC mixes because when PFA mixes are compared against equivalent PC mixes, it is observed that PFA mixes contains greater amount of cement materials.

When compacting factor results achieved from silica fume are compared against results obtained from OPC mixes, silica fume is found to result similar compacting factor with PC mixes. However, it is concluded that since particles in silica fume have large surface areas and the mixes containing silica fume have less amount of cement, PC mixes have a higher workability than silica fume.

4.3 Hardened Concrete

4.3.1 Compressive Strength of the concrete mixes

The compressive strength of the concrete mixes cured in water tank. Three samples from each type of specimen are tested for each mix. This means that three concrete cubes

(100x100x100mm) and three cylinder (150x300mm) are tested for compressive strength from each mix per testing day. The compressive strength tests are carried out on cubes and cylinders for both 7-day and 28-day concrete mixes. The three figures below; from figure 4-1 shows the results of the concrete mixes respectively from group A, group B and group C (The compressive strength results are shown in Appendix 9.1).

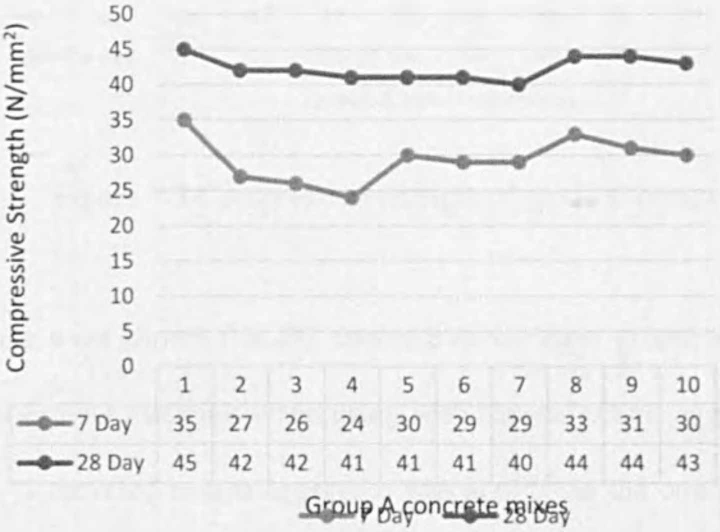


Figure 4-1 Compressive strength of group A concrete mixes

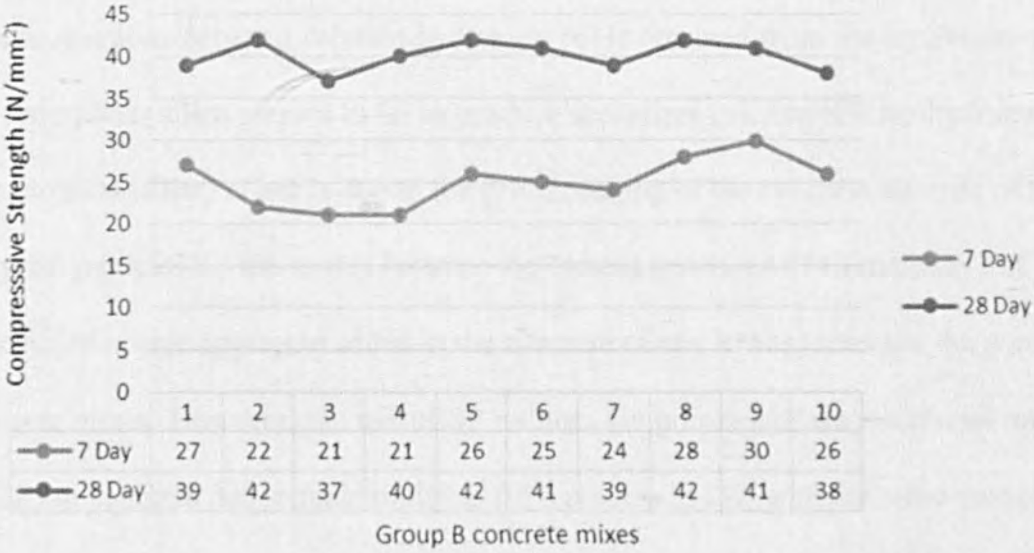


Figure 4-2 Compressive strength for group B concrete mixes

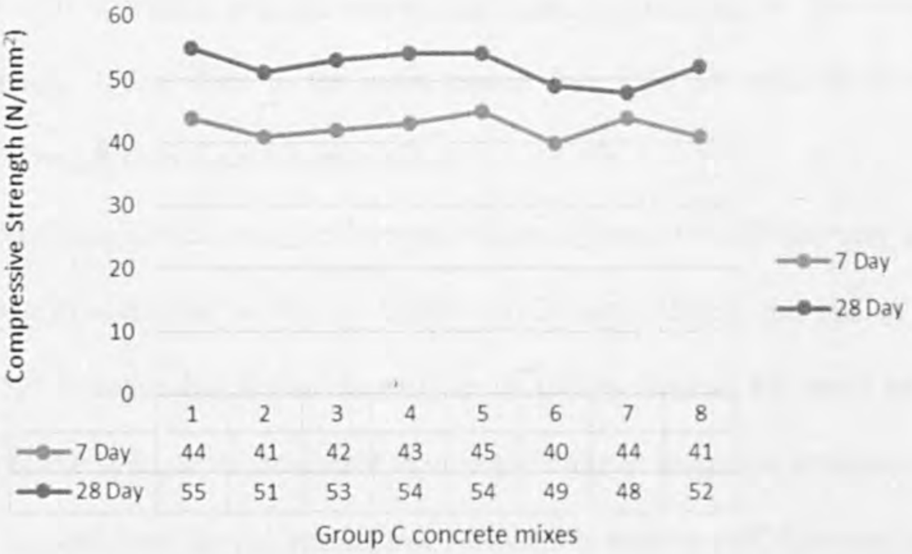


Figure 4-3 Compressive strength of group C concrete mixes

The test results were shown that PC concrete mixes have greater compressive strength and other types of cement materials when using with Natural coarse aggregate. On the other hand when the 30 % recycled coarse aggregate was applied in the concrete mixes. 15% SF with 30% RCA content concrete mix (B9) was higher compressive strength than PC concrete mix. Compressive strength enhancement in concrete mixes containing SF is possibly because of chemical and physical effects contributed by SF. Chemical effect is largely because of the pozzolanic reactions between calcium hydroxide (CH) obtained from the hydration of OPC and the amorphous silica present in SF to produce secondary calcium-silicate-hydrates (C–S-H). The physical (filler) effect is due to the dense packing of the concrete because of SF fine particles. SF particles fill the spaces between the cement grains. (ACI Committee 234, 1995). When recycled coarse aggregate added in the concrete mixes, it was increased the porosity of the concrete mixes. However, the use of SF reduces the porosity of the interfacial transition zone (ITZ) in concrete due to their ability to fill the pores in ITZ with the silica particles and reduces the amount of calcium hydoxide (CH) due to its high pozzolanic reactivity (Roy, 1989). The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete (Maage, 1986). This is the main reason that 15% SF with RCA was greater compressive strength than other concrete mixes.

The particle size and surface area also increase the rate of reactivity. SF has very fine particle size (0.1-0.3 μm) compared to that of GGBS (10-20 μm). Hence, the rate of pozzolanic reaction of SF is noticeably higher than those of GGBS. Hence, SF starts to pay much contribution to the strength enhancement at an early stage in hydration compared to GGBS. However, it is clear from the test results that sufficient quantities of CH should be available before getting the benefit of SF.

PFA replacement levels was consistently lower than other mixes at 7 and 28 days. The figure demonstrate that also an increase in PFA content further reduced the strength. As all the mixes were cast with the slump was similar, the reduction in the strength of PFA mixes is considered to be the result of slower pozzolanic reaction of the PFA in these mixes. Finally the research was considered only the same compressive strength (C40 and C50) in the all mixes.

4.3.2 Flexural Strength of the concrete mixes

For each concrete mix flexural test was performed after curing for 7 and 28 days. The flexural test was performed on the dimensions of the beams (100x100x500mm). The flexural strength test was applied three specimens from each mix. From figure 4-4 to 4-6 show the results of the concrete mixes respectively from group A, group B and group C (Flexural Strength Results are available in Appendix 9).

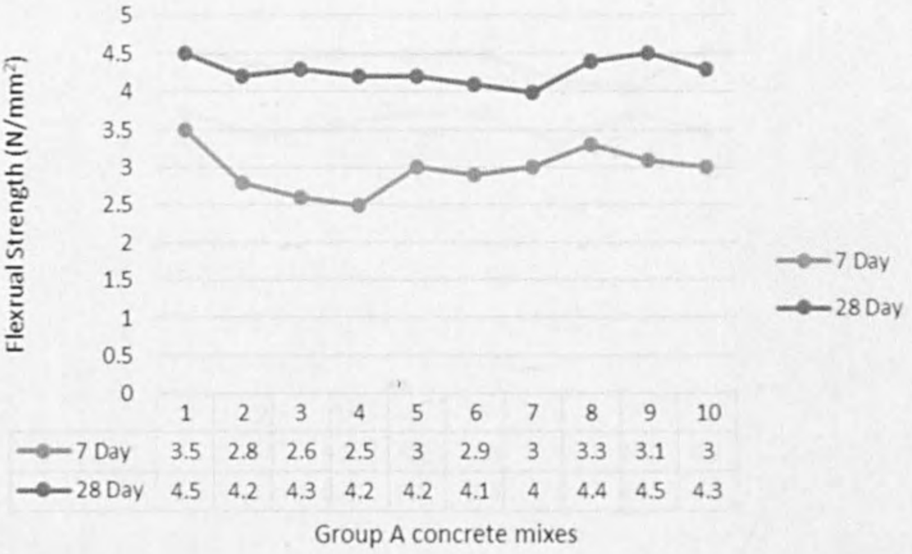


Figure 4-4 Flexural strength of group A concrete mixes

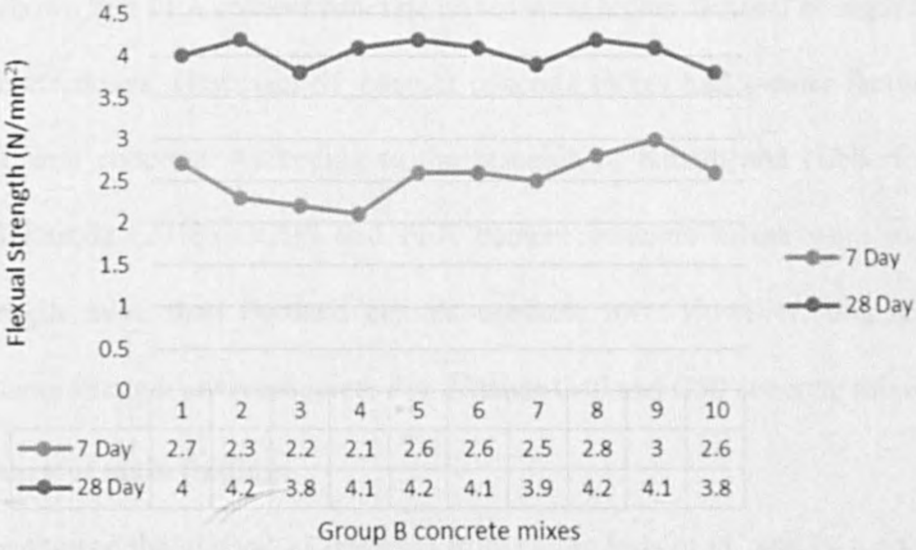
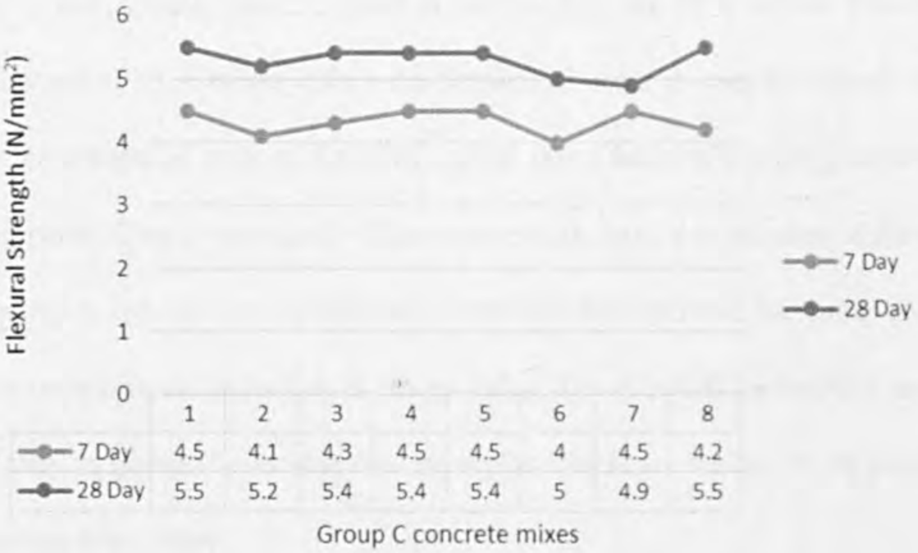


Figure 4-5 Flexural strength of group B concrete mixes



	1	2	3	4	5	6	7	8
7 Day	4.5	4.1	4.3	4.5	4.5	4	4.5	4.2
28 Day	5.5	5.2	5.4	5.4	5.4	5	4.9	5.5

Figure 4-6 Flexural strength of group C concrete mixes

The results shown that PFA content concrete mixes were higher flexural strength than GGBS content concrete mixes. However, SF content concrete mixes had greater flexural strength than PFA content concrete. According to the research of Khatib and Hibbert (2005) and Solanki and Pitroda (2013) GGBS and PFA content concrete mixes were increased the flexural strength more than Portland cement concrete mix. However, this research was applied the same strength are considered. For instance C40 and C50 concrete mixes.

4.4 Summary of main findings

Observations showed that the values obtained from slump tests of PC and PFA concretes with RCA are lower than the equivalent natural aggregate concretes. Beside of this, GGBS mixes with RCA result even lower slump values. The reason for this is explained as a result of increasing the amount of the high absorption attached cement paste by using RCA content in the concrete mix. Whereas, silica fume mixes, addition of RCA is found to have slightly difference in the value obtained from slump test. When PFA mixes are compared against PC mixes, since PFA mixes have lower water content and higher cement material, PFA mixes are found to have marginally lower slump values than equivalent PC mixes. When RCA is used in the concrete mix, greater water content is needed than the PFA mixes. Therefore, using PFA mixes instead of RCA mixes reduce the demand of water in concrete mixes. When silica fume mixes are compared over all types of mixes, silica fume mixes are found to have the lowest slump value. This is because in silica fume mixes, large surface area of the silica fume particles requires to use more water content which will then increase the water content in the mix and hence result in the reduction of slump value. The effect of having low water cement ratio specifically in group C conclude that superplasticizers are needed to be included in the mixes containing silica fume.

The laboratory test results were explained that SF content concrete mixes were increased the compressive and flexural strength of the concrete. Specially, 15% SF content concrete was helped to improve the compressive and flexural strength with using 30% RCA content in the concrete mix, because of chemical and physical effects contributed by SF. Chemical effect is largely because of the pozzolanic reactions between calcium hydroxide (CH) obtained from the hydration of PC and the amorphous silica present in SF to produce secondary calcium-silicate-hydrates (C–S-H). On the other hand, PFA content concrete mixes had greater compressive and flexural strength results than GGBS content concrete mixes. On the other hand, if GGBS and SF content concrete mixes were investigated, the particle size and surface area also increase the rate of reactivity. SF has very fine particle size (0.1-0.3 μm) compared to that of GGBS (10-20 μm). Hence, the rate of pozzolanic reaction of SF is noticeably higher than those of GGBS. Hence, SF starts to pay much contribution to the strength enhancement at 7 days in hydration compared to GGBS. However, it is clear from the test results that sufficient quantities of CH should be available before getting the benefit of SF. As mentioned before, this research was considered only the same strength and flexural strength in all of the mixes.

5 Thermal Properties of Concrete Mixes

5.1 Introduction

In this chapter, twenty eight mixes are examined to understand that how different types of cement materials (PFA, GGBS, SF) affect the thermal properties of concrete. Secondly, types of aggregates are used to identify the effects of thermal properties on the concrete. 30% of natural aggregate was replaced by recycled coarse aggregate to analyse the effect of thermal properties. Thirdly, Water-cement ratio of mixes can be investigated. In other words, especially Group C concrete mixes were minimized the water cement ratio to define the effects on thermal properties of the concrete.

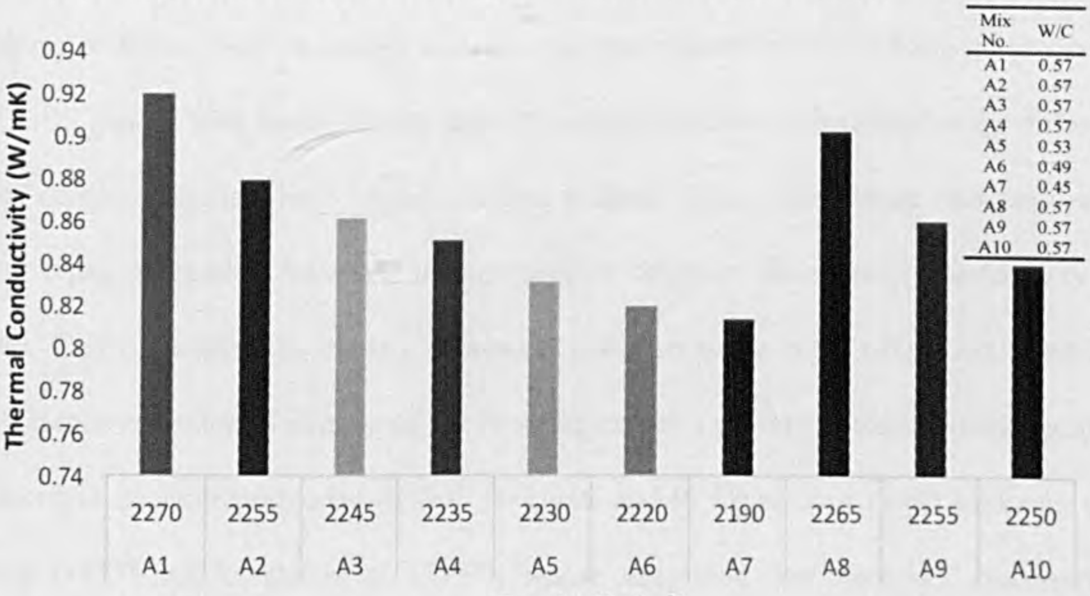
According to BS EN ISO 10456:2007 tests relating to thermal namely: thermal conductivity, density and specific heat capacity of the concrete are carried out and results are reported given that moisture content of the mixes are kept at constant value by using the dry conditions of all materials before casting. By this way, the effect of moisture content is not taken into account. Curing condition where the concretes were kept was water tank is 22 degrees. The concrete samples were tested after 28 day of curing. Before testing of each concrete sample, samples are dried by using oven that is ranged between 100-110 degrees of temperature until the unit weight of the concrete is observed to be constant.

There is not too much available information about thermal properties of concrete. However, this research provides deeply investigation related about thermal properties of concrete construction materials. This chapter is helped to identify the different type of cement materials and type of aggregates are improved the thermal properties of concrete hence developing the thermal mass of the concrete for future.

5.2 Thermal Properties

In this section, after the concrete samples were curried 28 days, the related tests were applied for thermal properties of concrete samples. According to related samples size were applied for thermal properties tests. Such as Thermal conductivity test sample was used 75x300x300mm (slab), with dried condition whereas, the unit weight of samples were constant at room temperature 20 +/- 2°C. The second thermal properties test of specific heat capacity of samples size were used 70x70x70mm (cube) with dried condition. The last thermal test is density of the concrete, the samples size was applied 100x100x100mm (cube). All of these tests were done by testing 3 specimens for each test to accurate the exact results for thermal properties of concrete mixes. The following section, different types of cement material such as PFA,GGBS and SF content concrete mixes (Group A), 30% RCA was added concrete mixes (Group B), and water cement ratio was minimized the range of 0.5-0.6 to 0.3-0.35 (Group C) are compared the thermal properties of concrete. This section is helped to understand the construction materials effect on the thermal properties of concrete.

5.2.1 Effects of Different Types of Cements on the Thermal Properties of Concrete



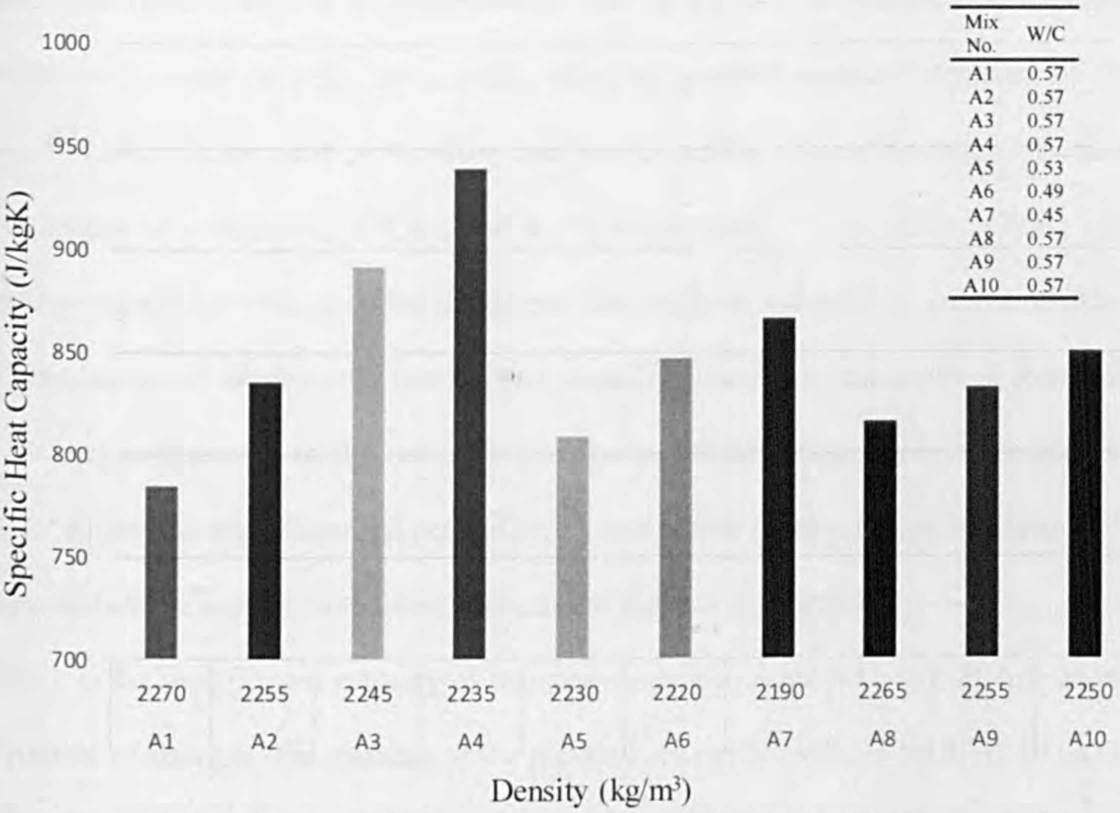
Mix No.	W/C
A1	0.57
A2	0.57
A3	0.57
A4	0.57
A5	0.53
A6	0.49
A7	0.45
A8	0.57
A9	0.57
A10	0.57

Figure 5-1 Thermal Conductivity of concrete varying density (Group A mixes)

The tests results were done for different types of cement materials used separately in the concrete mixes. Such as PFA, GGBS and SF materials were replaced with different percentage in the cement content of the concrete mixes. The first concrete mix is 100 % Portland cement (A1) to be control mix. PC was replaced by GGBS, 45 (A2), 55 (A3), and 65 (A4) % in the concrete mixes. PFA was replaced part of Portland cement by 10 (A5), 20 (A6), 30 (A7) % in the concrete content. SF was added in the cement content by 10 (A8), 15 (A9), and 20 (A10) % in the concrete mixes. In all of the concrete mixes were used only natural coarse aggregate to make the concrete mixes. This section aim is to compare the different types of cement materials with different percentages used in the concrete mixes. In other words, the different types of cement materials how can be affected the thermal properties of concrete hence thermal mass of concrete. Such as thermal conductivity, specific heat capacity and density of the concrete were done to analyse the thermal properties of concrete.

Since, replacing cement by PFA or SF reduces the density of concrete content. When the Portland cement is replaced by PFA, GGBS or SF, an association of the higher the percentage of applying different types of cement material, the lower the thermal conductivity achieved. PFA, GGBS and SF have lower density than PC content concrete. it is related to the different types of cement materials have higher air-void content. This is the reason that increasing different types of cement materials in the concrete decrease the thermal conductivity of concrete. This is because the density decreased with increasing types of cement materials content. Hence reduction of density of the concrete causes a decline in thermal conductivity. Such decrease is also reported by R. Gul, H. Uysal and R. Demirboga (1997), Akman and Tasdemir (1977) and Lu-shu et al. (1980), whose suggested that there is a relationship between density and thermal conductivity where the thermal conductivity increases as the density gets greater.

The results are shown that when SF, GGBS and PFA are used instead of PC percentage the thermal conductivity and density are decreased. When the percentage of PFA content in the concrete mix is increased to 10 (A5), 20 (A6) and 30 % (A7) by replacement of PC, this results in the reduction of the thermal conductivity value by 9.8, 10.9, 12 % respectively. When the PC is replaced by GGBS, 45 (A2), 55 (A3), 65 % (A4) replacement of PC decrease thermal conductivity by 4.5, 6.5, and 7.6 % respectively. On the other hand, when 10 (A8), 15 (A9) and 20 % (A10) of PC is substituted with SF, this interchange reduces the thermal conductivity by 2.2, 6.5 and 8.7 % correspondingly. As a result of this, it can be concluded that the higher percentage of cement replaced, the lower thermal conductivity is achieved. However, it is the also vital to take account the chemical and physical properties of cement replacement. For instance, the percentage of GGBS content in concrete mix is higher than SF concrete mix but the effect of SF is higher than the GGBS. As well as this, replacing cement by silica fume reduce the thermal conductivity of the concrete. The main reason is silica fume and PFA are more reactive material than GGBS. Silica fume is mainly based on amorphous (non-crystalline) silicon dioxide (SiO2). The individual particles in silica fume are very small in size such 1/100th amount of a mean cement size. This property of silica fume and in addition to this, having fine particles with large surface area and high SiO2 content, enables silica fume to act as an extremely reactive pozolan when this material is used in the production of concrete.



Mix No.	W/C
A1	0.57
A2	0.57
A3	0.57
A4	0.57
A5	0.53
A6	0.49
A7	0.45
A8	0.57
A9	0.57
A10	0.57

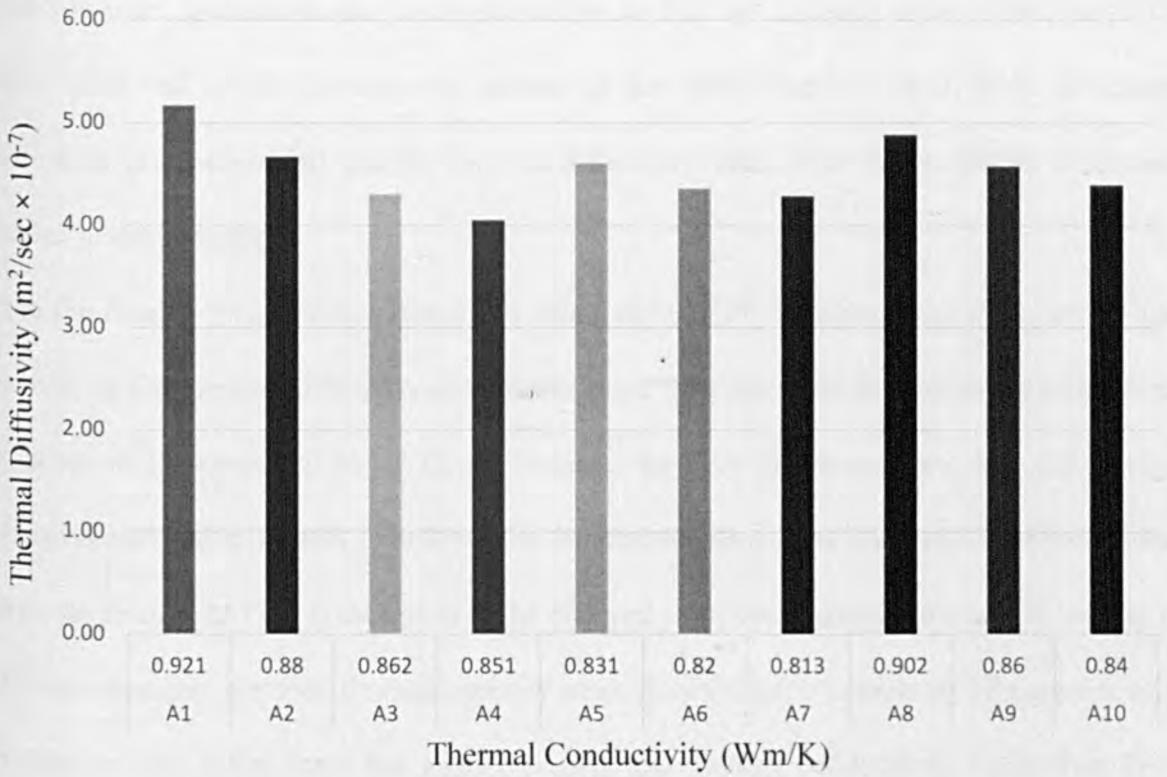
Figure 5-2 Specific heat capacity of concrete varying density (Group A mixes)

When the different types of cement material is included in cement, the results obtained showed that increasing the amount of types of cement (such as GGBS, PFA and SF) results in raising the specific heat capacity of the concrete. The lowest specific heat capacity concrete is obtained when is used 100% PC. It is because the Portland cement has lower air-void contents than the other different types of cement materials. This is the reason that specific heat capacity of PC concrete has less value than others.

Whereas, the highest percentage of the specific heat capacity of the concrete is obtained when GGBS is used instead of a point of PC is replaced by GGBS, 45 (A2), 55 (A3), and 65 (A4) %. For instance, when this replacement of PC results in increase specific heat capacity of concrete by 6.5, 13.6, and 19.7 % correspondingly. Because of GGBS may have large interface area than Portland cement to increase the specific heat capacity of the concrete, And also the results are shown that GGBS content increased in the concrete with increasing the specific heat capacity of the concrete.

When silica fume is used as a replacement of part of the PC. the specific heat capacity of concrete is increased as well. For example. when the portland cement is replaced by Silica fume. 10 (A8). 15 (A9), and 20 % (A10) . this interchange of cement increased the specific heat capacity of conctere by 3.9. 6.1 and 8.3 % respectively. Y.Xu. D.D.L. Chung (2002) state that when silica fume is added in cement, this results in reduction in thermal diffusivity and simultaneously improve the specific heat capacity. Therefore. this causes a reduction in the thermal conductivity of the concrete. The reason for this reduction is explained as the boarder among the silica fume and cement acting as a barrier relative to heat conduction. That is why silica fume content in concrete decrease the thermal conductivity.

Increase in the specific heat capacity of the concrete is also achieved when PFA is added to the content of concrete. For instance, if the portland cement is replaced by PFA. 10 (A5), 20 (A6) and 30% (A7) admixtures of cement results in increase the specific heat capacity of concrete by 3.1. 7.9. and 10.3 % respectively. However. the results of the experiments concluded that Silica Fume concrete mixes are shown higher specific heat capacity than PFA concrete mixes. 10 % Sf (A8) is found to have greater specific heat capacity than 10 % PFA (A5).



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
W/C Ratio	0.57	0.57	0.57	0.57	0.53	0.49	0.45	0.57	0.57	0.57
Density (kg/m^3)	2270	2255	2245	2235	2230	2220	2190	2265	2255	2250
Specific Heat Capacity (J/kgK)	785	836	892	940	809	847	866	816	833	850

Figure 5-3 Thermal Conductivity of concrete varying thermal diffusivity (Group A)

Thermal diffusivity is related to the three thermal properties of concrete namely; specific heat capacity, density and thermal conductiviy. Particularly, the specific heat capacity of concrete is increased when of the concrete is reduced the thermal conductivity. However, the thermal conductivity of concrete is increased when the thermal diffusivity of concrete is raised. The results are explained that when PC is replaced by PFA, 10 (A5), 20 (A6) and 30% (A7) this alternate usage results in reduction of the thermal diffusivity 11.5, 15.4, and 17.3% respectively. This reduction is related to add PFA in the concrete mixes decrease the density with decreasing thermal conductivity and increasing specific heat capacity of the concrete. On the other hand, when silica fume is used the reduction in thermal conductivty more than

GGBS is used in the concrete as an alternative to PC. For instance when reduction in the Silica fume and GGBS concrete are compared that Silica fume is used 20 % of cement content in the conrete has greater thermal diffusivity value than 45 % GGBS of cement content in the concrete.

From the results, it can be concluded that when 10 % of PC is replaced by PFA, this results decrease in the thermal diffusivity of concrete more than the same amount of the silica fume replacement However, 20 % of PC is replaced by PFA in the concrete has the thermal diffusivty resulted to be less than the same amount of silica fume concrete. This means that when the amount of PFA is increased in the concrete with decreasing in thermal diffusivity as well as increasing the specific heat capacity more than the same amount of SF concrete mix. .In other words, Silica fume has greater density and thermal conductivity value than PFA. Beside of this, thermal diffusivity is concluded to have indirect proportional with the specific heat capacity of concrete. The laboratory results are observed that the density of concrete is slightly decreased with increasing the different types of cement material. The results are also identified that the density and thermal conductivity have a direct proportional. In other words, the density of concrete is increased with increasing thermal conductivty of concrete.

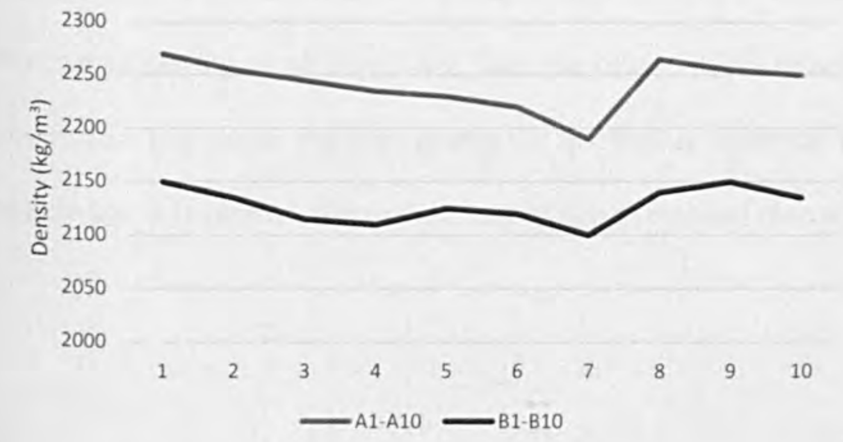
5.2.2 Effects of Recycled Coarse Aggregate on the Thermal Properties of Concrete

Essensitially, aggregate types are investigated by using Natural coarse aggregate and Recycled Coarse aggregate. In this section, the natural coarse aggregate was replaced 30 % by Recycled coarse aggregate used in the all of the mixes (Group B). Firstly RCA content in the concrete mixes were investigated to understand the effects on the thermal properties of the concrete. Secondly, 30% RCA content with different types of cements were applied together to analyze the influence of the thermal properties of the concrete.

Group B concrete mixes were used same different types of cement with using same percentage in the concrete like Group A. The first concrete mix is included 100% Pc with

30% RCA content to be a control mix. Portland cement was replaced by GGBS, 45 (B2), 55 (B3), 65 (B4) % with adding 30% RCA in the concrete mixes. PFA was added in the cement content by 10 (B5), 20 (B6), 30 (B7) % with adding 30 % RCA in the concrete mixes. SF was applied in the cement content by 10 (B8), 15 (B9) and 20 (B10) % with using 30 % RCA in the concrete mixes.

The laboratory results are found that the Recycled Coarse Aggregate is decreased the density and thermal conductivity of the concrete mixes. This decreasing is related about the recycle aggregate has grea ter air voids content than natural coarse aggregate material. On the other hand, RCA is included different types of material such as plastic, wood and etc. This is also affected thermal properties of concrete compared against the natural coarse aggregate.

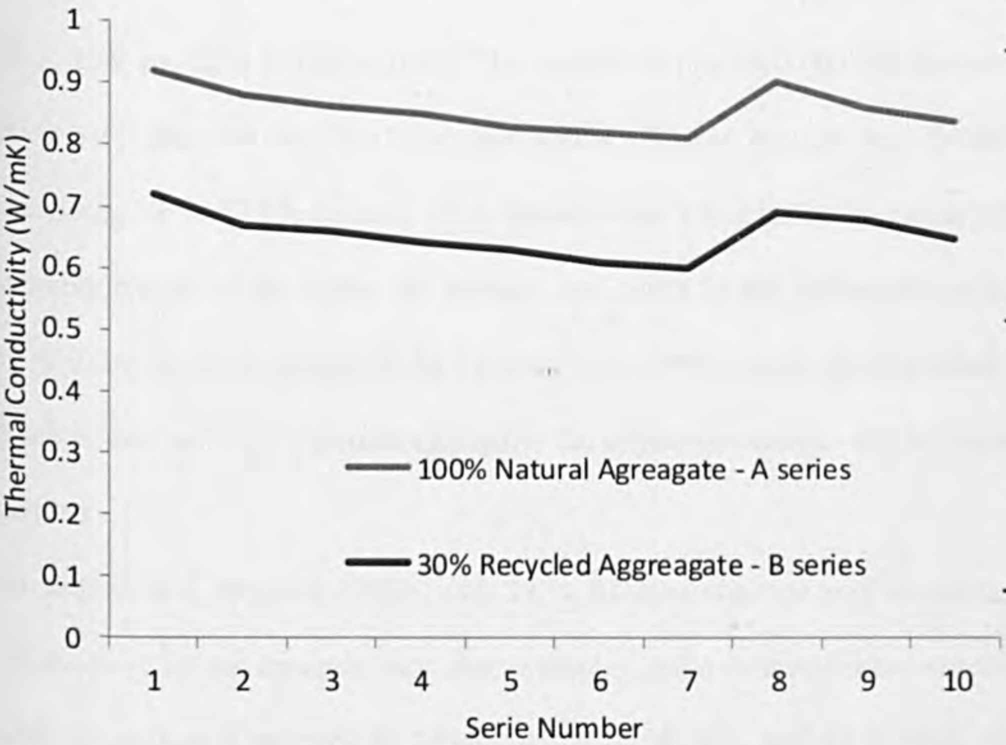


Mix No.	W/C
A1	0.57
A2	0.57
A3	0.57
A4	0.57
A5	0.53
A6	0.49
A7	0.45
A8	0.57
A9	0.57
A10	0.57
B1	0.59
B2	0.59
B3	0.59
B4	0.59
B5	0.55
B6	0.51
B7	0.47
B8	0.59
B9	0.59
B10	0.59

Figure 5-4 Comparing density of 100% NA and 70% NA + 30%RCA concrete mixes

The Figure 5.4 shows that when Natural Coarse aggregate is replaced by Recycled Coarse aggregate with 30 % content in concrete mixes, the density of the concrete is decreased. For instance, 100 % portland cement with 30 % RCA content concrete mix is decreased the density by 5.3 % by comparing with 100 % PC and 100 % NA content concrete mix.

The results are reported that when 30 % RCA and PFA is added in the concrete mixes, this decreased the density by 4.7, 4.5 and 4.1 % when compared against A5, A6 and A7 concrete mixes. On the other hand, if the 100 % PC and 30 % RCA content concrete mix is compared against PFA and 30 % RCA content mixes, B1 is found to decrease density greater than PFA and 30 % RCA content mixes. Examination of GGBS and 30 % RCA content concrete mixes showed that the density of the concrete is decreased when such mixes are used. For instance, when 30 % RCA with the cement is replaced by GGBS by 45, 55 and 65 %, this interchange results in decrease in the density by 5.3, 5.8 and 5.6 % by observing with A2, A3 and A4 concrete mixes. 45 % GGBS and 30 % RCA content concrete mix is equally decrease the same percentage when compared against 100 % Portland cement with 30% RCA content concrete mix. Whereas, when 45 % GGBS with 30 % RCA content concrete mix is used, the decrease in density is observed less than the other GGBS concrete mixes. Because of the porous and less dense residual mortar lumps that is adhering to the surfaces. When the particle size is increased, the volume percentage of residual mortar will increase too.



Mix No.	W/C
A1	0.57
A2	0.57
A3	0.57
A4	0.57
A5	0.53
A6	0.49
A7	0.45
A8	0.57
A9	0.57
A10	0.57
B1	0.59
B2	0.59
B3	0.59
B4	0.59
B5	0.55
B6	0.51
B7	0.47
B8	0.59
B9	0.59
B10	0.59

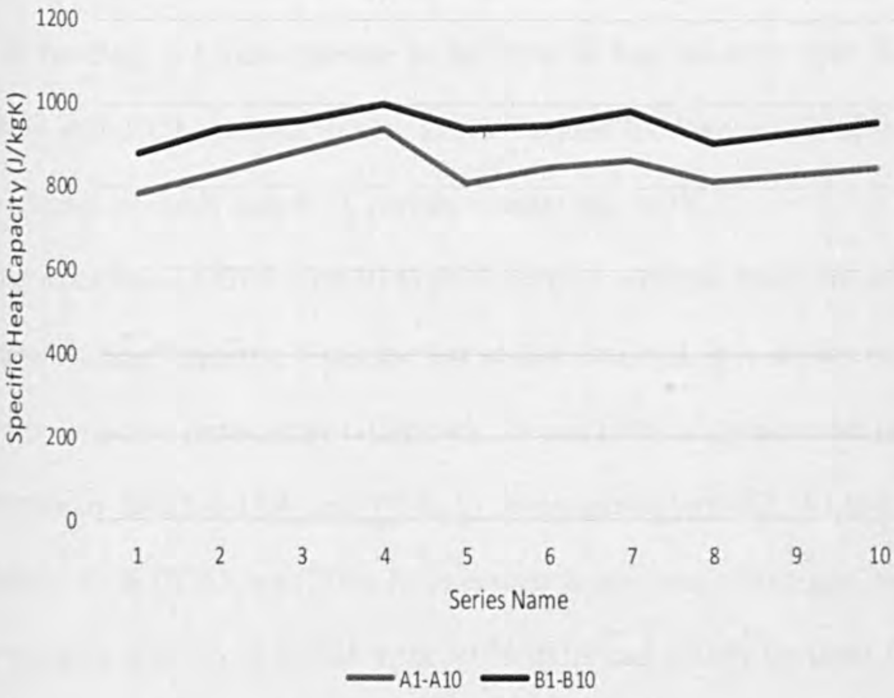
Figure 5-5 Thermal Conductivity values of 100% NA and 70% NA + 30% RCA concretes

The Figure 5.5 is shown the effects of the recycled coarse aggregate on the thermal conductivity of the concrete mixes. The figure is compared the group A and B mixes to investigate the influence of the RCA material on the thermal conductivity of concrete. The laboratory test results conclude that Recycled Coarse Aggregate is replaced by 30 % of coarse aggregate in all the concrete mixes. Containing 100 % NA with 100 % PC (A1) is compared with100 % PC with 30 % RCA concrete mix (B1), it is found that B1 is 21.7 % less thermal conductivity than A1 mix. However, the greatest decreasing in thermal conductivity which is 25.9 % of thermal conductivity in B7 concrete mix (30 PFA + 30% RCA) by comparing with A7 concrete mix. On the other hand, when 30 % RCA content with the cement is replaced by PFA, 10 (B5), and 20 % (B6) replacement of Portland cement is resulted in decrease the thermal conductivity 24.1, and 25.6 % by making observation with A5 and A6 concrete mixes respectively. When Silica Fume and Recycled coarse aggregate are used in concrete mix, it is concluded that both materials decrease the thermal conductivity of the concrete. For instance, 30 % RCA content with the cement is replaced by Silica Fume, 10 (B8), 15 (B9) and 20 % (B10) of replacement of PC is decreased the thermal conductivity 23.3, 20.9 and 22.6 % respectively. The results are provided that B8 concrete mix is greater decreasing than B9 and B10 concrete mixes. This is because the density reduced with increasing SF and PFA content. RCA concrete has less density by means of SF and PFA is possibly related to the higher air content, and partly to the amorphous structure of SF and PFA. From the study conducted by Fu and Chung (1997), it can be concluded that when silica fume is used with light weight aggregate, the effect on concrete will be increase in air void content.

As well as this, applying GGBS with 30 % RCA in concrete mix is decreased the thermal conductivity of the concrete mix. For example, in the concrete mix containing 30 % RCA with the cement is replaced by GGBS, 45 (B2), 55 (B3), and 65 % (B4) of replacement of Portland cement is decreased the thermal conductivity 21.7, 23.9 and 23.3 % by observing from 45 (A2), 55 (A3) and 65 (A4) with 100 % natural aggregate concrete mixes. The results are shown that 55 % GGBS with 30 % RCA concrete mix is decreasing the thermal conductivity more than B2 and B4 concrete mixes. The test results are shown that up to certain point adding GGBS such as 55% in the concrete content decreased the thermal conductivity more than 65% GGBS content in RCA concrete mixes. in other words, after 55% GGBS, cannot be affected thermal conductivity compared against 65% GGBS.

At the same time, the results are provided that 10 and 20 PFA % with 30 % RCA concrete mixes are decreasing the thermal conductivity greater than 10 and 20 Silica Fume with 30 % RCA content concrete mix. However, 45 GGBS with 30 % RCA concrete mix is greater thermal conductivity than all of the PFA content with 30 % RCA concrete mixes. This is because PFA is more affective material than other different types of cement materials.

Additionally, the researchers also reported that the thermal conductivity decreased due to the decrease observed in density of the concrete. Lu-shu et al. (1980) mentioned that thermal conductivity increases by increasing the density of the concrete by applying formulations generated experimentally. (R. Gul, H. Uysal and R. Demirboga (1997), Akman and Tasdemir (1977) and Blanco et al. (2000)).



Mix No.	W/C
A1	0.57
A2	0.57
A3	0.57
A4	0.57
A5	0.53
A6	0.49
A7	0.45
A8	0.57
A9	0.57
A10	0.57
B1	0.59
B2	0.59
B3	0.59
B4	0.59
B5	0.55
B6	0.51
B7	0.47
B8	0.59
B9	0.59
B10	0.59

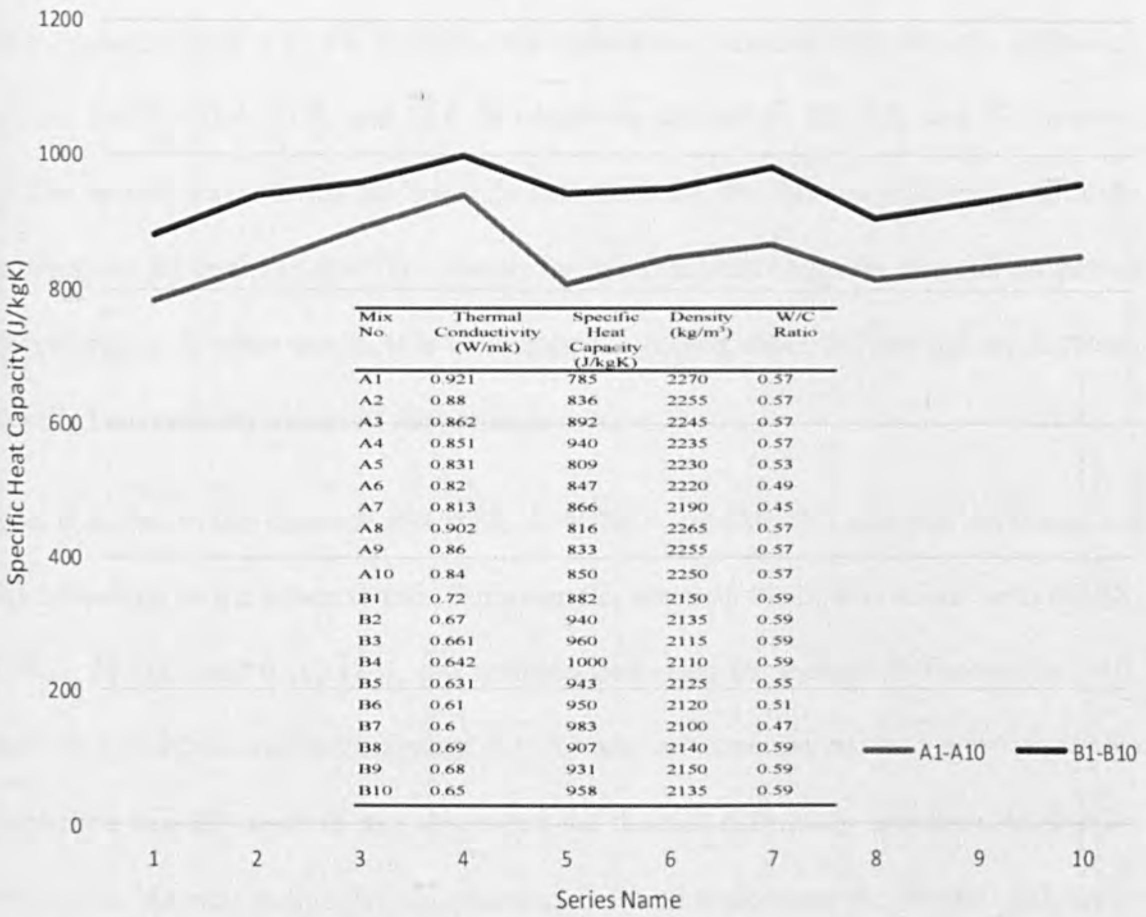
Figure 5-6 comparing the specific heat capacity of 100% NA and 70% NA + 30% RCA concrete mixes

The Figure 5.6 is shown that using 30 % Recycled Coarse aggregate in the concrete mix is increased the Specific Heat Capacity of concrete mix. The main reason for this is RCA content concrete mixes have higher air voids content than natural aggregate concrete mixes. This is affected the thermal properties of concrete. For instance, high air voids content decrease the density and thermal conductivity, increase the specific heat capacity. For example, 100% PC with 30 % RCA content concrete mix is increased the specific heat capacity of concrete by 12.4 % compared with 100 % portland cement with 100 % Natural aggregate concrete mix.

By using Silica Fume with 30 % RCA content in concrete mixes resulted an increase in the specific heat capacity of concrete. For example, when the proportion of PC in the concrete such as 10%, 15% and 20% is replaced by silica fume, the mix containing 30 % RCA with the the silica fume results in increase in the specific heat capacity by 11.2, 11.8, and 12.7 % by comparing against 10, 15 and 20 % Silica Fume with 100 % Natural aggregate. At the same time, the laboratory reults are identified that 10 % silica fume with 30 % RCA concrete mix is resulting a higher increase in the specific heat capacity than the other silica fume contents with RCA concrete mixes. This is because RCA and SF used in the concrete mixes have greater air-voids than RCA content conrete mix (A1).

On the other hand, GGBS with 30 % RCA content concrete mixes are resulted an increase in the specific heat capacity. From the test results obtained, it is shown that when 30 % RCA with the cement is replaced by GGBS, 45, 55 and 65 % of replacement increased the specific heat capacity by 12.4, 12.4 and 7.6 % by investigating with A2, A3 and A4 concrete mixes. However, 45 % GGBS with 30 % RCA content concrete mix is equaly increasing the specific heat capacity with 55 % GGBS with 30 % RCA and 100 % Portland Cement with 100 % Natural aggregate content concrete mixes. As well as this, 65 % GGBS with 30 % RCA content concrete mix resulted in an increase in the specific heat capacity less than B2 and B3 concrete mixes. The main reason is when greater quantity of GGBS content in the concrete mix is used, this results in increase in the air-voids in the concrete and hence affect the specific capacity value directly. In other words, increasing GGBS content in the concrete is increased the specific heat capacity of the concrete.

The observation is made that 30 % RCA with the portland cement is replaced by PFA, 10, 20 and 30 % of replacement is increased the specific heat capacity 16.6, 12.2 and 13.5 % by defining with A5, A6 and A7 concrete mixes. the results are shown that 10 % PFA and 30 % RCA content concrete mix is increased the specific heat capacity greater than other mixes. on the other hand, B6 concrete mix is increased the specific heat capacity less than B1 concrete mix. It can be possible that RCA content was not known exactly how much materials such as wood plastic or cement paste included in RCA materials in the concrete mix. This is the reason that 10 % PFA with 30 % RCA content concrete mix have higher reduction by comparing B1 concrete mixes. there is not enough information about it.



Mix No.	Thermal Conductivity (W/mk)	Specific Heat Capacity (J/kgK)	Density (kg/m^3)	W/C Ratio
A1	0.921	785	2270	0.57
A2	0.88	836	2255	0.57
A3	0.862	892	2245	0.57
A4	0.851	940	2235	0.57
A5	0.831	809	2230	0.53
A6	0.82	847	2220	0.49
A7	0.813	866	2190	0.45
A8	0.902	816	2265	0.57
A9	0.86	833	2255	0.57
A10	0.84	850	2250	0.57
B1	0.72	882	2150	0.59
B2	0.67	940	2135	0.59
B3	0.661	960	2115	0.59
B4	0.642	1000	2110	0.59
B5	0.631	943	2125	0.55
B6	0.61	950	2120	0.51
B7	0.6	983	2100	0.47
B8	0.69	907	2140	0.59
B9	0.68	931	2150	0.59
B10	0.65	958	2135	0.59

Figure 5-7 Comparing the thermal diffusivity of 100% NA and 70% NA + 30% RCA concrete mixes

Figure 5.7 is shown that adding the Recycled Coarse aggregate in the concrete is decreased thermal diffusivity in all mixes. By using 30 % RCA with 100 % PC content, concrete mix resulted in a decrease in the thermal conductivity by 26.9 % when compared against 100 % PC and 100 % Natural aggregate mix. The main reason is thermal diffusivity is related about thermal conductivity, specific heat capacity and density of the concrete. In other words, RCA content concrete mixes have lowest thermal diffusivity because RCA content concrete has lower density and thermal conductivity value hence greater specific heat capacity of the concrete.

Conversely, the greatest decrease in thermal diffusivity is observed when PFA with 30 % RCA content is used in concrete mixes. For instance, when 30 % RCA with the Portland cement is replaced by PFA by 10, 20, 30%, this replacement decreased the thermal diffusivity of concrete mix by 32.6, 31.8, and 32.6 % which are defined by B5, B6, and B7 concrete mixes. The results showed that B5 concrete mix decrease the thermal diffusivity with the same amount as B7 concrete mix. The reason for this is related about the thermal properties of concrete mixes. In other words, it is related mostly related about the thermal conductivity and specific heat capacity values of the concrete mix.

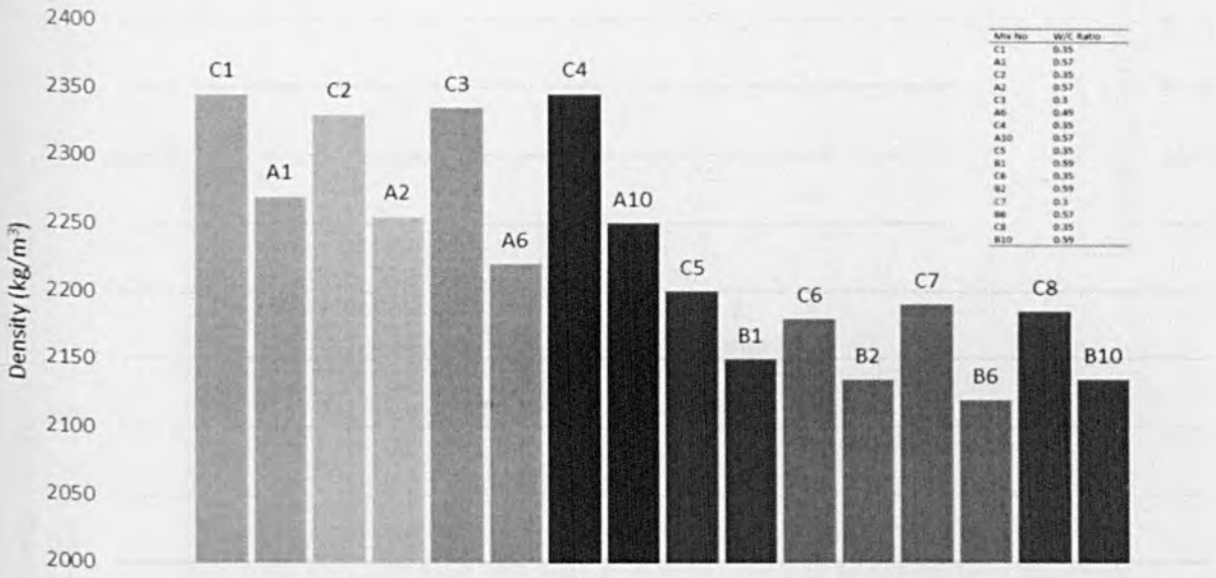
If GGBS is added to the concrete mix with 30 % RCA content, this addition decreases the thermal diffusivity of the concrete mix. For example, when 30 % RCA is added with GGBS, by 45 (B2), 55 (B3) and 65 (B4) %, this addition decreased the thermal diffusivity by 29.8, 23.3 and 26.8 % when contrasted against A2, A3 and A4 concrete mixes. Likewise, results also explained that B3 concrete mix decreased the thermal diffusivity less than B2 and B4 concrete mixes. As well as this, B1 concrete mix is found to decrease the thermal diffusivity more than B2 concrete mix when the figures of this decrease are compared. The laboratory results are proven that PC concretes have greater thermal conductivity and lowest specific heat capacity value. However, GGBS concretes have less thermal conductivity and better specific heat capacity compared with PC concretes.

Instead, when Silica fume is added to the concrete with 30 % RCA content, this addition decrease the thermal diffusivity of concrete. For instance, when 30 % RCA with the Portland cement is replaced Silica fume by 10, 15, and 20%, this interchange with Portland cement decrease the thermal diffusivity by 16.3, 26.1 and 27.3 % respectively which are defined by

B8, B9 and B10 concrete mixes. The results obtained conclude that, using 10 % of silica fume with 30 % RCA content (B8), decreased the thermal diffusivity approximately 1.5 times more than B9 and B10 concrete mixes. As well as this, it is found that B8 concrete mix decreased the thermal diffusivity less than B1 concrete mix. This is because B8 concrete mix has lower thermal conductivity and higher specific heat capacity comparing against B1 concrete.

5.2.3 Water – Cement Ratio Effects on Thermal Properties of Concrete

In this section, water cement ratio is minimized to investigate the effects on the thermal properties of the concrete mixes. For each different type of cements and recycled coarse aggregate were used in the concrete mixes. There are 8 mixes made to analyse the influence on thermal properties such as specific heat capacity, thermal conductivity and density of the concrete mixes. This eight mixes are chosen from Group A and B. Group C is divided into 2 sections. The first section was only used 100 % Natural coarse aggregate. Such as 100% PC with 100 % NA (C1), 45 % GGBS with 100 % NA (C2), 20 % PFA with 100 % NA (C3), 20 % SF with NA (C4). The second section of Group C was 70 % NA with 30% RCA in the concrete content, Such as 100% PC with 30%RCA (C5), 45 % GGBS with 30 % RCA (C6), 20 % PFA with 30 % RCA (C7), 20 % SF with RCA (C8). Investigation was made by comparing C1 and A1, C2 and A2, C3 and A6, C4 and A10, C5 and B1, C6 and B2, C7 and B6, C8 and B10 are compared in pairs due to each pair generating by using the same material. There are 2 different water cement ratio applied to investigate the effects on the thermal properties of concrete mixes. The water cement ratio ranges are 0.5 to 0.6 and 0.3 to 0.35.



Mix No	W/C Ratio
C1	0.35
A1	0.57
C2	0.35
A2	0.57
C3	0.3
A6	0.49
C4	0.35
A10	0.57
C5	0.35
B1	0.59
C6	0.35
B2	0.59
C7	0.3
B6	0.57
C8	0.35
B10	0.59

Figure 5-8 Density of concrete mixes

The Figure 5.8 described that the water cement ratio is minimized with increasing the density of the concrete mixes. For instance, when the water cement ratio range between 0.5 to 0.6, the density of RCA concrete is found to range between 2100 to 2150 kg/m^3. When the range of water cement ratio is between 0.3 and 0.35, the density of RCA concrete is observed as between 2150 to 2200 kg/m^3. Whereas, when the water-cement ratio is between 0.5 to 0.6, the density of Natural Aggregate concrete is found to range between 2200 to 2270 kg/m^3. At the same time, when the water cement ratio is between 0.3 to 0.35, the density of the natural aggregate concrete is found to be between 2335 to 2345 kg/m^3. Clearly, if the cement content increases with increasing thermal conductivity and density of the concrete mixes, this results in better dry density of concrete. Excessive water added to the paste is problematic by reducing the density of concrete. This is due to the reduction of density and increase in porosity.

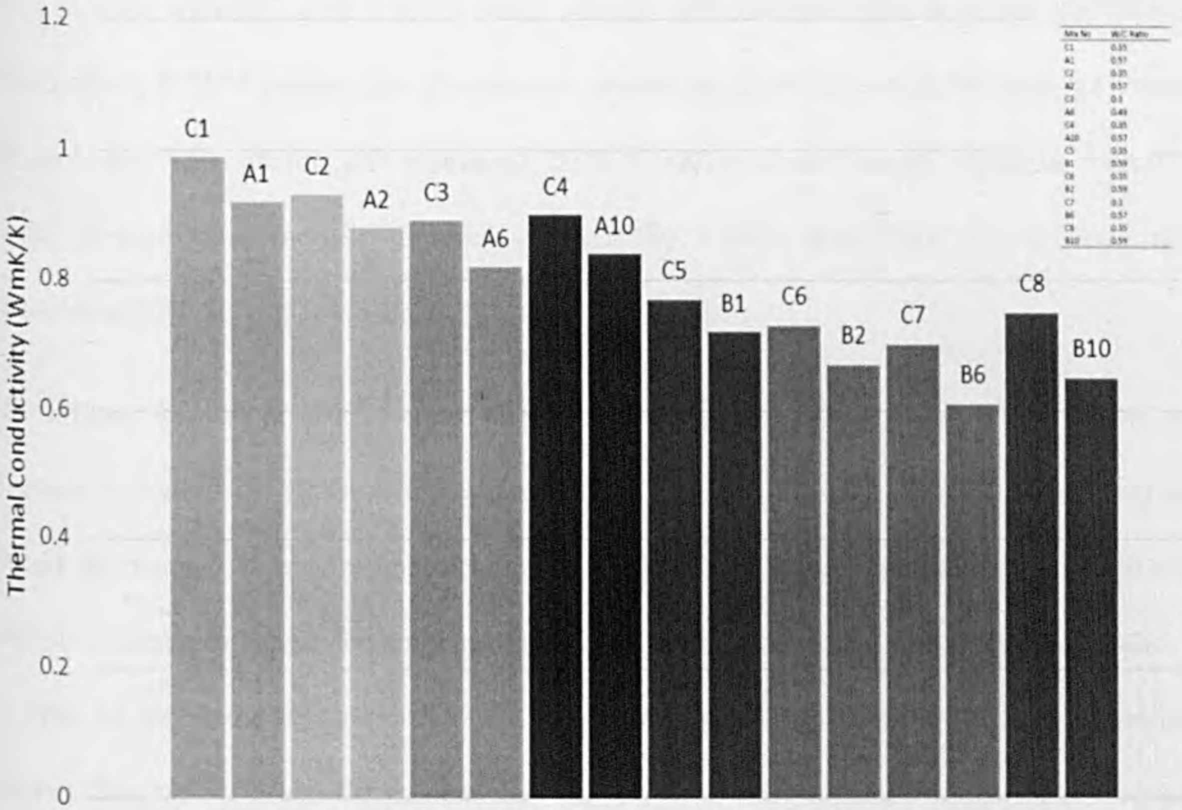


Figure 5-9 Thermal Conductivity of concrete mixes tested

The results explained that W/C ratio is minimised with increasing the thermal conductivity in all types of concrete mixes. This is because minimizing water cement ratio is improved the density of the concrete. The highest thermal conductivity values are achieved in Group C. The reason for this is Group C has the W/C ratio between 0.3 and 0.35. Instead, 100 % PC concrete mix (C1) is the concrete mix where the highest thermal conductivity is obtained. The main reason is thermal conductivity of cement is greater than thermal conductivity of water. The water cement ratio of concrete is minimized, the density of concrete increases with increasing thermal conductivity.

If the PC with NA is compared against Group C, in concrete mixes containing 100 % PC with NA (C1), an increase in the thermal conductivity is observed by 7.49 % greater than A1. From Group C, 45 % GGBS with NA concrete (C2) increases the thermal conductivity 5.80 % more than the concrete containing 45 % GGBS with NA (A2) using 0.57 W/C. When 20 %

PFA is used with NA with 0.30 of water cement ratio concrete, this increases the thermal conductivity 8.78 % greater than the concrete containing 20 % PFA with NA with 0.49 water cement ratio. The concrete mix containing 20 % Silica Fume and Natural aggregate with 0.35 water cement ratio increase thermal conductivity 7.26% more than the concrete mix containing 20% SF and NA using 0.57 water cement ratio.

Kook-Hand Kim et al (2002) stated that W/C ratio is a significant factor that affects the thermal conductivity. Because the water cement ratio is vital to produce denser concrete. When the concrete is heavier (denser), thermal conductivity of concrete is increased with unit weight of concrete. Since, the amount of aggregate used in cement is affected by W/C ratio, it is vital to determine this ratio. The reason is the thermal conductivity of aggregates has greater than water. When the cement that has low W/C ratio is added to the paste, thermal conductivity rises due to the cement having greater thermal conductivity compared to water.

As well as this, the investigation is carried out for the Recycled coarse aggregate concrete. The results showed that when RCA is used with minimizing water cement ratio; it is achieved to improve the thermal conductivity of concrete. For instance, Group C when 100 % PC with RCA concrete mix (C5) is used, this increase the thermal conductivity 6.94 % more than Group B, containing 100 % PC with RCA concrete mix (B1). The highest increase in thermal conductivity is obtained as increase in 15.38 % by using silica fume and RCA content in concrete when compared against B10 and C8. On the other hand, W/C ratio is minimized in different type of cements concrete mixes to improve the thermal conductivity of concrete mixes. It is significant to mention that RCA material has less thermal conductivity than natural aggregate. However, water cement ratio is minimized to improve the thermal conductivity of RCA content concrete. In other words, cement content is increased and make denser of RCA content concrete. It is helped to develop greater thermal conductivity of RCA content concrete.

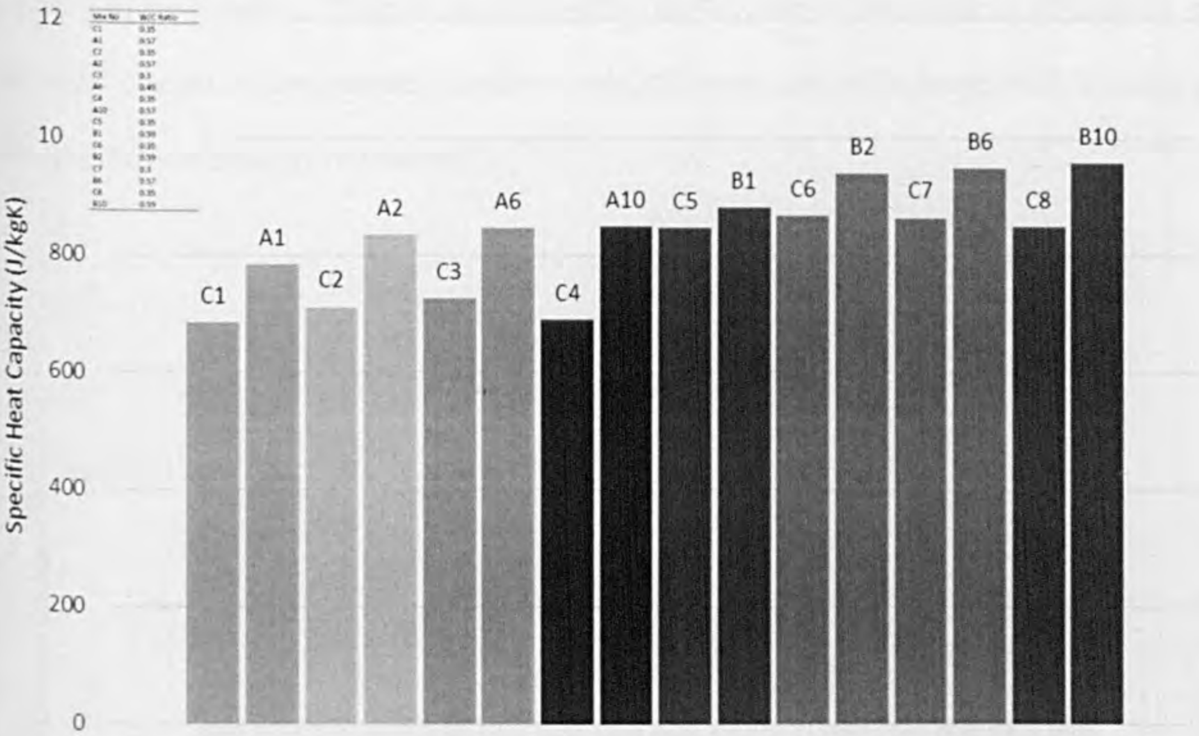


Figure 5-10 the specific heat capacity of concrete tested

The laboratory results showed that W/C ratio is minimized when the specific heat capacity of concrete mixes are decreased. This is because minimizing water cement ratio in the concrete mix provides less water and air voids content in the mix. And also the specific heat capacity of cement is lower than water. 100 % PC with 100% NA (C1) decreased the specific heat capacity by 12.6 % when compared against A1. The lowest decrease in the specific heat capacity is obtained as 3.9 % by using 100 % PC with 30 % RCA content concrete mix (C5). This is because RCA content concrete has higher air voids content, when water cement ratio is minimized to help the reduction of the specific heat capacity of concrete. Whereas, when the w/c ratio minimized such as in the GGBS concrete mix (C2), the specific heat capacity is decreased by 14.8 % that results in the highest decrease in specific heat capacity in all the mixes. This means that using GGBS in the concrete is increased the specific heat capacity but water cement ratio is minimized, it is decreased the specific heat capacity of the concrete mixes. Generally, since the water has greater specific heat capacity value than cement and aggregate, the water cement ratio is decreased in the concrete by decreasing the specific heat capacity of the concrete. The main reason to effect on the specific heat capacity of concrete is the water content of the concrete. In other words, the water content increases with increasing the specific heat capacity of concrete

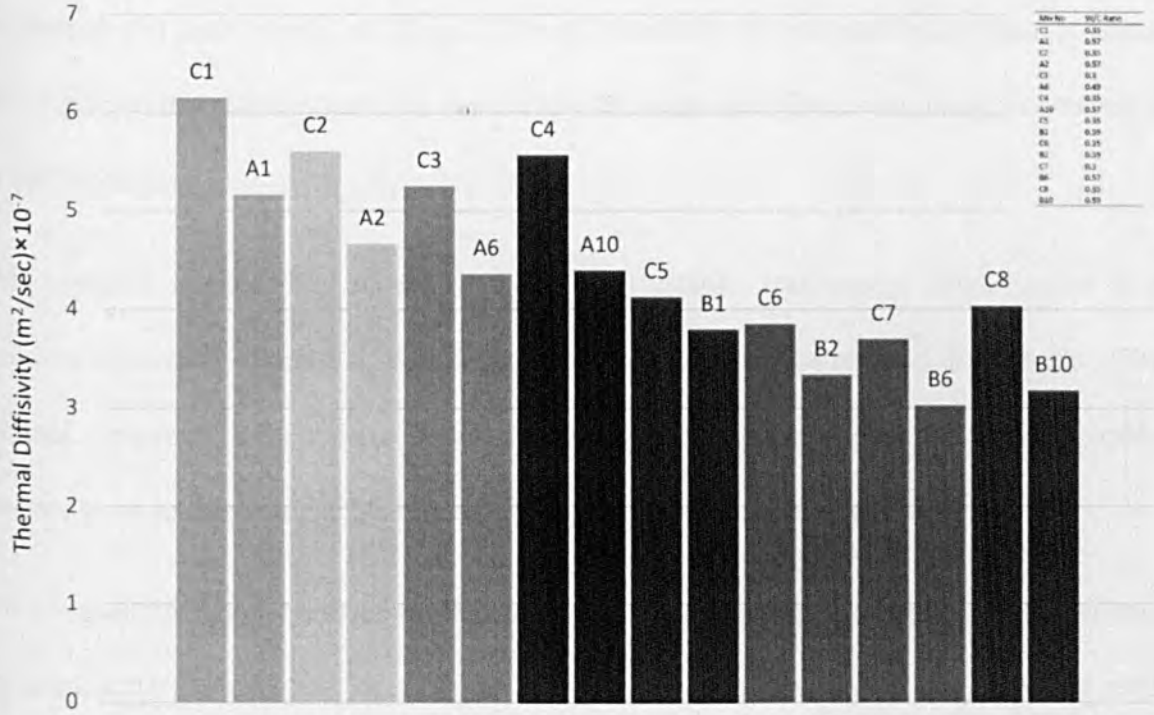


Figure 5-11 Thermal diffusivity results

Figure 5.11 shows that when minimizing water – cement ratio is used in the concrete; the thermal diffusivity of the concrete is improved. For instance, when C4 concrete mix is used, the thermal diffusivity is increased by 27.3 % when compared against A10 concrete mix. The main reason of this increase is obtaining an increase in thermal conductivity and density of concrete when decreasing the specific heat capacity of mix. In other words, the mathematical calculation is shown that the specific heat capacity of concrete is indirectly proportional with the thermal diffusivity of the concrete. Beside of this, minimizing water cement ratio is improved the thermal diffusivity of the different types of cement materials concrete mix. It is also concluded that the differences between different type of cements and PC concretes have similar range of thermal diffusivity value.

5.3 Practical Implications

Thermal properties of concrete construction materials are very important. This study provides information on how the concrete materials will be used efficiently in the construction industry. In other words, when the designing of concrete mixes for housing, commercial, residential and multi-storey buildings. Thermal properties of concrete mixes namely specific heat capacity, thermal conductivity and density are main actor for saving energy consumption in the buildings.

This research is helped to minimize the CO_2 emissions and energy consumption in the building concretes. Beside of this, research opens up the opportunity to discuss the various thermal properties of concrete materials simultaneously and hence finding the optimal thermal mass to concrete the best thermal comfort in the concrete buildings.

For instance, different types of cements and aggregates materials identified in this research are used to decide the effect of such materials on thermal properties of concrete. The results achieved from this research can be used to suggest the kind of materials can be applied in either dense or light block, concrete slab, beam, floor or wall of the building concrete components.

5.4 Summary of main findings

The laboratory tests results were analysed that PFA content concrete mixes were decreased the thermal conductivity more than other type of cements content mixes (such as SF and GGBS). 30% PFA content in concrete mix has greater reduction thermal conductivity of the concrete mix. On the other hand, 15 % SF was decreased the thermal conductivity equal percentage (6.5%) with 55% GGBS content concrete mix. Thermal conductivity of concrete is related about the types of material chemical properties. The laboratory results are shown that 10 and 20% SF content concrete has greater specific heat capacity than 10 and 20% PFA content concrete. 65% GGBS content concrete mix has greatest specific heat capacity of the concrete mix than all of the mixes. However, GGBS content was greater than SF and PFA content in the concrete. Therefore, Silica Fume content concrete mixes are more specific heat capacity values than other types of cements content concrete mixes. When the thermal diffusivity is taken into consideration, 20% SF content concrete mix has higher thermal diffusivity than 45% GGBS content concrete mix. It can be found that 10% PFA content concrete mix has decreased the thermal diffusivity more than 10% SF content concrete mix. However, 20% PFA content concrete mix has less thermal diffusivity than 20% SF content concrete mix.

When 30% natural aggregate is replaced by recycled coarse aggregate, the concrete mixes have more lightly. It means that the concrete mixes are less dense than NA concrete mixes. From the test results, the recycled coarse aggregate are affected thermal properties of concrete mixes more than the different types of cements content concrete mixes. RCA content concrete mixes have greater specific heat capacity value than NA content concrete mixes. The laboratory results are identified that 10 % silica fume with 30 % RCA concrete mix is resulting a higher increase in the specific heat capacity than the other silica fume contents with RCA concrete mixes. Recycled Coarse aggregate in the concrete is decreased thermal diffusivity in all mixes. By using 30 % RCA with 100 % PC content, concrete mix resulted in a decrease in the thermal conductivity by 26.9 % when compared against 100 % PC and 100 % Natural aggregate mix. Likewise, results also explained that 55% GGBS with 30% RCA (B3) concrete mix decreased the thermal diffusivity less than B2 and B4 concrete mixes. As well as this, B1 concrete mix is found to decrease the thermal diffusivity more than B2 concrete mix when the figures of this decrease are compared. It is found that B8 concrete mix decreased the thermal diffusivity less than B1 concrete mix.

The thermal properties of concrete mixes results are provided that Water cement ratio was minimized. The results explained that W/C ratio is minimised with increasing the thermal conductivity in all types of concrete mixes. The highest thermal conductivity values are achieved in Group C. The reason for this is Group C has the W/C ratio between 0.3 and 0.35. Instead. 100 % PC concrete mix (C1) is the concrete mix where the highest thermal conductivity is obtained. From Group C. 45 % GGBS with NA concrete increase the thermal conductivity 5.80 % more than the concrete containing 45 % GGBS with NA using 0.57 W/C. When 20 % PFA is used with NA with 0.30 of water cement ratio concrete. This increase the thermal conductivity 8.78 % greater than the concrete containing 20 % PFA with NA with 0.49 water cement ratio. The concrete mix containing 20 % Silica Fume and Natural aggregate with 0.35 water cement ratio increase thermal conductivity 7.26% more than the concrete mix containing 20% SF and NA using 0.57 water cement ratio. As well as this. the investigation is carried out for the Recycled coarse aggregate concrete. The results showed that when RCA is used with minimizing water cement ratio: it is achieved to improve the density and thermal conductivity of concrete. The highest increase in thermal conductivity is obtained as increase in 15.38 % by using silica fume and RCA content in concrete when compared against B10 and C8. On the other hand. W/C ratio is minimized in different type of cements concrete mixes to improve the thermal conductivity of concrete mixes. The laboratory results showed that W/C ratio is minimized when the specific heat capacity of concrete mixes are decreased. The lowest decrease in the specific heat capacity is obtained as 3.9 % by using 100 % PC with 30 % RCA content concrete mix (C5). Whereas. when the w/c ratio minimized such as in the GGBS concrete mix (C2). the specific heat capacity is decreased by 14.8 % that results in the highest decrease in specific heat capacity in all the mixes. The results are defined that when minimizing water – cement ratio is applied in the concrete: the thermal diffusivity of the concrete is improved.

6 Thermal Dynamic Calculation

6.1 Introduction

In this chapter, the excel spreadsheet is set up to calculate the thermal dynamic properties of concrete mixes by applying the thermal properties data (thermal conductivity, density and specific heat capacity) of the concrete mixes. Factors which affect the thermal storage are taken under examinations that include thermal admittance, decrement factor, areal heat capacity and thermal transmittance. The main aim of this chapter is to understand the effects of different types of cement materials, recycled coarse aggregate and water- cement ratio of the concrete mixes on the thermal admittance and hence thermal mass, the thermal transmittance and decrement factor of the concrete mixes. Before setting up the excel calculator, the thermal dynamic properties are calculated theoretically. That's why BS EN ISO 13786:2007 standard is used to calculate those parameters.

BS EN ISO 13786:2007 suggests that thermal performance of the component can be defined when the component dependent on changing boundary conditions such as variable heat flow rate or changing temperature on either or both of the boundaries. Variation of boundaries taken into account in this standard is only sinusoidal boundary condition where the changes in temperature or heat flow on these boundaries are considered. Thermal admittances and thermal dynamic transfer properties are concerned about associating cyclic heat flow rate and cyclic temperature changes.

Thermal admittance associate heat flow rate to temperature changes that it is occurring on the same side of the component. The thermal dynamic transfer properties depend on physical measures of one part of the component to other. By using previously indicated properties, the heat capacity of a given component is described that measures the heat storage of the component.

6.2 Underline Theory for Thermal Dynamic Calculation

According to EN 13786:2007 standard, thermal admittance is classified as the proportion amongst the complex amplitude of the heat flux density across the wall surface. This is also called as adjacent m-zone. On the other hand, same standard defines the periodic thermal transmittance as either the proportion of complex amplitude of the temperature of the m-zone or as the temperature of the zone n given that the temperature of the alternative side is kept at constant.

Periodic Penetration Depth [δ] is $\frac{\lambda T}{\pi \times \rho \times c}$ (EN 13786:2007). In uniform substances which have infinite width, deepness is reduced by the element of "e". e is the base of natural logarithms; e = 2.718...

Again, same standard is used to classify heat transfer matrix Z for each layer as the association between the temperature and heat flux in one side of the component external side e, with the same physical quantities on the other side, for example the internal side I (EN 13786:2007) (See Appendix 9.3 for more detail)

Another representation of the concept is: $\frac{\bar{Q}_2}{q_2} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \times \begin{bmatrix} Q_1 \\ q_1 \end{bmatrix}$

The periodic penetration depth for the material of the layer [δ], is calculated from its thermal properties and the period of variations [T] applying Equation of penetration depth. Then, the ratio of the thickness of the layer to the penetration depth is defined to be $\xi=\frac{d}{\delta}$.

In this case, the specific heat capacity of the layer is ignored. The thermal resistance of air layer consisting convection, conduction and radiation. The heat transfer matrix is $Z_a = \begin{bmatrix} 1 & -R_a \\ 0 & 1 \end{bmatrix}$. The thermal resistance of the air layer may be evaluated by using ISO 6946.

In building elements, the layer 1 is described as the inner layer. The heat transfer matrix is defined by the formula $Z_{ee} = Z_{S2}\, Z\ \ Z_{S1}$ where Z_{S1} and Z_{S2} are elements from heat transfer matrix. Those heat transfer matrices indicate the limits of the building component and $Z_s = \begin{bmatrix} 1 & -R_s \\ 0 & 1 \end{bmatrix}$ where R_S displays the surface resistance of the limit of the component, containing convection as well as radiation. Figures for surface resistance are in agreement with ISO 6946.

$$Z_N = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = Z_N\ Z_{N-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Z_3\, Z_2\, Z_1$$

A figure of surface resistance that is suitable to location of the component is used to evaluate the heat transfer matrix and also the features of the building. Vertical location which is heat flow horizontal is used to calculate the heat transfer matrix if the location of element is unknown. In the situation where the limits are considered individually, the periodic heat capacity of the element can be estimated by ignoring the limits of the element. The dynamic thermal characteristics of any component are four periodic thermal conductance's, *Lmn* is complex number relating the periodic heat flow into a component to the periodic temperatures on either side of it under sinusoidal conditions and also two heat capacities, *Cm* which modulus of the net periodic thermal conductance divided by the angular frequency.

The thermal admittances are $Y_{11} = \frac{-Z_{11}}{Z_{12}}$ and $Y_{22} = \frac{-Z_{22}}{Z_{12}}$ where Y_{11} is for the internal side of the component, while Y_{22} is for the external side. The time shift [Δt] of admittance, is: $\Delta t_Y = \frac{T}{2\pi} \arg(Y_{mm})$ with the argument evaluated in the range 0 to 2π radians.

There is a relationship between periodic heat flow and differences in periodic temperature when the differences in temperature are equal at both parts of panel.

The areal heat capacities are $K_1 = \frac{T}{2\pi}\left|\frac{Z_{11}-1}{Z_{12}}\right|$ and$K_2 = \frac{T}{2\pi}\left|\frac{Z_{22}-1}{Z_{12}}\right|$. These equations apply to both external elements and to internal partitions.

On the other hand, the periodic thermal transmittance is given by $Y_{12} = -\frac{1}{Z_{12}}$ and the decrement factor is given by $F = \frac{Periodic\ Thermal\ Transmittance\ (Y_{12})}{Thermal\ Transmittance\ (U_0)}$ where the thermal transmittance, U_0 is calculated in accordance with ISO 6946 ignoring any thermal bridges. Calculation of U_0 is performed by neglecting dependency while estimating the dynamic characteristics. The rule state that the decrement factor should always be less than 1. In the time range from -2π to 0, change in periodic thermal admittance is shown by $\Delta t_f = \frac{T}{2\pi}\arg(Z_{12})$.

6.3 Application of Method

Parameters investigated were internal thermal admittance, external thermal admittance, periodic thermal transmittance, internal areal heat capacity, external areal heat capacity and thermal transmittance. The main purpose was to assess the factors affecting the dynamic thermal properties of concrete. This is done by using Microsoft Excel program. However, before setting up the program itself, an example in appendix D1 of BS EN ISO 13786-2007 is used to formulate a foundation for the program. In this section, firstly the example that is used to form the foundation of the excel spreadsheet is explained and after that, detailed information is provided on how to set up the excel spreadsheet for the thermal dynamic calculations for this research.

6.3.1 Single layer component example

In the single layer component example used, because the research tests samples were single layer slab to make testing. This example was used from BS EN ISO 13786 to develop the foundation of excel spreadsheet to calculate the thermal dynamic properties of the research samples. A concrete made up with a 200mm wall is used. The physical characteristics of this concrete is given as having a thermal conductivity ʎ=1.8W/(mK), density P=2400 kg/m^3 and specific heat capacity C=1000 J/(kgK).

Time period of examination is taken as 24 hours, therefore the periodic penetration depth σ=0.144m and ε=1.393. Periodic penetration depth is calculated by using the formula σ=(ʎT)/(πpc) and the ratio of the thickness of the layer to the penetration depth, ε is calculated by using the formula ε=layer/s.

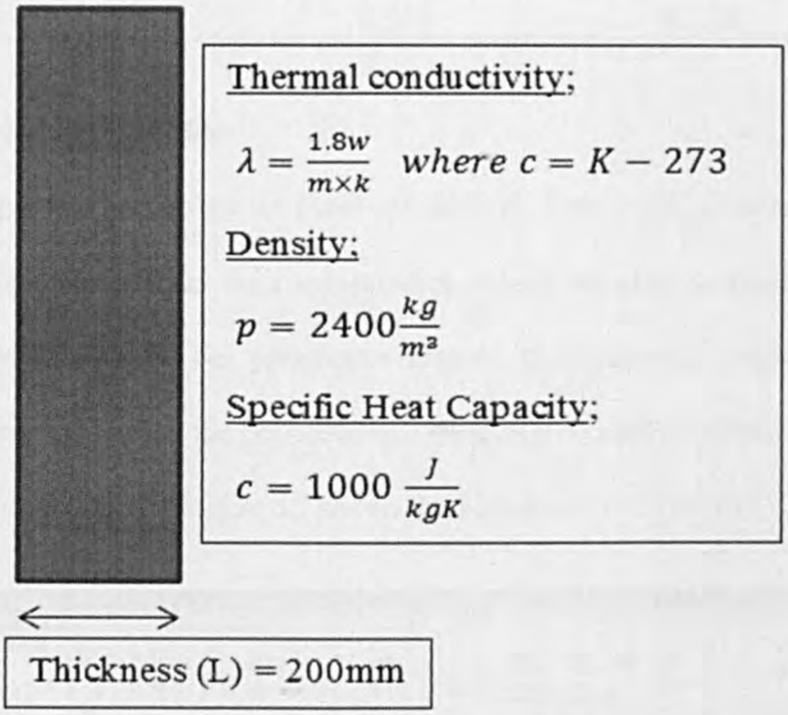


Figure 6-1 The specifications of Concrete sample (BS EN ISO 13786 example)

Table 6.1 is shown that Surface resistance values used in calculations are needed to be appropriate such as normal to high emissivity as like mentioned in the BS EN ISO 6946;

Table 6-1 The Surface Resistance of corresponding elements [BS EN ISO 6946]

Heat Flow Direction	Type of Element	Rsi (m^{2}K/W)	Rse (m^{2}K/W)
Horizontal	Wall, window	0.13	0.04
Upwards	Roof	0.10	0.04
Downwards	Floor	0.17	0.04

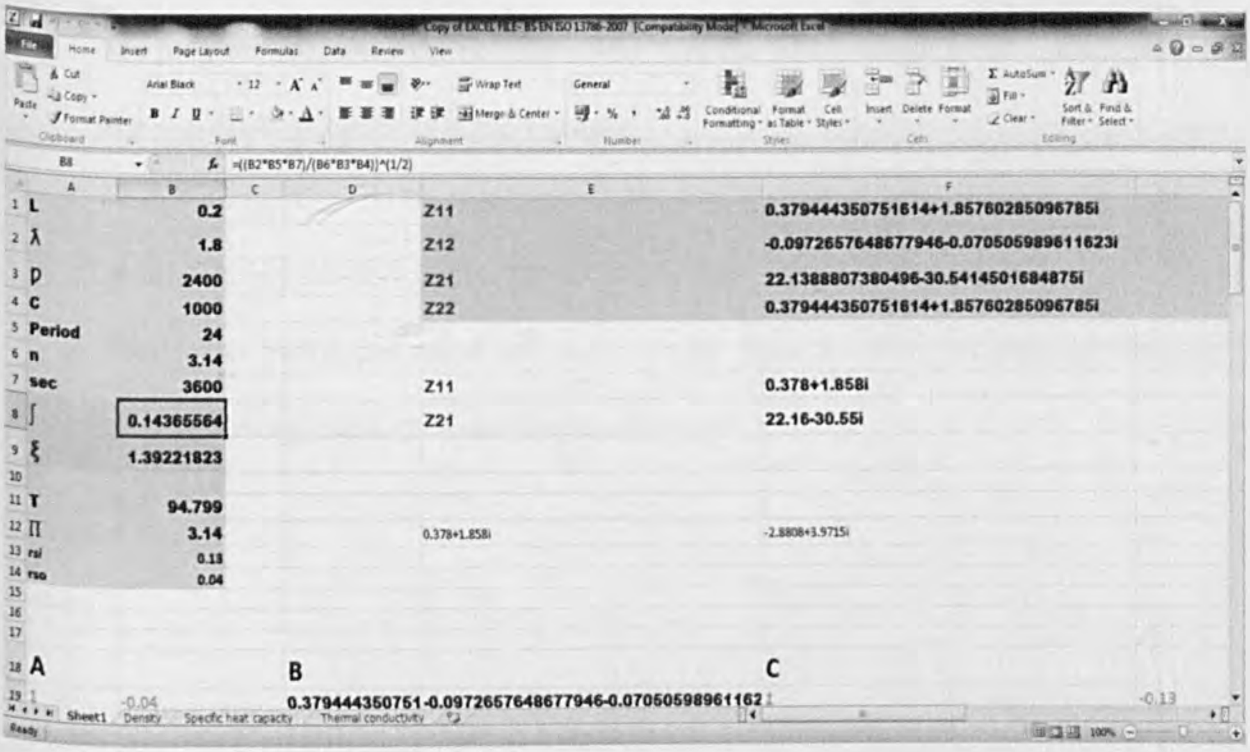
As a result, the values calculated in excel for each parameter are given at the table 5.2 below;

Table 6-2 The results obtain from excel dynamic thermal properties calculator

Name of the Parameter	BS EN ISO 13786 (Example Result)	Excel Calculator (Example Result)	Unit
Internal Thermal Admittance	5.70	5.707435	$W/m^2.K$
External Thermal Admittance	11.59	11.59949438	$W/m^2.K$
Periodic Thermal Admittance	1.83	1.828361339	$W/m^2.K$
Internal Areal Heat Capacity	86	86.10567197	$KJ/m^2.K$
External Areal Heat Capacity	171	171.0527534	$KJ/m^2.K$
Thermal Transmittance (U)	3.56	3.56	$W/m^2.K$
Decrement Factor	0.514	0.514	-

6.3.2 Developing the excel file

This section explained how to set up excel spreadsheet. First of all, in column A, names of each parameter are entered and the corresponding values for each parameter are entered in column B. After the figures for parameters namely layer, thermal conductivity, density, specific heat capacity, period, the phi-value specified as n second per depth, rsi, rso, π and T are entered in column B. The Figure 6.2 shows the foundation of excel file.



B8 =((B2*B5*B7)/(B6*B3*B4))^(1/2)

	A	B	C	D	E	F
1	L	0.2		Z11		0.379444350751614+1.85760285096785i
2	λ	1.8		Z12		-0.0972657648677946-0.070505989611623i
3	ρ	2400		Z21		22.1388807380496-30.5414501684875i
4	C	1000		Z22		0.379444350751614+1.85760285096785i
5	Period	24				
6	n	3.14				
7	sec	3600		Z11		0.378+1.858i
8	∫	0.14365564		Z21		22.16-30.55i
9	ξ	1.39221823				
10						
11	T	94.799				
12	Π	3.14		0.378+1.858i		-2.8808+3.9715i
13	rsi	0.13				
14	rso	0.04				
15						
16						
17						
18	A			B		C
19	1	-0.04		0.379444350751-0.0972657648677946-0.07050598961162		1 -0.13

Figure 6-2 Foundation of Excel ~Spreadsheet

	A	B	C	D	E	F	
1	L	0.2			Z11	0.379444350751614+1.85760285096785i	
2	λ	1.8			Z12	-0.0972657648677946-0.0705059896116231	
3	ρ	2400			Z21	22.1388807380496-30.5414501684875i	
4	c	1000			Z22	0.379444350751614+1.85760285096785i	
5	Period	24					
6	n	3.14					
7	sec	3600			Z11	0.378+1.858i	
8	ʃ	0.14365564			Z21	22.16-30.55i	
9	ξ	1.39221823					
10							
11	T	94.799					
12	Π	3.14			0.378+1.858i	-2.8808+3.9715i	
13	rsi	0.13					
14	rso	0.04					
15							
16							
17							
18	A			B		C	
19	1	-0.04		0.379444350751-0.0972657648677946-0.07050598961162		1	-0.13

Figure 6-3 Imputing the corresponding formulas

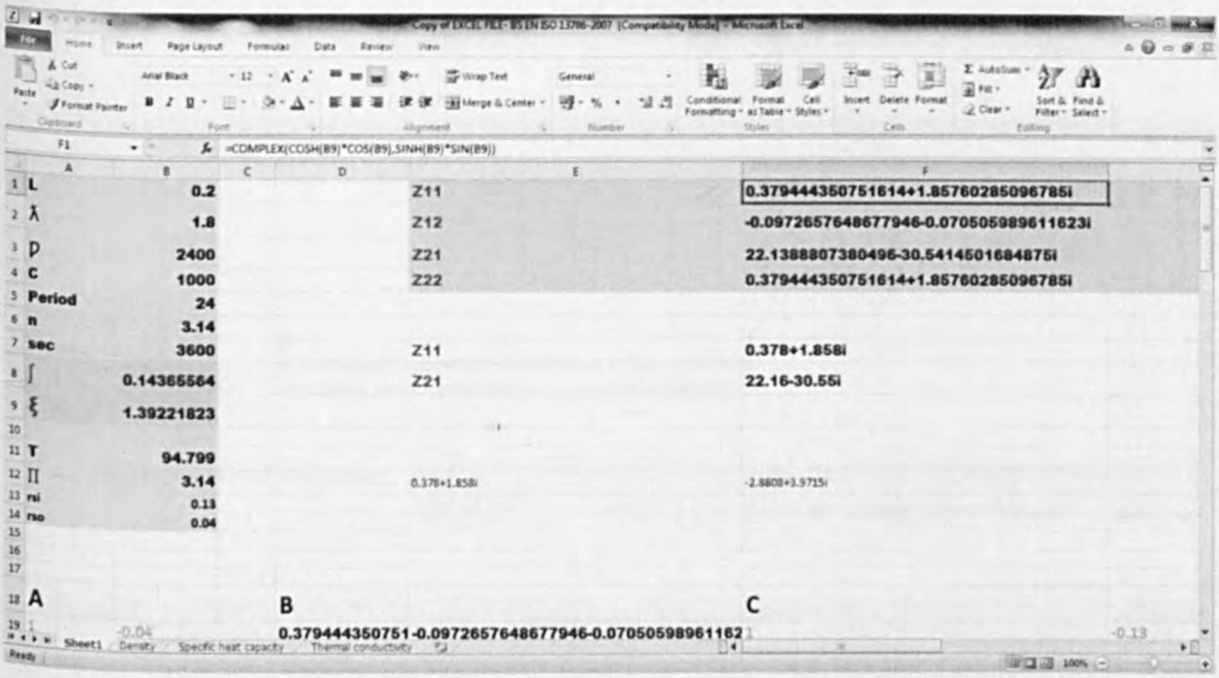
The value of "ʃ" (as seen from the highlighted box in figure 6.3) is calculated by imputing corresponding formula in excel. The formula is imputed by following the steps below;

1- Click on the individual cell at the active spread sheet.

2- Go to the blank space next to the function "fx" and type "=" sign, this sign will allow the program to impute the corresponding formula by clicking the cells which include the individual parameters in the formula.

3- Complete the formula by checking the relationship between the entered cells such as multiplication and division.

4- Press enter button and excel will work out the value by using the imputed formula. The worked out value is located in the active cell.

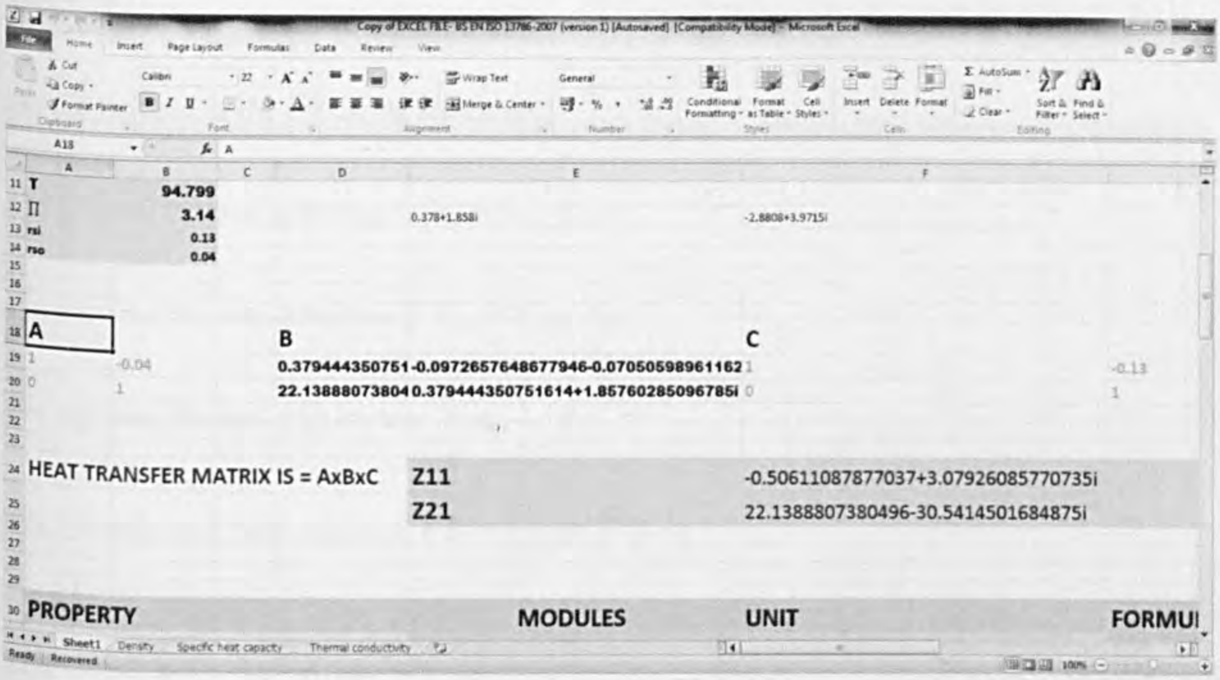


F1 `=COMPLEX(COSH(B9)*COS(B9),SINH(B9)*SIN(B9))`

	A	B	C	D	E	F	
1	L	0.2			Z11	0.379444350751614+1.85760285096785i	
2	λ	1.8			Z12	-0.0972657648677946-0.0705059896116231i	
3	ρ	2400			Z21	22.1388807380496-30.5414501684875i	
4	C	1000			Z22	0.379444350751614+1.85760285096785i	
5	Period	24					
6	n	3.14					
7	sec	3600			Z11	0.378+1.858i	
8	∫	0.14365564			Z21	22.16-30.55i	
9	ξ	1.39221823					
10							
11	T	94.799					
12	Π	3.14			0.378+1.858i	-2.8808+3.9715i	
13	rsi	0.13					
14	rso	0.04					
15							
16							
17							
18	A			B		C	
19	1	-0.04		0.379444350751-0.0972657648677946-0.07050598961162		1	-0.13

Figure 6-4 Calculations of heat transfer matrix

After imputing the formulas to calculate ∫ and ε, the corresponding values are found. The elements needed to calculate the heat transfer matrix namely Z_{11} (as can be seen from the highlighted box in figure 6.4), Z_{12}, Z_{21}, Z_{22} are calculated separately at different cells by imputing corresponding formulas for each element at different cells. Since each element of heat transfer matrix is a complex number, while imputing a formula for each element, after the "=" sign at step 2 of the imputation process explained at above, complex function from excel is used by typing the "COMPLEX" command. By using this function, excel will calculate the trigonometric formulas in complex number format.



T 94.799
Π 3.14
rsi 0.13
rso 0.04

0.378+1.858i

-2.8808+3.9715i

A

1 -0.04
0 1

B

0.379444350751 -0.0972657648677946-0.07050598961162
22.13888073804 0.379444350751614+1.85760285096785i

C

1 -0.13
0 1

HEAT TRANSFER MATRIX IS = AxBxC

Z11 -0.50611087877037+3.07926085770735i
Z21 22.1388807380496-30.5414501684875i

PROPERTY MODULES UNIT FORMUL

Figure 6-5 Matrix Calculations

Matrix A (as can be seen from the highlighted box in figure 6.5) is imputed in columns A and B in two rows, matrix B is imputed next to matrix A and matrix C is imputed next to matrix B (Matrix A,B, and C are shown in Appendix 8.1). Each matrix is a (2x2) matrix and each element in the matrix is imputed by using a complex function in excel. Matrix B is the matrix formed by the elements Z_{11}, Z_{12}, Z_{21} and Z_{22} which is calculated before. Matrix A is a matrix where the diagonal elements is equal to 1, the upper triangular element equal to negative rso and lower triangular element equal to zero. Matrix C is a matrix where the diagonal elements is equal to 1, the upper triangular element equal to negative rsi and the lower triangular element equal to zero.

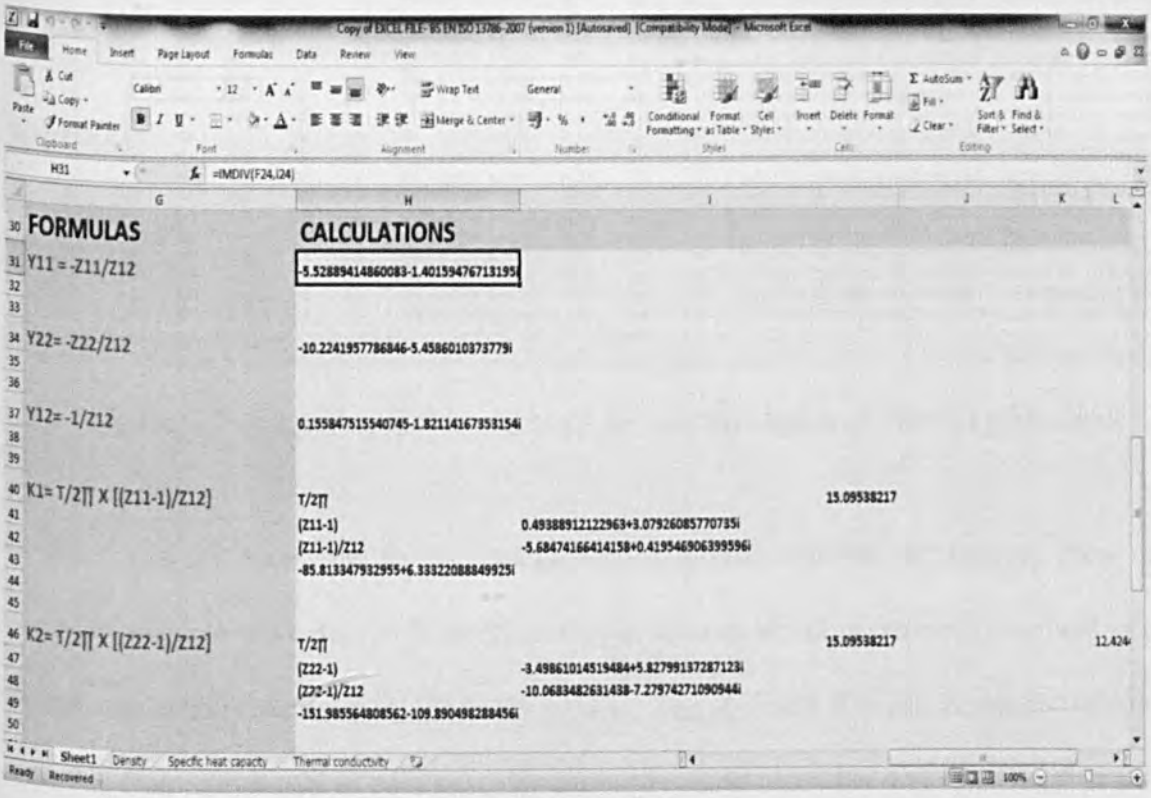
Heat transfer matrix is then calculated by multiplying `the matrix A, B and C (as can be seen from figure 6.5). Firstly, the matrix A and matrix B is multiplied and the resulting matrix is multiplied by matrix C. Matrix multiplication process is computed by using IMSUM and IMPRODUCT commands after the "=" sign or by choosing the specific function from the function menu. Function menu list can be opened by clicking the "fx" button at the left top of the spread sheet. For the calculation of different parameters, the corresponding formulas that should be used in the following sheets are;

For internal thermal admittance; $Y_{11}=Z_{11} / Z_{12}$

For external thermal admittance; $Y_{22}= -Z_{22} / Z_{12}$

For periodic thermal admittance; $Y_{12}= -1 / Z_{12}$

For internal areal heat capacity; $K1 = \left(\frac{1}{2\pi}\right) \times \left[\frac{Z_{11}-1}{Z_{12}}\right]$

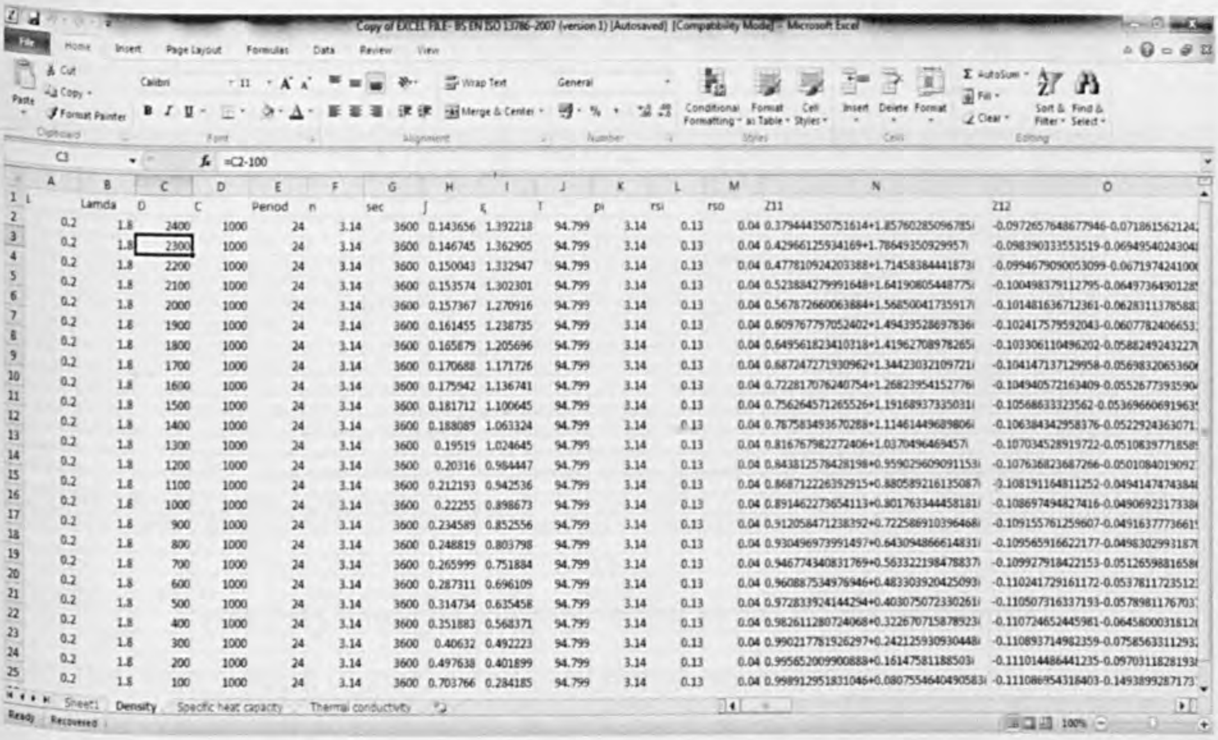


H31 =IMDIV(F24,I24)

	G	H	I	J	K	L
30	**FORMULAS**	**CALCULATIONS**				
31	Y11 = -Z11/Z12	-5.52889414860083-1.40159476713195				
32						
33						
34	Y22= -Z22/Z12	-10.2241957786846-5.4586010373779i				
35						
36						
37	Y12= -1/Z12	0.155847515540745-1.82114167353154i				
38						
39						
40	K1= T/2∏ X [(Z11-1)/Z12]	T/2∏	15.09538217			
41		(Z11-1)	0.49388912122963+3.07926085770735i			
42		(Z11-1)/Z12	-5.68474166414158+0.419546906399596i			
43		-85.813347932955+6.33322088849925i				
44						
45						
46	K2= T/2∏ X [(Z22-1)/Z12]	T/2∏	15.09538217			12.424
47		(Z22-1)	-3.49861014519484+5.82799137287123i			
48		(Z22-1)/Z12	-10.0683482631438-7.27974271090944i			
49		-151.985564808562-109.890498288456i				
50						

Figure 6-6 Calculations of complex numbers in a matrix division

Where Z_{11}, Z_{12}, Z_{21} and Z_{22} are used at above formulas are the values found for heat transfer matrix. In order to calculate Y_{11}, Y_{22}, Y_{12} and K1. Since elements Z_{11} to Z_{22} are complex numbers in a matrix for the division of those elements in the above formulas, "IMDIV" command is used which allows excel program to perform a matrix division. Then, the absolute value of the resulted complex number should be taken as a value for Y_{11} (as can be seen from the highlighted box in figure 6.6), Y_{22}, Y_{12} and K1. Absolute values are found by using the command "IMABS" which is an automated function in excel that allows the program to take the absolute value of the complex number.

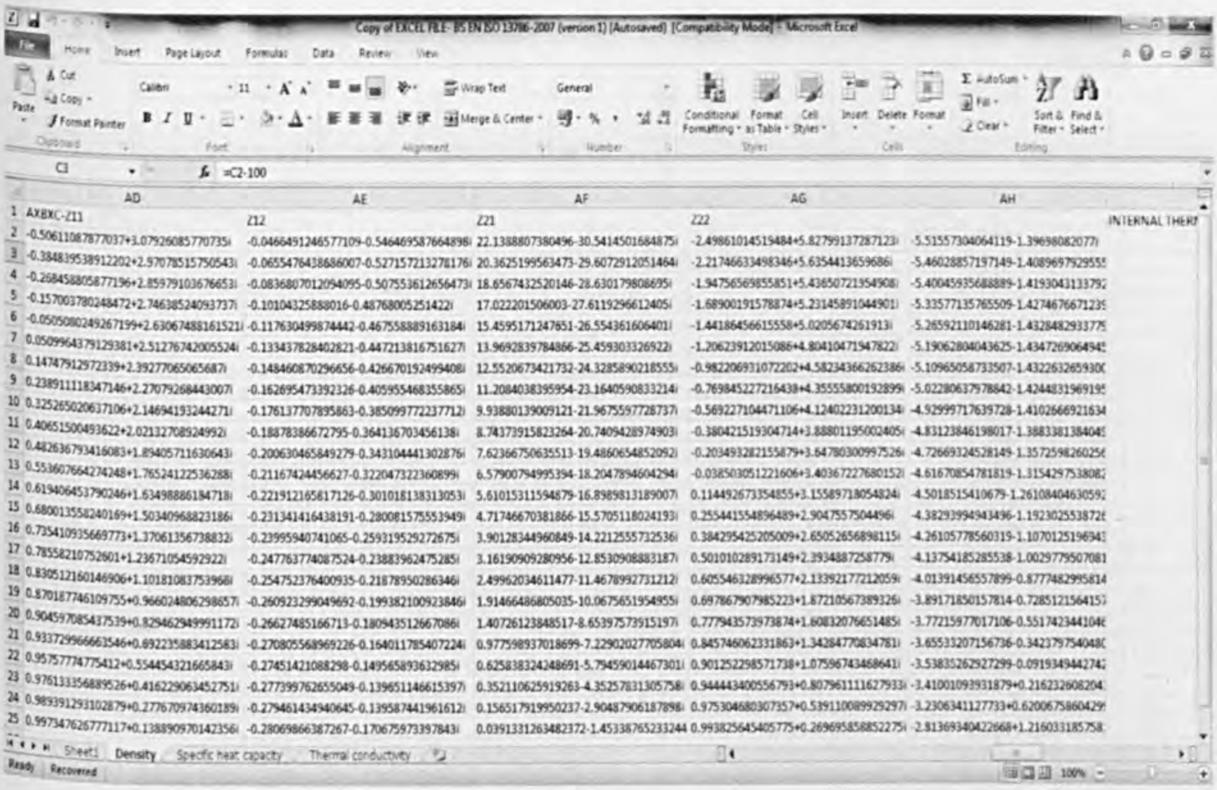


C3 =C2-100

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	L	Lamda	D	C	Period	n	sec	∫	ξ	T	pi	rsi	rso	Z11	Z12
2	0.2	1.8	2400	1000	24	3.14	3600	0.143656	1.392218	94.799	3.14	0.13	0.04	0.379444350751614+1.85760285096785i	-0.0972657648677946-0.0718615621242
3	0.2	1.8	2300	1000	24	3.14	3600	0.146745	1.362905	94.799	3.14	0.13	0.04	0.42966125934169+1.78649350929957i	-0.098390333553519-0.0694954024304
4	0.2	1.8	2200	1000	24	3.14	3600	0.150043	1.332947	94.799	3.14	0.13	0.04	0.477810924203388+1.71458384441873i	-0.0994679090053099-0.067197424100
5	0.2	1.8	2100	1000	24	3.14	3600	0.153574	1.302301	94.799	3.14	0.13	0.04	0.523884279991648+1.64190805448775i	-0.100498379112795-0.0649736490128
6	0.2	1.8	2000	1000	24	3.14	3600	0.157367	1.270916	94.799	3.14	0.13	0.04	0.567872660063884+1.56850041735917i	-0.101481636712361-0.0628311378588
7	0.2	1.8	1900	1000	24	3.14	3600	0.161455	1.238735	94.799	3.14	0.13	0.04	0.609767797052402+1.49439528697836i	-0.102417579592043-0.0607782406653
8	0.2	1.8	1800	1000	24	3.14	3600	0.165879	1.205696	94.799	3.14	0.13	0.04	0.649561823410318+1.41962708978265i	-0.103306110496202-0.0588249243227
9	0.2	1.8	1700	1000	24	3.14	3600	0.170688	1.171726	94.799	3.14	0.13	0.04	0.687247271930962+1.34423032109721i	-0.104147137129958-0.0569832065360
10	0.2	1.8	1600	1000	24	3.14	3600	0.175942	1.136741	94.799	3.14	0.13	0.04	0.722817076240754+1.26823954152776i	-0.104940572163409-0.0552677393590
11	0.2	1.8	1500	1000	24	3.14	3600	0.181712	1.100645	94.799	3.14	0.13	0.04	0.756264571265526+1.19168937335031i	-0.10568633323562-0.05369660691963
12	0.2	1.8	1400	1000	24	3.14	3600	0.188089	1.063324	94.799	3.14	0.13	0.04	0.787583493670288+1.11461449689806i	-0.106384342958376-0.0522924363071
13	0.2	1.8	1300	1000	24	3.14	3600	0.19519	1.024645	94.799	3.14	0.13	0.04	0.816767982272406+1.0370496469457i	-0.107034528919722-0.0510839771858
14	0.2	1.8	1200	1000	24	3.14	3600	0.20316	0.984447	94.799	3.14	0.13	0.04	0.843812578428198+0.959029609091153i	-0.107636823687266-0.0501084019092
15	0.2	1.8	1100	1000	24	3.14	3600	0.212193	0.942536	94.799	3.14	0.13	0.04	0.868712226392915+0.880589216135087i	-0.108191164811252-0.0494147474384
16	0.2	1.8	1000	1000	24	3.14	3600	0.22255	0.898673	94.799	3.14	0.13	0.04	0.891462273654113+0.801763344458181i	-0.108697494827416-0.0490692317338
17	0.2	1.8	900	1000	24	3.14	3600	0.234589	0.852556	94.799	3.14	0.13	0.04	0.912058471238392+0.722586910396468i	-0.109155761259607-0.0491637773661
18	0.2	1.8	800	1000	24	3.14	3600	0.248819	0.803798	94.799	3.14	0.13	0.04	0.930496973991497+0.643094866614831i	-0.109565916622177-0.0498302993187
19	0.2	1.8	700	1000	24	3.14	3600	0.265999	0.751884	94.799	3.14	0.13	0.04	0.946774340831769+0.563322198478837i	-0.109927918422153-0.0512659881658
20	0.2	1.8	600	1000	24	3.14	3600	0.287311	0.696109	94.799	3.14	0.13	0.04	0.960887534976946+0.483303920425093i	-0.110241729161172-0.0537811723512
21	0.2	1.8	500	1000	24	3.14	3600	0.314734	0.635458	94.799	3.14	0.13	0.04	0.972833924144294+0.403075072330261i	-0.110507316337193-0.0578981176703
22	0.2	1.8	400	1000	24	3.14	3600	0.351883	0.568371	94.799	3.14	0.13	0.04	0.982611280724068+0.322670715878923i	-0.110724652445981-0.0645800031812
23	0.2	1.8	300	1000	24	3.14	3600	0.40632	0.492223	94.799	3.14	0.13	0.04	0.990217781926297+0.242125930930448i	-0.110893714982359-0.0758563311293
24	0.2	1.8	200	1000	24	3.14	3600	0.497638	0.401899	94.799	3.14	0.13	0.04	0.995652009900888+0.16147581188503i	-0.111014486441235-0.0970311828193
25	0.2	1.8	100	1000	24	3.14	3600	0.703766	0.284185	94.799	3.14	0.13	0.04	0.998912951831046+0.0807554640490583i	-0.111086954318403-0.1493899287173

Figure 6-7 Computing matrix elements for the calculation of thermal admittance

In sheet 1 of the excel file, for the calculation of internal thermal admittance, enter all the parameters across the columns from column A to column M, all parameters are fixed at row 1 except the density parameter. Elements of Z_{11}, Z_{12}, Z_{21} and Z_{22} are computed across the columns from column N to column Q by using the same formulas that have used in sheet 1. Each element in matrix A is computed across the columns from column R to column U. Each element in matrix C is computed across the columns from column R to column U. Each element in matrix C is computed across the columns from column V to column Y.

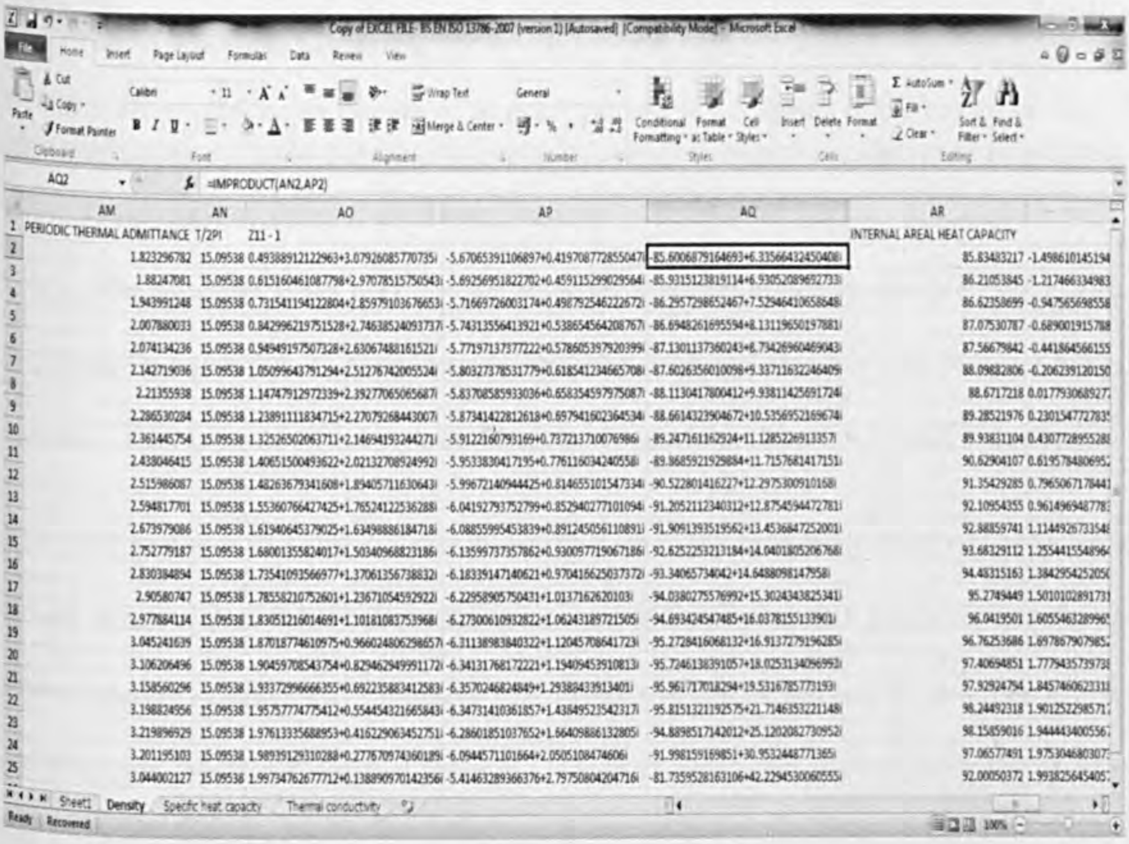


C3 =C2-100

	AD	AE	AF	AG	AH	
1	AXBXC-Z11	Z12	Z21	Z22		INTERNAL THER
2	-0.50611087877037+3.07926085770735i	-0.0466491246577109-0.546469587664898i	22.1388807380496-30.5414501684875i	-2.49861014519484+5.82799137287123i	-5.51557304064119-1.39698082077i	
3	-0.384839538912202+2.97078515750543i	-0.0655476438686007-0.527157213278176i	20.3625199563473-29.6072912051464i	-2.21746633498346+5.6354413659686i	-5.46028857197149-1.408969792955	
4	-0.268458805877196+2.85979103676653i	-0.0836807012094095-0.507553612656473i	18.6567432520146-28.630179808695i	-1.94756569855851+5.43650721954908i	-5.40045935688889-1.419304311337	
5	-0.157003780248472+2.74638524093737i	-0.10104325888016-0.48768005251422i	17.022201506003-27.6119296612405i	-1.68900191578874+5.23145891044901i	-5.33577135765509-1.427467667123	
6	-0.0505080249267199+2.63067488161521i	-0.117630499874442-0.467558889163184i	15.4595171247651-26.554361606401i	-1.44186456615558+5.0205674261913i	-5.26592110146281-1.432848293377	
7	0.0509964379129381+2.51276742005524i	-0.133437828402821-0.447213816751627i	13.9692839784866-25.459303326922i	-1.20623912015086+4.80410471947822i	-5.19062804043625-1.434726906494	
8	0.14747912972339+2.39277065065687i	-0.148460870296656-0.426670192499408i	12.5520673421732-24.3285890218555i	-0.982206931072202+4.58234366262386i	-5.10965058733507-1.432263265930	
9	0.238911118347146+2.27079268443007i	-0.162695473392326-0.405955468355865i	11.2084038395954-23.1640590833214i	-0.769845227216438+4.35555800192899i	-5.02280637978842-1.424483196919	
10	0.325265020637106+2.14694193244271i	-0.176137707895863-0.385099772237712i	9.93880139009121-21.9675597728737i	-0.569227104471106+4.12402231200134i	-4.92999717639728-1.410266692163	
11	0.40651500493622+2.02132708924992i	-0.18878386672795-0.364136703456138i	8.74373915823264-20.7409428974903i	-0.380421519304714+3.88801195002405i	-4.83123846198017-1.388338138404	
12	0.482636793416083+1.89405711630643i	-0.200630465849279-0.343104441302876i	7.62366750635513-19.4860654852092i	-0.203493282155879+3.64780300997526i	-4.72669324528149-1.357259826025	
13	0.553607664274248+1.76524122536288i	-0.21167424456627-0.322047322360899i	6.57900794995394-18.2047894604294i	-0.0385030512216 06+3.40367227680152i	-4.61670854781819-1.315429753808	
14	0.619406453790246+1.63498886184718i	-0.221912165817126-0.301018138313053i	5.61015311594879-16.8989813189007i	0.114492673354855+3.15589718054824i	-4.50185154410679-1.261084046305	
15	0.680013558240169+1.50340968823186i	-0.231341416438191-0.280081575553949i	4.71746670381866-15.5705118024193i	0.255441554896489+2.9047557504496i	-4.38293994943496-1.192302553872	
16	0.735410935669773+1.37061356738832i	-0.23995940741065-0.259319529272675i	3.90128344960849-14.2212555712536i	0.384295425205009+2.65052656898115i	-4.26105778560319-1.107012519694	
17	0.78558210752601+1.23671054592922i	-0.247763774087524-0.23883962475285i	3.16190909280956-12.8530908883187i	0.501010289173149+2.3934887258779i	-4.13754185285538-1.0029779507081	
18	0.830512160146906+1.10181083753968i	-0.254752376400935-0.21878950286346i	2.49962034611477-11.4678992731212i	0.605546328996577+2.13392177212059i	-4.01391456557899-0.8777482995814	
19	0.870187746109755+0.966024806298657i	-0.260923299049692-0.199382100923846i	1.91466486805035-10.0675651954955i	0.697867907985223+1.87210567389326i	-3.89171850157814-0.728512156415	
20	0.904597085437539+0.829462949991172i	-0.26627485166713-0.180943512667086i	1.40726123848517-8.65397573915197i	0.777943573973874+1.60832076651485i	-3.77215977017106-0.551742344104	
21	0.933729966663546+0.692235883412583i	-0.270805568969226-0.164011785407224i	0.977598937018699-7.22902027705804i	0.845746062331863+1.34284770834781i	-3.65533207156736-0.342379754048	
22	0.95757774775412+0.554454321665843i	-0.27451421088298-0.149565893632985i	0.625838324248691-5.79459014467301i	0.901252298571738+1.07596743468641i	-3.53835262927299-0.091934944274	
23	0.976133356889526+0.416229063452751i	-0.277399762655049-0.139651146615397i	0.352110625919263-4.35257831305758i	0.944443400556793+0.807961111627933i	-3.41001093931879+0.216232608204	
24	0.989391293102879+0.277670974360189i	-0.279461434940645-0.139587441961612i	0.156517919950237-2.90487906187898i	0.975304680307357+0.539110089929297i	-3.2306341127733+0.620067586042	
25	0.997347626777117+0.138890970142356i	-0.2806986638726 7-0.170675973397843i	0.0391331263482372-1.45338765233244	0.993825645405775+0.269695858852275i	-2.81369340422668+1.216033185758	

Figure 6-8 Computing complex number to find thermal admittance

After that, each element of matrix AxB is computed across columns Z to AC. Finally, each element of matrix (AxB)xC is computed across columns AD to AH. These columns will result the values for each element in heat transfer matrix. By using the IMDIV function which performs the matrix division, the formulas mentioned at previous section is used to compute complex number which will be used to find thermal admittance. Then, IMABS function is used to take the absolute value of this complex number which is imputed at column AH. The resulted thermal admittance value is located at AI column. By using the same procedure and the formulas in section 2, external thermal admittance is calculated at column AL and periodic thermal admittance at column AM. The location of these columns are located in figure 6.8.



AQ2 =IMPRODUCT(AN2,AP2)

	AM	AN	AO	AP	AQ	AR	
1	PERIODIC THERMAL ADMITTANCE	T/2PI	Z11 - 1			INTERNAL AREAL HEAT CAPACITY	
2	1.823296782	15.09538	0.49388912122963+3.07926085770735i	-5.67065391106897+0.419708772855047i	-85.6006879164693+6.33566432450408i	85.83483217	-1.498610145194
3	1.88247081	15.09538	0.615160461087798+2.97078515750543i	-5.69256951822702+0.459115299029564i	-85.9315123819114+6.93052089692733i	86.21053845	-1.217466334983
4	1.943991248	15.09538	0.731541194122804+2.85979103676653i	-5.71669726003174+0.498792546222672i	-86.2957298652467+7.52946410658648i	86.62358699	-0.947565698558
5	2.007880033	15.09538	0.842996219751528+2.74638524093737i	-5.74313556413921+0.538654564208767i	-86.6948261695594+8.13119650197881i	87.07530787	-0.689001915788
6	2.074134236	15.09538	0.94949197507328+2.63067488161521i	-5.77197137377222+0.578605397920399i	-87.1301137360243+8.73426960469043i	87.56679842	-0.441864566155
7	2.142719036	15.09538	1.05099643791294+2.51276742005524i	-5.80327378531779+0.618541234665708i	-87.6026356010098+9.33711632246409i	88.09882806	-0.206239120150
8	2.21355938	15.09538	1.14747912972339+2.39277065065687i	-5.83708585933036+0.658354597975087i	-88.1130417800412+9.93811425691724i	88.6717218	0.017793068927
9	2.286530284	15.09538	1.23891111834715+2.27079268443007i	-5.87341422812618+0.697941602364534i	-88.6614323904672+10.5356952169674i	89.28521976	0.230154772783
10	2.361445754	15.09538	1.32526502063711+2.14694193244271i	-5.91221607931690+0.737213710076986i	-89.247161162924+11.1285226913357i	89.93831104	0.430772895528
11	2.438046415	15.09538	1.40651500493622+2.02132708924992i	-5.95338304171950+0.776116034240558i	-89.8685921929884+11.7157681417151i	90.62904107	0.619578480695
12	2.515986087	15.09538	1.48263679341608+1.89405711630643i	-5.99672140944425+0.814655101547334i	-90.522801416227+12.2975300910168i	91.35429285	0.796506717844
13	2.594817701	15.09538	1.55360766427425+1.76524122536288i	-6.04192793752799+0.852940277101094i	-91.2052112340312+12.8754594472781i	92.10954355	0.961496948778
14	2.673979086	15.09538	1.61940645379025+1.63498886184718i	-6.08855995453839+0.891245056110891i	-91.9091393519562+13.4536847252001i	92.88859741	1.114492673354
15	2.752779187	15.09538	1.68001355824017+1.50340968823186i	-6.13599737357862+0.930097719067186i	-92.6252253213184+14.0401805206768i	93.68329112	1.255441554896
16	2.830384894	15.09538	1.73541093566977+1.37061356738832i	-6.18339147140621+0.970416625037372i	-93.34065734042+14.6488098147958i	94.48315163	1.384295425205
17	2.90580747	15.09538	1.78558210752601+1.23671054592922i	-6.22958905750431+1.0137162620103i	-94.0380275576992+15.3024343825341i	95.2749449	1.501010289173
18	2.977884114	15.09538	1.83051216014691+1.10181083753968i	-6.27300610932822+1.06243189721505i	-94.693424547485+16.0378155133901i	96.0419501	1.605546328996
19	3.045241639	15.09538	1.87018774610975+0.966024806298657i	-6.31138983840322+1.12045708641723i	-95.2728416068132+16.9137279196285i	96.76253686	1.697867907985
20	3.106206496	15.09538	1.90459708543754+0.829462949991172i	-6.34131768172221+1.19409453910813i	-95.7246138391057+18.0253134096993i	97.40694851	1.777943573973
21	3.158560296	15.09538	1.93372996666355+0.692235883412583i	-6.3570246824849+1.29388433913401i	-95.961717018294+19.5316785773193i	97.92924794	1.845746062331
22	3.198824956	15.09538	1.95757774775412+0.554454321665843i	-6.34731410361857+1.43849523542317i	-95.8151321192575+21.7146353221148i	98.24492318	1.901252298571
23	3.219896929	15.09538	1.97613335688953+0.416229063452751i	-6.28601851037652+1.66409886132805i	-94.8898517142012+25.1202082730952i	98.15859016	1.944443400556
24	3.201195103	15.09538	1.98939129310288+0.277670974360189i	-6.0944571101664+2.0505108474606i	-91.998159169851+30.9532448771365i	97.06577491	1.975304680307
25	3.044002127	15.09538	1.99734762677712+0.138890970142356i	-5.41463289366376+2.79750804204716i	-81.7359528163106+42.2294530060555i	92.00050372	1.993825645405

Figure 6-9 Calculation of internal and external areal heat capacity

For the internal areal heat capacity and external areal heat capacity calculations; Z_{11}-1 and Z_{22}-1 elements should be calculated first in a complex number format using IMSUB function in automated excel function. After that, matrix multiplication is performed by using IMDIV, this will give the value of $(Z_{11}-1)/Z_{12}$ and using the IMPRODUCT function will result the value of $\left(\frac{T}{2\pi}\right)\times\left[\frac{(Z_{11}-1)}{Z_{12}}\right]$. Taking the absolute value of the complex number will result the value of K1. Similar procedure is applied to find out the value of K2. These values represent internal areal heat capacity and external areal heat capacity respectively. Thermal transmittance (U) is calculated by imputing the formula at the column AW, the thermal transmittance value is fixed and this value is copied down. Decrement factor is calculated by dividing thermal transmittance to periodic thermal admittance. Decrement factor is calculated at column AX. The location of these columns can be seen at figure 6.9.

The functioning of this program should be validated by using an example from BS EN ISO 13786:2007 where the validation of this programme is explained in the next section.

6.4 Validation of Excel Calculator Results

Firstly, the program is set up by using the example mentioned in BS EN ISO 13786 that is explained in appendix A. Then, results obtained from the example and some of the concrete samples are compared by using both Concrete Centre calculator and excel calculator.

The results shown in Table 6.3 concluded that since the difference obtained between the two results are less than 0.5, both results are found to be similar and hence the results achieved from concrete samples are validated. The reason for the difference of less than 0.5 is due to the rounding made to 2 decimal place in Concrete Centre calculation where the exact value is used in excel calculator.

Table 6-3 Validation of Thermal Dynamic Properties

NO.	**BS EN ISO 13786**		**Concrete Centre Calculator**		**Excel Calculator**	
	Thermal Admittance	**Decrement Factor**	**Internal Thermal Admittance**	**Decrement Factor**	**Internal Thermal Admittance**	**Decrement Factor**
D1*	5.70	0.514	5.70	0.51	5.70	0.514
A1	-	-	4.45	0.92	4.19	0.87
B1	-	-	4.26	0.90	4.03	0.86
C1	-	-	4.45	0.94	4.18	0.88

D1* = Example from BS EN ISO 13786

6.5 Results & Discussion

In this section, the study investigated the thermal dynamic properties of the concrete mixes. The laboratory test results were used to calculate the thermal dynamic properties. In other words, thermal properties of concrete mixes were applied to evaluate the thermal dynamic properties of the concrete mixes. The results obtained from previous chapters were taken into consideration to calculate the thermal dynamic results. The main aim is to evaluate the value of thermal admittance and hence thermal mass of the concrete. This is the reason that the excel spreadsheet was developed by applying thermal performance of building components – Dynamic thermal characteristics-calculation methods (BS EN ISO 13786). Thermal properties of 28 mixes were applied to calculate their thermal dynamic properties. This research was provided the thermal properties of concrete such as thermal conductivity, specific heat capacity and density of concrete. After that, in this chapter, these thermal properties were used to find the thermal dynamic properties of concrete mixes.

In this section, thermal dynamic properties were calculated. Thermal dynamic properties results are shown in Appendix B. This section was taken account into thermal transmittance (U-value), Decrement factor and Thermal admittance hence thermal mass of the concrete mix. The reason for taking these factors into consideration is to describe the heat transfer inside the buildings, such as through walls or floors, by using the U-value. Additionally, decrement factor is also important in expressing the heat transfer since as mentioned in chapter 2, it is the proportion of maximum heat flow of the external surface of the element per unit degree of external temperature swing through the walls per unit change in the variation of external and internal temperatures until it reaches to the steady state condition of heat flow. Furthermore, another vital concept in explaining the heat transfer is thermal admittance value where it represents the quantity of energy going out from the internal surface of the element into the room per unit degree of temperature swing. However, such condition only occurs when the internal temperature experiences periodic oscillation and at the same time external temperature is kept at constant level. In the following section, the effects of different types of Cement materials, Recycled Coarse Aggregate and Water-Cement ratio were examined on the effects of Thermal Admittance Value, U-value and Decrement Factor of Concrete.

6.5.1 Effects of different types of Cement, Recycled Coarse Aggregate and Water-Cement ratio on U-Value

Since U-Value is mainly a measure representing the heat loss through a structural element, the effect of various different types of cements, recycled coarse aggregate and water cement ratio on thermal transmittance (U-value) are examined in this research. U-value is also defined as the inverse of R-value where the R-value is a measure expressing the residence to heat flow via given thickness of material. Before continuing the discussion, it is also important to state that the thickness of the sample is also a significant concept on U-value of the concrete. However, all of the concrete samples have same thicknesses in this research which is 0.075m. This is the reason that the thickness is not considered in this study. The main aim of this study is to understand the effects of different types of cement materials, types of aggregates and when minimizing the water-cement ratio how it affected the thermal transmittance of the concrete mixes. In other words, thermal conductivity of concrete mixes was taken into consideration to examine the effects of thermal transmittance value of concrete mixes.

6.5.1.1 Effects of different types of Cements on U-Value of Concrete Mixes

The different types of cement materials are used in concrete mixes and the effect of using such materials is decreasing the thermal conductivity with decreasing the U-value of concrete mixes in all groups [See Appendix B]. This is directly affected the U-value of the concrete mixes. In other words, Thermal conductivity is increased with decreasing R-Value with increasing the U-value of the concrete mix in all groups. The following figure is shown the thermal conductivity against the R-value of the concrete mixes in Group A.

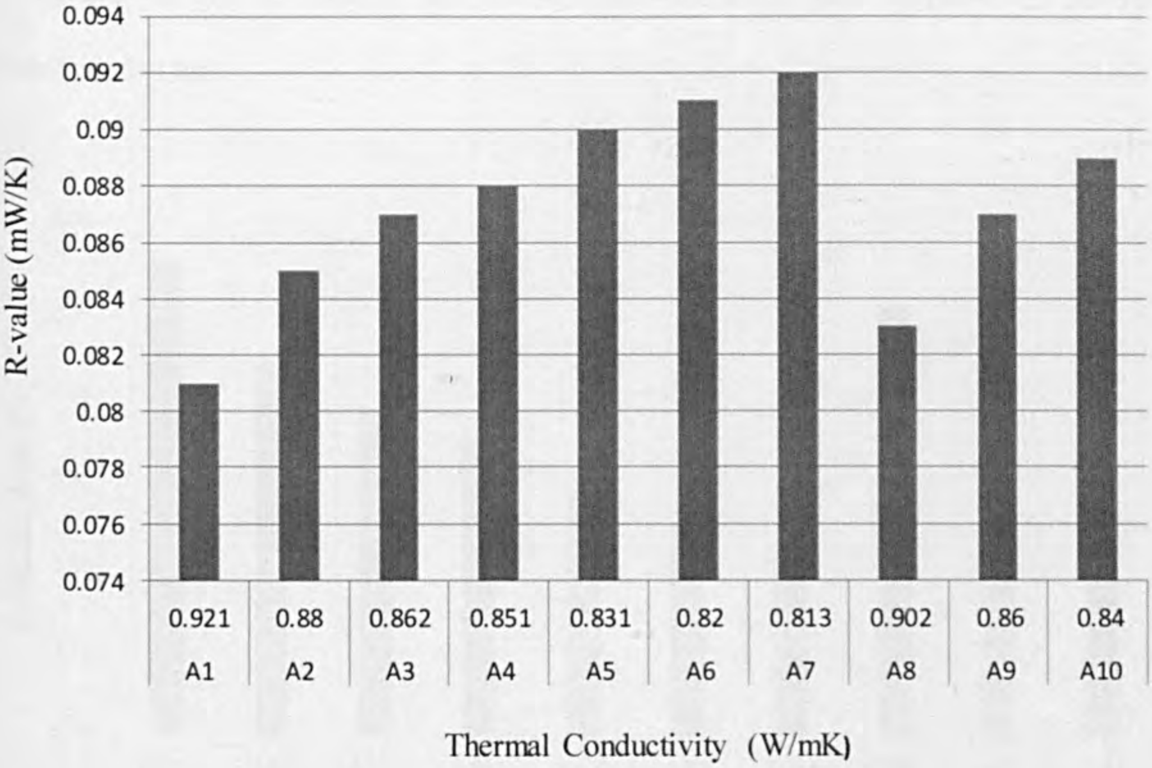


Figure 6-10 Thermal conductivity varying R-value of concrete mixes (Group A)

Figure 6.10 is shows how the thermal conductivity varies by changing the R-value in Group A concrete mixes. The concrete mix A1 is a control mix with thermal conductivity value of 0.921W/mk with R-value 0.08143 mW/K. As thermal conductivity decreases, R-value increases in all of the concrete mixes in Group A. The highest proportion of this increase in R-value which is 13.3% compared against control mix is observed when 30% of PC is replaced by PFA whereas the lowest increase in R-value which is 2.1% compared against control mix is seen in when 10% of PC is replaced by SF. This because PFA concrete mixes have lowest thermal conductivity than other concrete mixes. Furthermore, it is shown that when 45% of GGBS is used instead of 100% PC, thermal conductivity of the material is decreased by 4.45% compared to control mix which then results in increase in R-value by 4.67%. Similar patterns are achieved by decreasing the thermal conductivity when 55% GGBS, 15% SF, 65% GGBS, 20% SF, 10% PFA and 20% PFA is used resulting in 6.85%, 7.10%, 8.23%, 9.65%, 10.83% and 12.32% increase in R-value respectively compared against control mix

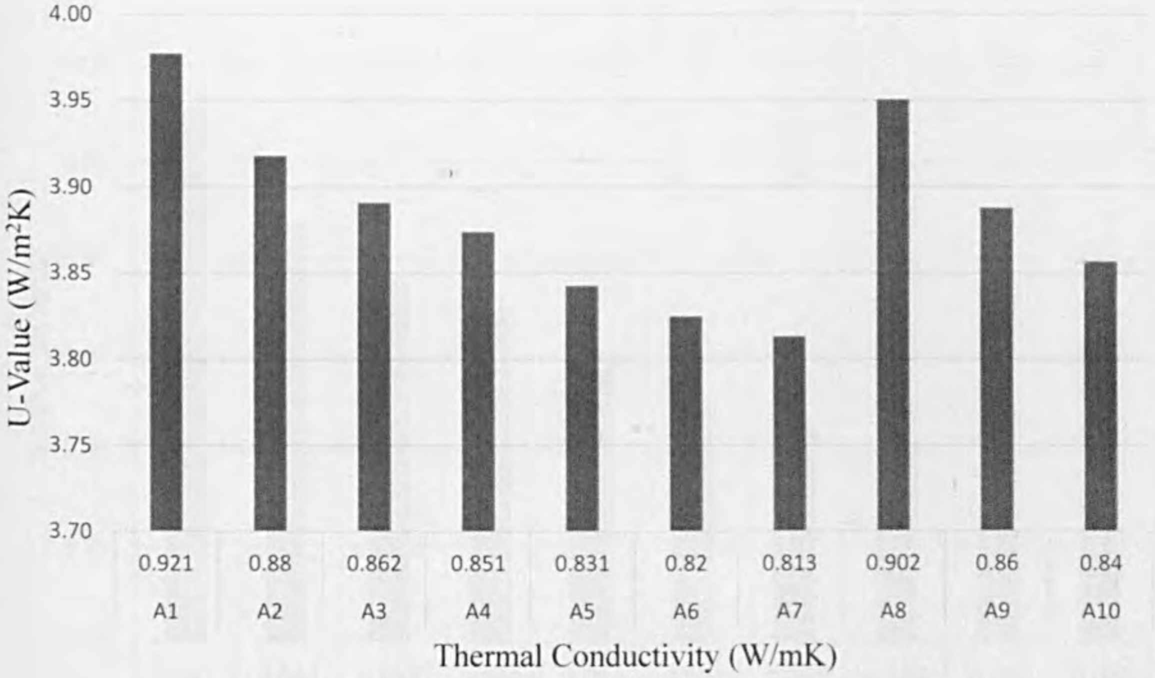


Figure 6-11 U-Values varying Thermal Conductivity of Concrete Mixes (Group A)

For instance, when Cement is replaced by Silica Fume, 10(A8), 15 (A9) and 20 % (A10), this replacement of PC decrease the U-value by 0.8, 2.3 and 3 % respectively. On the other hand, when 45 (A2), 55 (A3) and 65% (A4) of PC is replaced by GGBS, this interchange decreases the U-value by 1.5, 2.3, and 2.8% correspondingly. When the PFA is added in the concrete mix by 10 (A5), 20 (A6), and 30% (A7), this replacement of PC results in the reduction of the U-value by 3.5, 4, and 4.3% respectively. As a result of this, it can be concluded that the higher percentage of reductions are in PFA content concrete mixes. Primary cause of this is having lower thermal conductivity values of PFA content concrete mixes. Hence thermal conductivity is directly relationship with thermal transmittance (U-value) of the concrete and therefore, PFA has lower U-value. Even the GGBS content in concrete mixes are more than the percentage of PFA content, GGBS affects the U-value of concrete mix is less than PFA content concrete mixes. The results are found that GGBS affects the thermal conductivity of concrete less than the PFA. That's why GGBS content concrete mixes have greater thermal conductivity and u-value than PFA content mixes.

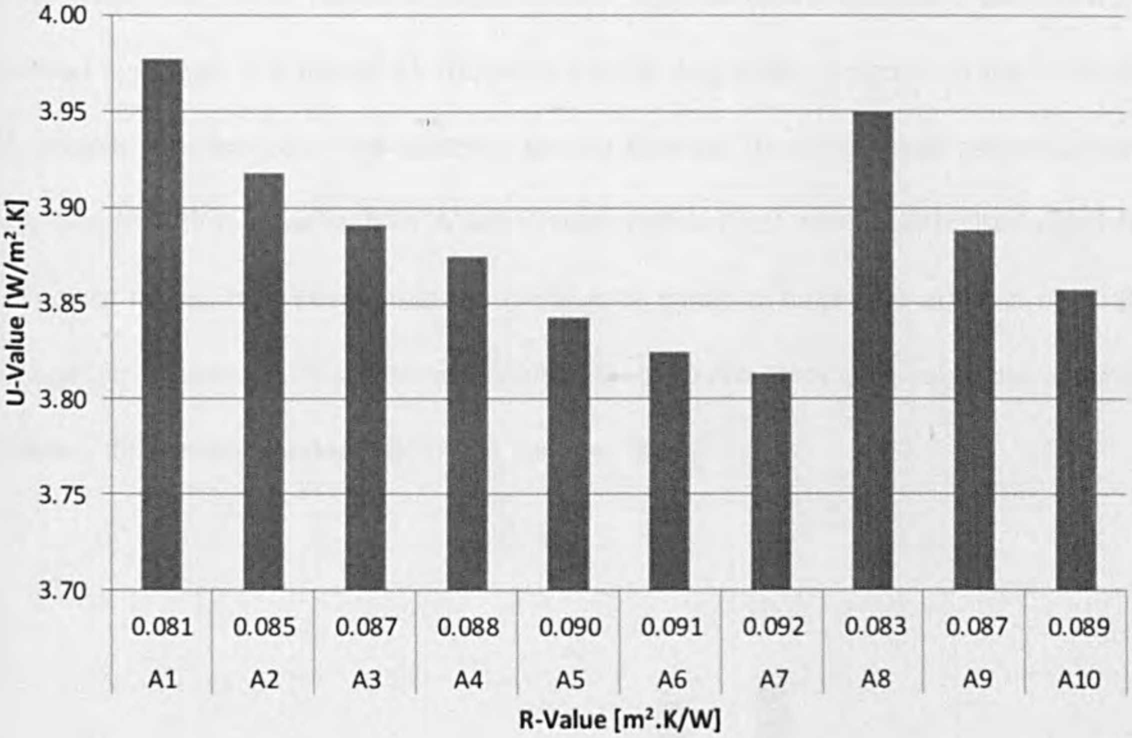


Figure 6-12 U-value varying R-Value of Group A concrete mixes

On the other hand, thermal conductivity is decreased the R-value of the concrete mixes. In other words, thermal conductivity is increased with decreasing the R-value. The main reason is the thermal conductivity is indirect proportional with R-value theoretically. At the same time, the thickness has been constant in the entire sample. That`s why thermal conductivity is directly affected the R-value of the concrete. As the Figure 6.12 is shown that cement replacement materials (PFA, Silica Fume and GGBS) are improved the R-value more than PC content mix. R-value is provided the concrete types such as light weight or normal weight. Essentially R-value is important for the insulating materials. The PFA content concretes are the highest R-value more than other concrete mixes. Comparing the silica fume and GGBS content concretes, the silica fume content concretes are increased the R-value more than GGBS content concretes. Specifically, 20 % Silica Fume content concrete results in higher R-value than 65 % GGBS content concrete mix.

6.5.1.2 Effects of Recycled Coarse Aggregate on U-Value of Concrete Mixes

The laboratory test results obtained from Group B concrete mixes concluded that when 30% of Natural aggregate is replaced by Recycled Coarse Aggregate, decrease in the U-value in RCA content concrete mixes are observed greater than the Binary cements content concrete mixes. Beside of this, when both RCA and Cement replacement materials are used together in the concrete mixes, it is shown that the U-value of concrete mixes are affected more than used together instead of using both separately. The main reason of decreasing the U-value is decreasing the thermal conductivity of the concrete mix.

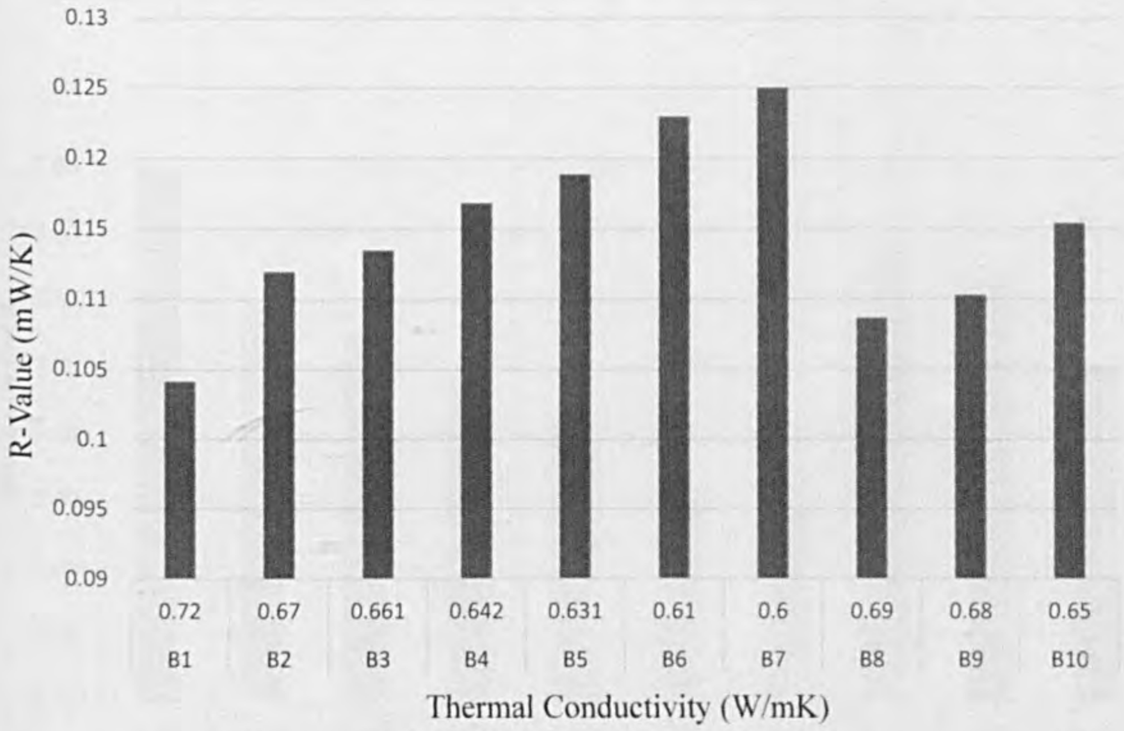


Figure 6-13 Thermal conductivity varying R-Value of concrete mixes (Group B)

The Figure 6.13 shows the change in thermal conductivity by varying the R-value of Group B concrete mixes. Recycled coarse aggregate concrete mixes have the lowest thermal conductivity value than natural aggregate concrete mixes. In other words, RCA content concrete mixes are low denser concretes comparing against the group A. This is the main reason why R-value of Group B concrete mixes have greater than group A concrete mixes. However, RCA content increased the R-value more than different types of cement materials. Because Type of aggregate is affected thermal properties more than types of cement materials. When the Group B concrete mixes are investigated, the concrete mix B1 is a control mix with thermal conductivity value of 0.72 W/mK with R-value 0.104 mW/K. As thermal conductivity decreases, the R-value of concrete mixes increases. The highest proportion of this increase in R-value is observed when 30% of PC is replaced by PFA and in addition to this, 30% RCA is used in the concrete mix whereas the lowest increase in R-value is seen when 10% of PC is replaced by SF with the addition of 30% RCA in concrete mix. The main reason for this is the thermal conductivity of the concrete mix.

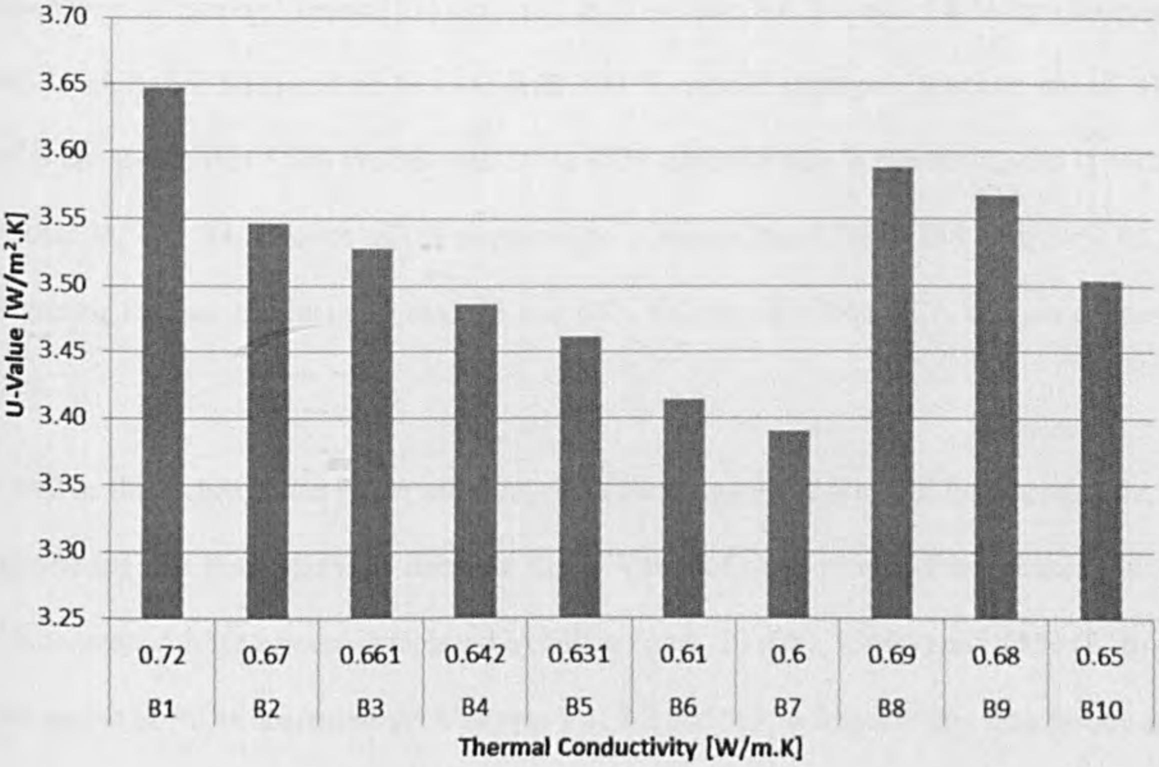


Figure 6-14 U-value varying Thermal Conductivity of Group B concrete mixes

When concretes containing 100% NA with 100 % PC (A1) is compared with 30 % RCA with 100 % PC concrete mix (B1), it is found that in B1, the U-value is 8.3% less than A1 concrete mix. On the other hand, the greatest decrease in U-value which is 11% of U-value in B7 concrete mix (30% PFA + 30% RCA) by comparing with A7 concrete mix. This is because PFA and RCA have lower thermal conductivity. Hence when RCA and PFA used in the concrete together, the reduction is higher than applying PFA and RCA separately.

When 30% RCA content with the cement is replaced by PFA, 10 (B5), and 20% (B6) replacement of PC is resulted in reduction the U-value 9.9, and 10.7% by making observation with A5 and A6 concrete mixes respectively. When GGBS with 30 % RCA are applied in concrete mix, decrease in the U-Value of the concrete mix is observed. The main reason for this is GGBS has lower thermal conductivity. For example, in the concrete mix containing 30 % RCA with the cement is replaced by GGBS, 45 (B2), 55 (B3), and 65 (B4) % of replacement of Portland cement is decreased the U-Value 9.4, 9.3 and 9.8 % by observing from 45 (A2), 55 (A3) and 65 % (A4) with 100 % natural aggregate concrete mixes. The results are shown that 55 % GGBS with 30 % RCA concrete mix is decreasing the U-Value less than B2 and B4 concrete mixes respectively. It means that 55% GGBS with 30% RCA has greater thermal conductivity than 45 and 65% GGBS with 30% RCA content concrete mixes.

As well as this, when Silica Fume and Recycled coarse aggregate are used in concrete mix, it is concluded that both materials decrease the U-Value of the concrete. For instance, 30 % RCA content with the cement is replaced by Silica Fume, 10 (B8), 15 (B9) and 20 % (B10) of replacement of PC is decreased the U-Value 9.1, 8.2 and 9.3 % respectively. The results are provided that B9 concrete mix is decreasing at a lower rate than B8 and B10 concrete mixes. This is due to the factors present in RCA material. In other words, RCA material is containg different materials such as wood, cement paste and etc.

The laboratory results show that when Recycled coarse aggregate is used in the concrete mixes, it makes concrete more lightly than normal concrete. This is the main reason that Group B concrete mixes have less thermal conductivity and U-value than other concrete mixes in different groups. The light concretes can be used as the best insulation properties in the buildings. Thermal insulation varies with density in indirect proportional manner, meaning that the lightweight concrete has better thermal insulation properties than normal-weight concrete.

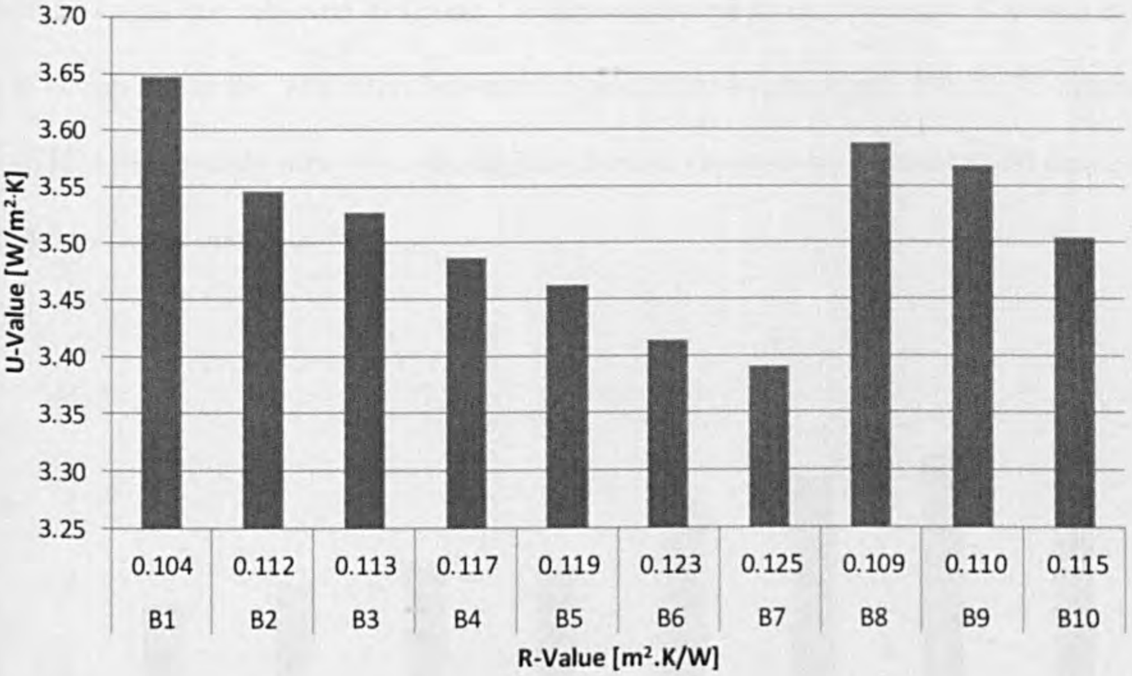


Figure 6-15 U-value varying R-value of Group B concrete mixes

As a result, addition of RCA content increased with decreasing thermal conductivity in all mixes. Therefore, R-Value increased and hence, this results in decrease in U-Value of the concrete mixes which is the thermal transmittance. This can also be shown by applying theoretical calculations. When the amount of RCA content is increased in the concrete mixes, the concretes become less dense than the concretes made without using any RCA content. Therefore, less dense concretes results in a lower thermal conductivity and this will result in a lower U-Value with greater insulation properties. Beside of this, when cement materials are used, the effect of cements materials on the decline of U-Value is less than using RCA content.

6.5.1.3 Effects of Water-Cement Ratio on U-Value of the Concrete Mixes

The results explained that W/C ratio is minimized with increasing the U-value in all types of concrete mixes at Group C. The main reason is Water cement ratio is decreased with increasing the thermal conductivity. This is helped to improve the U-Value of concrete. The highest U-values are achieved in Group C when compared to other groups. The reason for this is Group C has the W/C ratio between 0.3 and 0.35. Furthermore, 100 % PC concrete mix (C1) is the concrete mix where the highest thermal conductivity is present and hence the highest U-value is obtained.

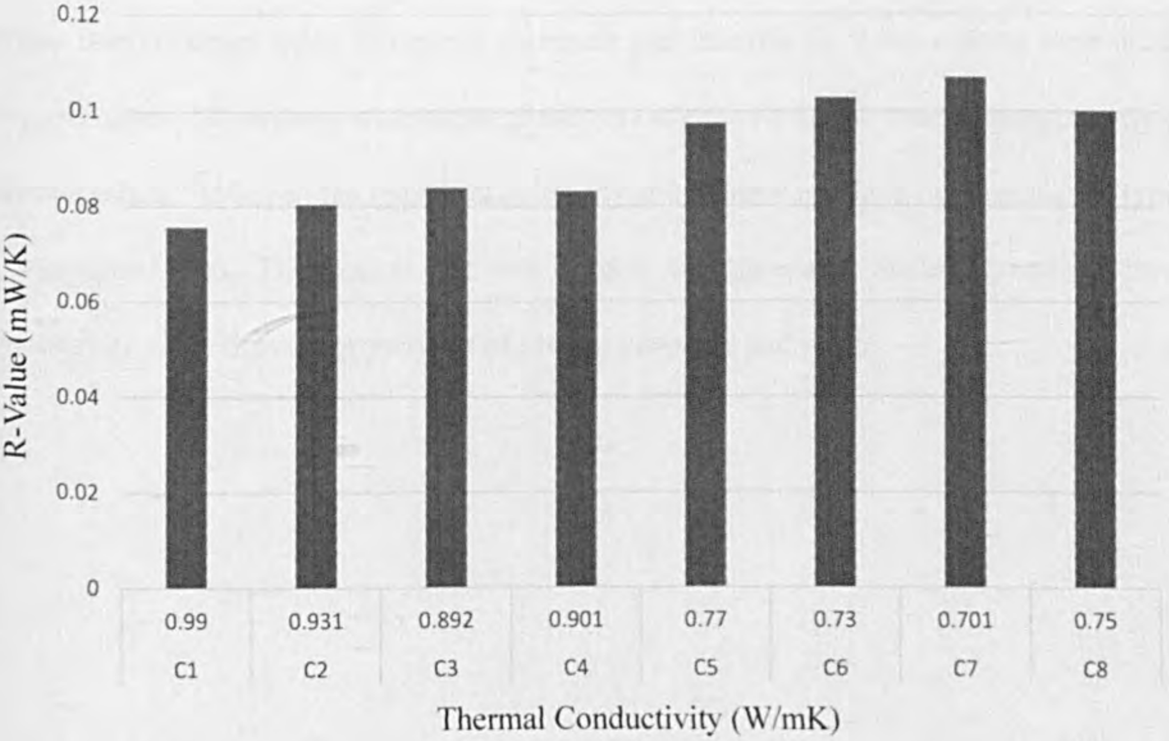


Figure 6-16 Thermal Conductivity varying R-value of Concrete mixes (Group C)

The Figure 6.16 is shows the change of thermal conductivity as changing the R-value of Group C concrete mixes. The laboratory results are explained that minimizing water-cement ratio in the concrete mix is increased the thermal conductivity of concrete mix. This is the main reason why Group C concrete mixes have the lowest R-value over all concrete mixes. In other words. Group C concrete mixes are denser than Group A and B concrete mixes. Therefore. Group C concrete mixes have greatest thermal conductivity value which results in decreasing the R-value of concrete mixes at Group C. If minimizing water-cement ratio is investigated with different types of cement materials and recycled coarse aggregate content concrete mixes. minimizing water-cement ratio shows an increase in thermal conductivity with decreasing R-value of concrete mix by using different types of cements materials and RCA content concrete mixes. For instance. when A1. B1 and C1 concrete mixes were compared. C1 have the higher thermal conductivity with lower R-value than A1 and B1 concrete mixes. On the other hand. types of aggregates are shown to affect thermal properties greater than different types of cement materials and minimizing water-cement ratio of the concrete mixes. Minimizing water-cement ratio is only improved the thermal conductivity of concrete mixes. However. the reduction in density and thermal conductivity depends on types of aggregate used. The reason for this is due to aggregates having greater thermal conductivity value than different types of cement materials and water.

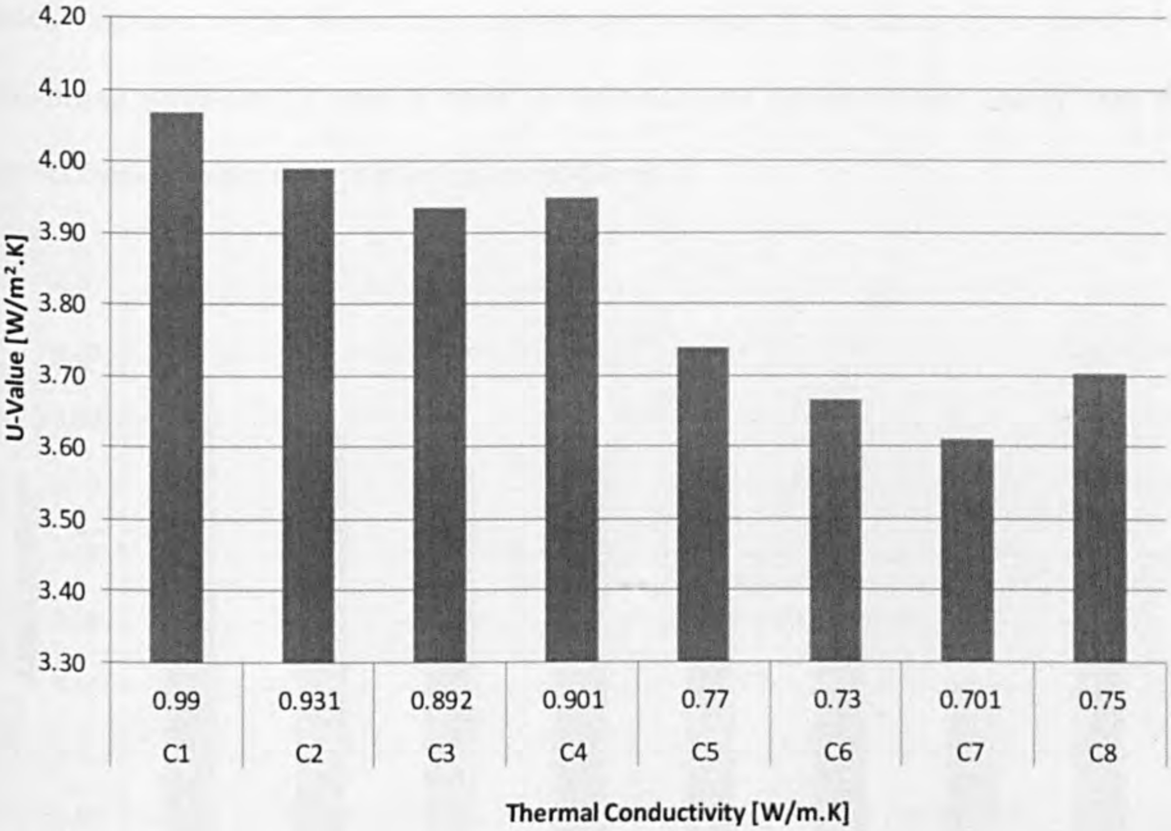


Figure 6-17 U-value varying Thermal Conductivity of Group C concrete mixes

From Group C, 20% PFA with 30 % RCA content concrete (C7) is found to have the highest percentage of increasing in U-value when compared with 20% PFA with 30% RCA content concrete (B6) concrete mix. The reason for this difference is C7 concrete has 0.3 w/c ratio whereas B6 concrete mix has 0.57 w/c ratio. At the same time, C8 concrete mix is 5.7 % increased the U-value more than B10 where both C8 and B10 contain 20% SF with 30% RCA. However, W/C ratio in C8 is 0.35 and 0.59 in B10. On the other hand, C6 concrete mix is increased the U-value 3.4 % by comparing with B2 concrete mix correspondingly where both C6 and B2 concretes consist of 45% GGBS with 30% RCA. The W/C ratio of C6 is 0.35 and W/C ratio of B2 is 0.59. Overall, when the results are examined, it is concluded that U-value of Natural aggregate concrete mixes increased slightly greater than 30% RCA content concrete mixes at Group C. The laboratory results are provided that Water-cement ratio is more important for RCA content concrete. The reasons for this, firstly because minimal

Water-cement ratio is improved the density of RCA content concrete and secondly, this is directly affected on the thermal conductivity and U-value of the concrete. In other word, minimising water-cement ratio is made the RCA content concrete mixes denser than the normal range of water cement ratio content at Group B.

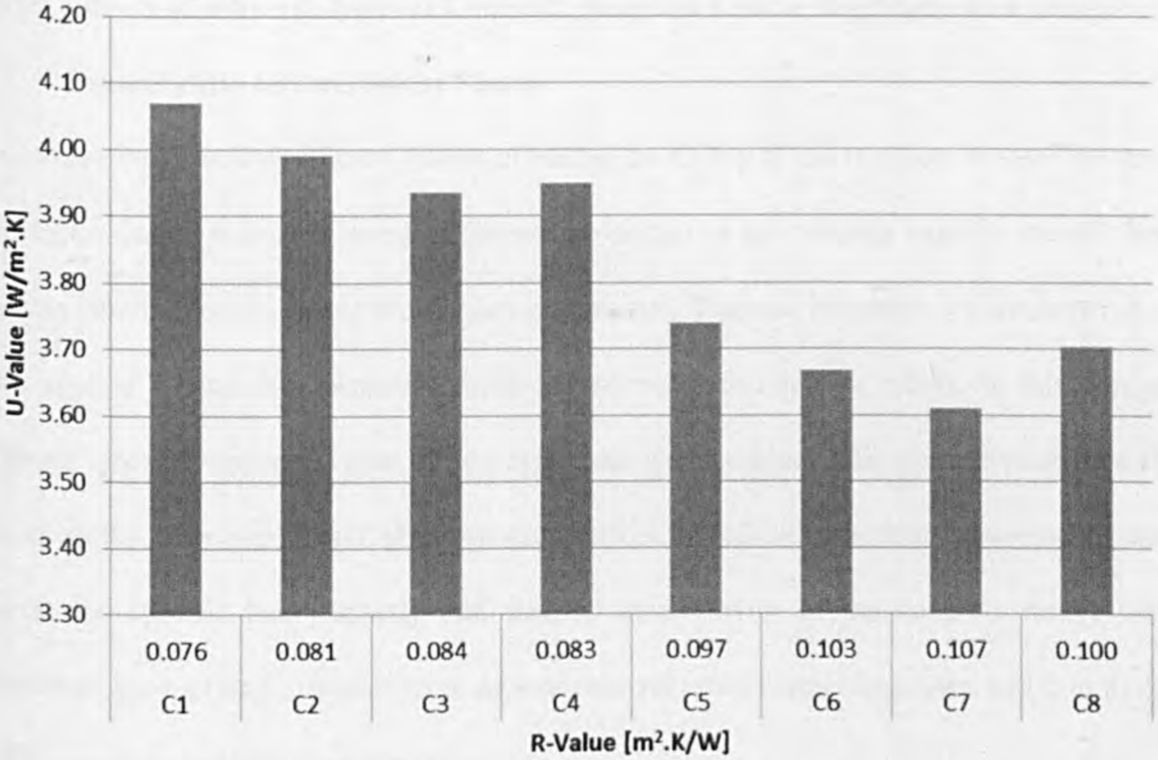


Figure 6-18 U-value varying R-value of Group C concrete mixes

On the other hand, R-Value is observed to be the lowest in group C where the water/cement ratio is kept at minimal compared with most of the concrete mixes obtained from other groups. The concretes in group C have the highest dense than other groups. This is due to concretes in group C having the lowest water/cement ratio compared to other concrete mixes in other groups.

In other words, group c concrete mixes are heavier concrete than the especially group B concrete mixes. At the same time, thermal conductivity of cement is higher than the water and hence this is the reason that why U-value is increased. When cement replacement materials or RCA content is used with minimal water/cement ratio in concrete mixes, this will still improve thermal conductivity and hence the U-Value of the concrete. The laboratory results provided that when water-cement ratio. RCA content and cement replacement materials are considered. water/cement ratio is act as a main actor of affecting the thermal properties of the concrete.

6.5.2 Effects of different types of Cements, Recycled Coarse Aggregate and Water-Cement ratio on Decrement Factor

Decrement factor is a significant feature affecting the ability of the concrete to store the heat. This factor can be evaluated based on thermal properties of the concrete namely; specific heat capacity. thermal conductivity and density of material. Thermal properties of concrete mixes were applied to find the decrement factor of the research concrete mixes. In this section. different types of cements. types of aggregate and water cement ratio were investigated the effects on the decrement factor of the concrete mixes. In following section. Decrement factor against the specific heat capacity and thermal conductivity of the concrete mixes were considered by applying different types of cements. recycled coarse aggregate and minimized water cement ratio of the concrete mixes.

6.5.2.1 Effects of different types of Cements on Decrement Factor of Concrete Mixes

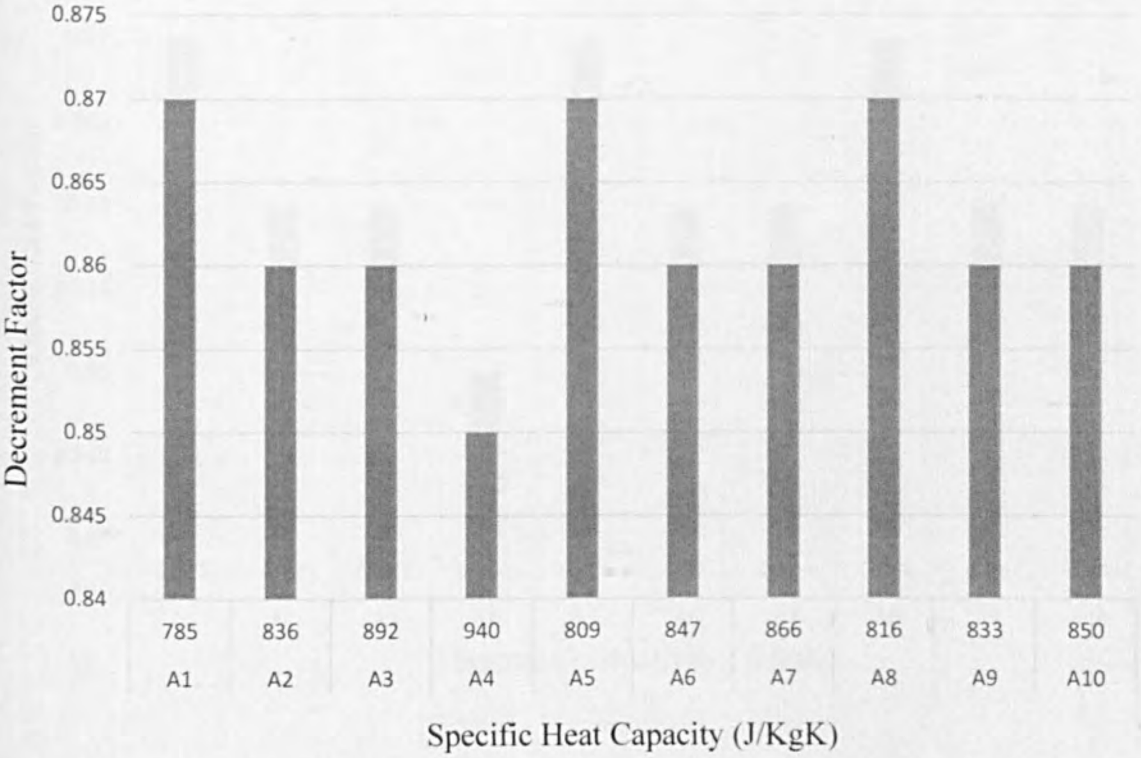


Figure 6-19 Decrement Factor varying Specific Heat Capacity of Group A concrete mixes

When decrement factor is compared within the group A concrete mixes, no significant difference is found between the mixes. When the specific heat capacity of the concrete is greater than 750 J/KgK, the decrement factors of such concretes are around 0.86-0.88. On the other hand, increasing thermal conductivity increase the decrement factor in concrete mixes.

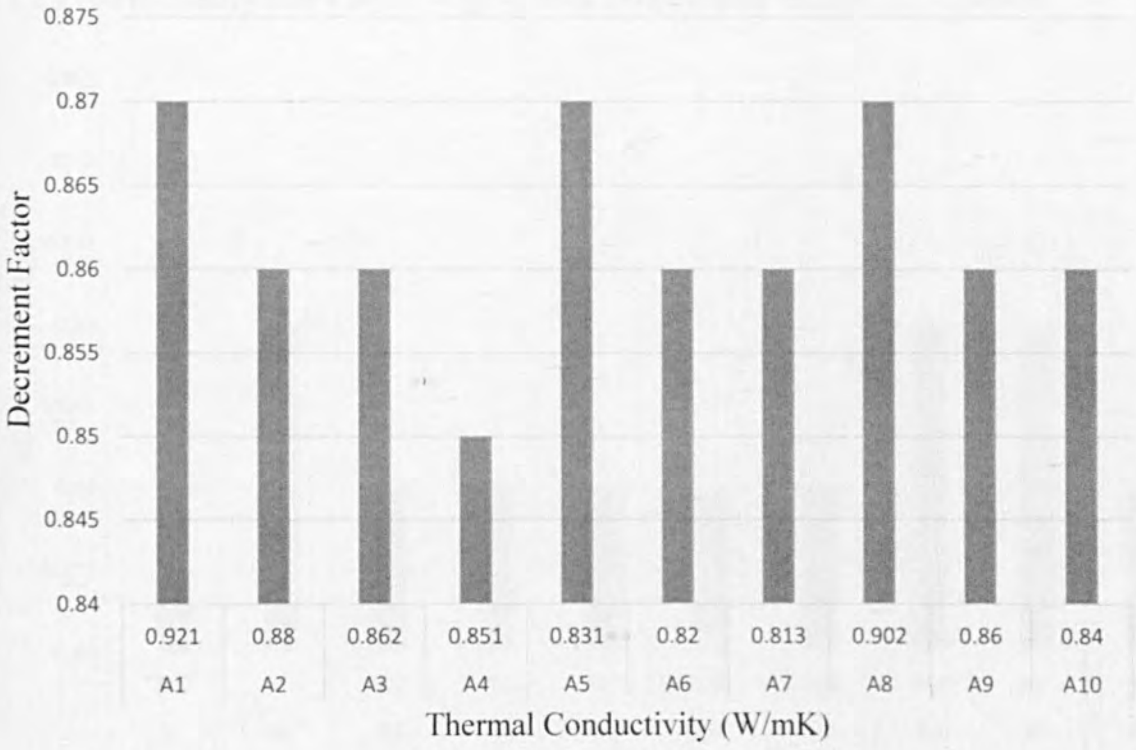


Figure 6-20 Decrement Factor varying Thermal Conductivity of Group A concrete Mixes

When thermal conductivity and specific heat capacity are taken into consideration simultaneously, it can be concluded that thermal conductivity increases the decrement factor. However, in specific heat capacity, after a certain value, the decrement factor will be decreased suddenly with an increasing of specific heat capacity beyond this point. It is also concluded that thermal conductivity is increased with increasing Decrement factor of the concrete at all Groups. Especially 100 % PC is the highest decrement factor value at all groups.

6.5.2.2 Effects of Recycled Coarse Aggregate on Decrement Factor of Concrete

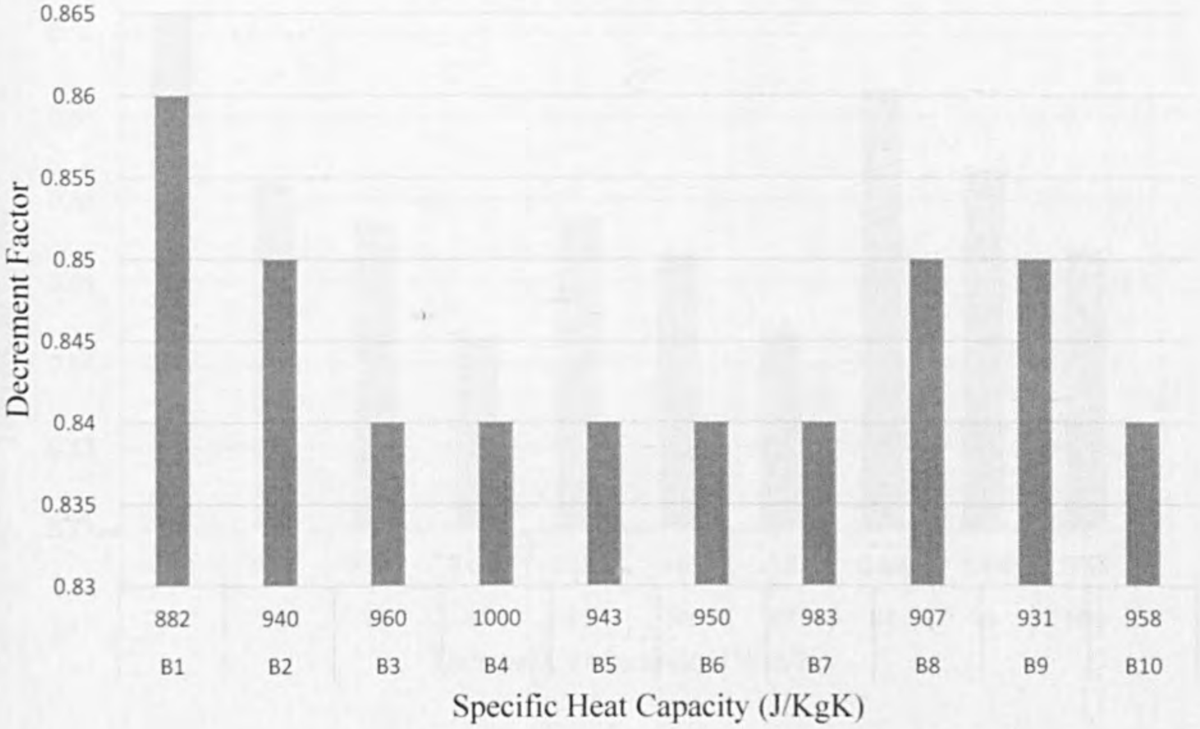


Figure 6-21 Decrement Factor varying the Specific Heat Capacity of Group B concrete mixes

When the RCA content in the concrete mixes increased, decrement factor of the concrete is decreased. Especially, when the specific heat capacity of the concrete is greater than 850 J/Kg.K, laboratory results have shown that this factor decreased the decrement factor of the concrete significantly. The reason for this decrease is not only specific heat capacity but also observing a decrease in thermal conductivity.

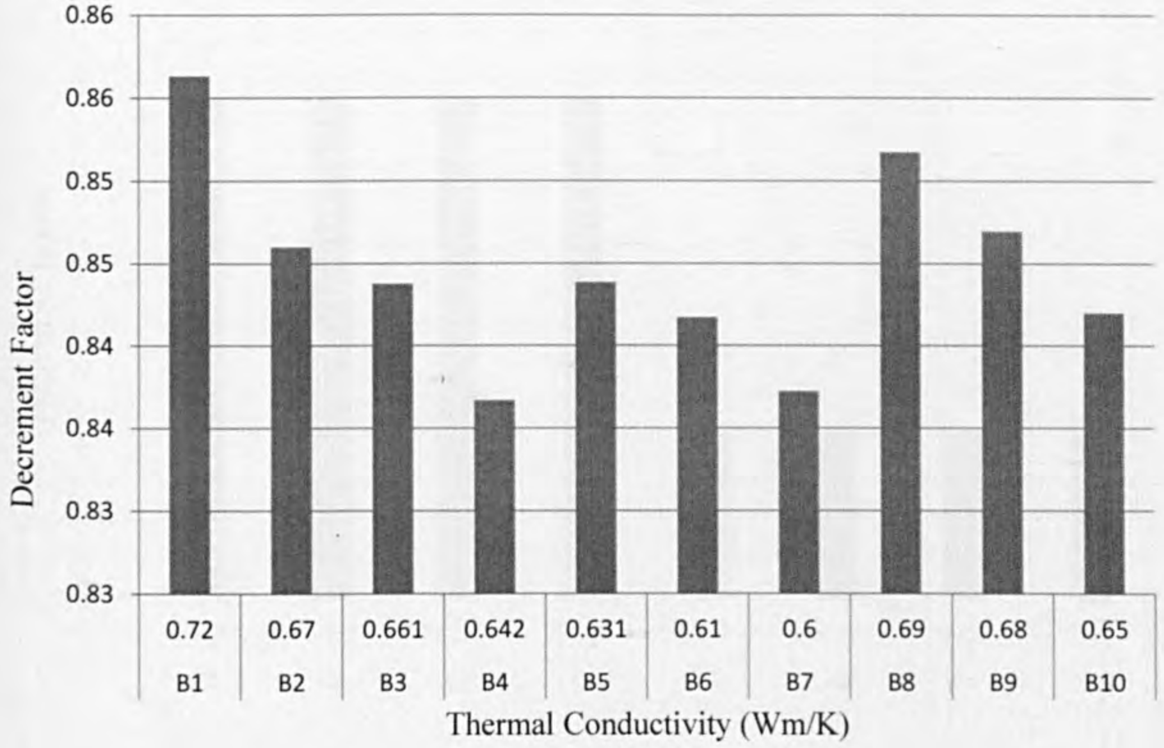


Figure 6-22 Decrement Factor varying Thermal Conductivity of Group B concrete mixes

When group A and group B concrete mixes are compared, even thermal conductivity values in group A are greater than group B, negligible difference is observed between the decrement factors. Hence, these results show that decrement factor is in fact depends on both thermal conductivity and specific heat capacity of the concrete mixes. Therefore, increase in only in thermal conductivity or specific heat capacity does not alter the decrement factor, the importance is to enable moderate raise in both simultaneously.

6.5.2.3 Effects of Water/Cement Ratio on Decrement Factor of Concrete

When the water-cement ratio is kept at minimal, this results in affecting the decrement factor in an indirect proportional manner greater than other groups. On the other hand, using such a minimal rate of water-cement ratio decreases the specific heat capacity of the concrete. This can also been demonstrated from the Figure 5.23.

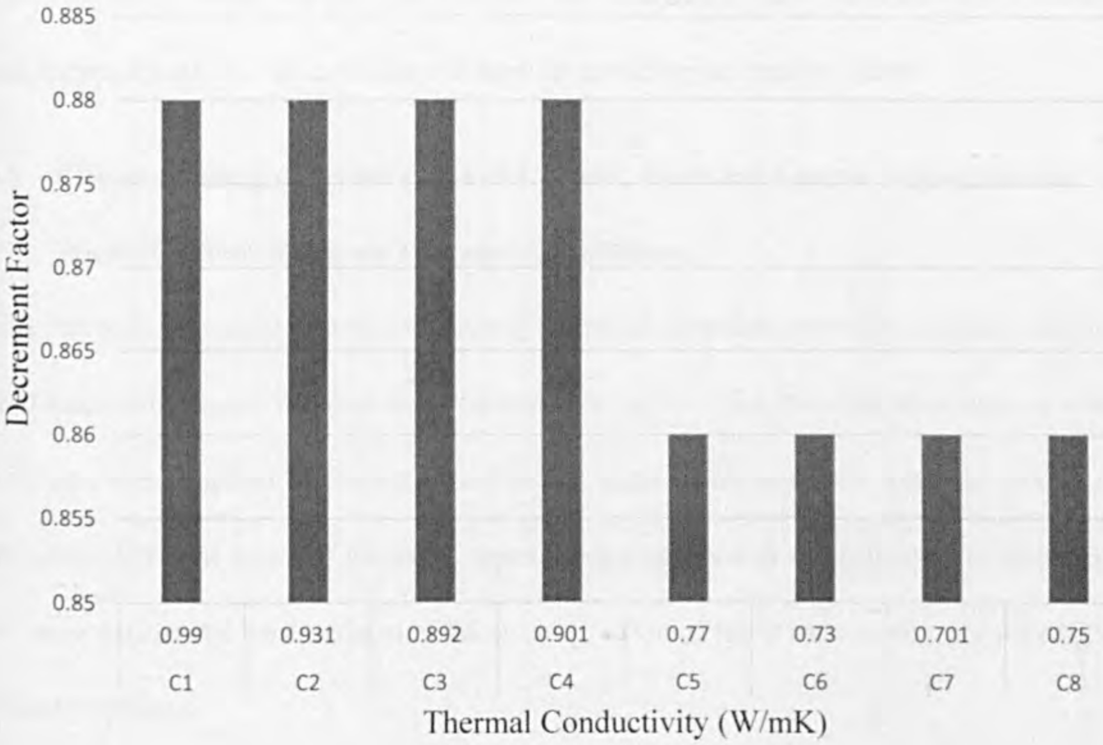


Figure 6-23 Decrement Factor varying Thermal Conductivity of Group C concrete mixes

From the figure 6.23, it can be concluded that since decreasing the water-cement ratio increases the thermal conductivity of the concrete, high thermal conductivity results in obtaining a decrement factor of 1 or less than 1. If the decrement factor is obtained as greater than 1, it is been classified as not an acceptable value under the reference range. Beside of this, since experimental results here are carried out by keeping the thickness of the concrete same, thickness of the concrete is not taken into account. However, in general, thickness of the concrete is another factor that needs to be taken into consideration because if the concrete has high thermal conductivity, as thermal conductivity of this concrete gets larger and at the same time as the thickness of the same concrete gets smaller, the decrement factor of the concrete is obtained as approximately zero. This can also be proven in a theoretical model. In order words, when the thickness of the concrete is increased, this results in increase in R-Value and hence a decrease in U-Value is observed which will then increase the decrement factor. However, when the thermal conductivity increased, this decreases the R-Value and hence increases the U-Value which will then increase the decrement factor.

6.5.3 Effects of using different types of Cement, Recycled Coarse Aggregate and Water/Cement Ratio on Thermal Admittance

In this research, the main aim of developing the excel spreadsheet was to measure the thermal admittance value hence thermal mass of concrete mixes. The thermal properties of concrete mixes data were applied to evaluate the thermal mass of the research concrete mixes. At the same time, different types of cements, types of aggregates and minimizing the water cement ratio were influenced on the thermal admittance value of the concrete mix identifying in the following sections.

6.5.3.1 Effects of using different types of Cement on Thermal Admittance of Concrete Mixes

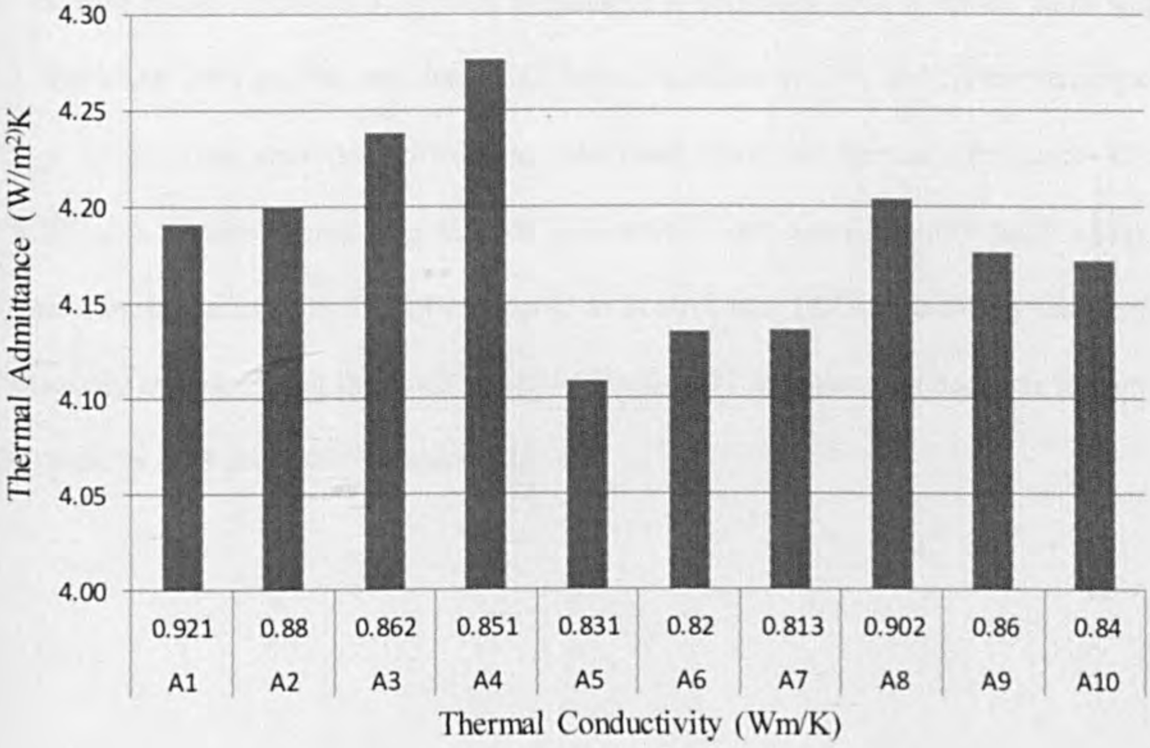


Figure 6-24 Thermal Conductivity varying thermal admittance value of concrete mixes (Group A)

When the effect of change in thermal conductivity on thermal admittance is investigated in group A concrete mixes, A1 concrete mix (100% PC + 100% NA) have 0.921 W/mK thermal conductivity value and thermal admittance 4.19 W/m^{2}K is taken as a control mix. In this group of concrete mixes, the laboratory results shows that increase in decreasing the thermal conductivity of the concrete mixes, increases the thermal admittance in GGBS content concrete mixes compared against control mix. Increasing the GGBS content in the concrete mix from 45 to 65% have increased the thermal admittance value of the concrete mixes from 0.24% to 2.15% given that a decrease in thermal conductivity is observed from 4.45% to 7.60% compared with control mix. On the other hand, even further decrease in thermal conductivity is observed in concrete mixes containing PFA instead of GGBS, resulting in decrease in thermal admittance, having a greater decrease in the thermal admittance with increasing the reduction in thermal conductivity of PFA content concrete mixes. However, this increase in the reduction of thermal admittance is achieved up to a certain point where PFA was about 20% and beyond that point, further increase in PFA and further decrease in thermal conductivity does not provide any additional effect on thermal admittance. Using 10% SF with further decrease in thermal conductivity has approximately same effect in thermal admittance as 45% GGBS compared to control mix (A1). Decreasing the thermal conductivity and increasing the silica fume to 15 and 20 % have result in decrease in thermal admittance by 0.24 and 0.48 % respectively.

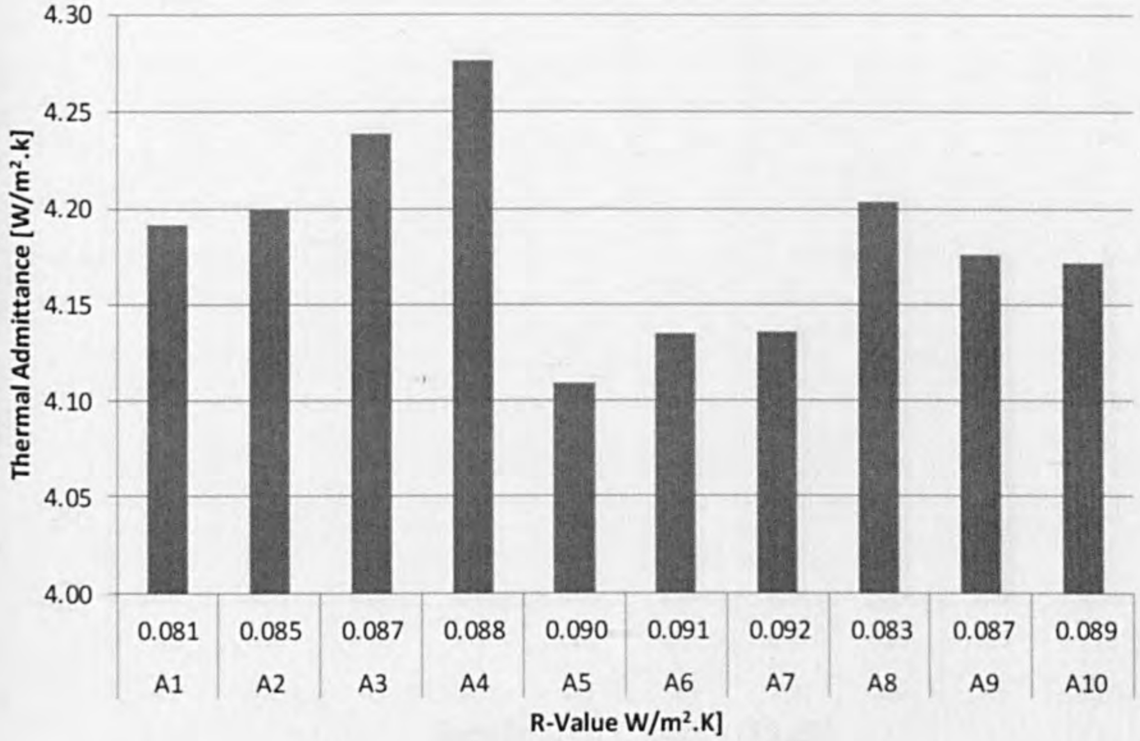


Figure 6-25 Thermal Admittance against R-value of Group A concrete mixes

Using GGBS in concrete mix, increase the thermal admittance as can be shown from the Figure 6.25 and at the same time, R-Value increase with increasing thermal admittance in GGBS concrete mixes. However, in PFA concrete mixes, thermal admittance is decreased with increasing R-Value of the PFA concrete mixes. Beside of this, PFA concrete mixes have the highest R-Value compared against all concrete mixes due to having less thermal conductivity in PFA concrete mixes which means observing improvements in R-Value of the concrete. The results obtained from laboratory sections have highlighted that for concretes with a greater R-value can be used in lightweight concretes and hence such concretes are appropriate to be used as good insulation. Even the R-value of silica fume content concrete mixes is greater than Portland cement concrete; Silica Fume content concrete mixes have the similar values in thermal admittance as Portland cement.

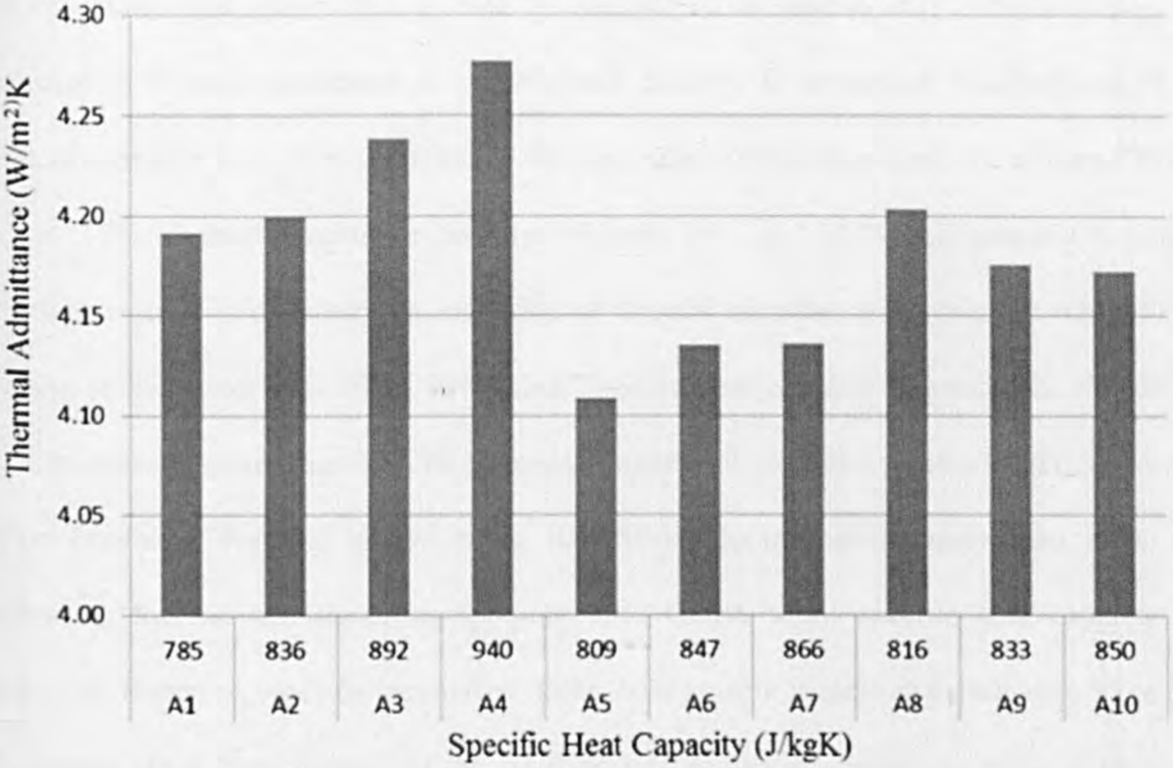


Figure 6-26 Specific Heat Capacity varying Thermal Admittance Value of Concrete mix (Group A)

Figure 6.26 shows the change in specific heat capacity varying thermal admittance Group A concrete mixes. The control mix is taken as A1 (100% PC + 100 % NA) with specific heat capacity 785 J/kgK and thermal admittance 4.19 W/m^{2}K. The aim in this section is to show how the increase in specific heat capacity affects the thermal admittance in the concrete mixes. Therefore all other concrete mixes in Group A are compared against A1. From the laboratory results, it can be concluded that increase in specific heat capacity results in increase in thermal admittance in concrete using GGBS content instead of PC. Having a greater GGBS content such as 55 and 65 % instead of 45 % and at the same time, increasing the specific heat capacity by 13.6 and 19.8 % respectively instead of 6.50% resulted a greater rise in thermal admittance concluding 1.19 and 2.15 % increase in thermal admittance respectively instead of 0.24 % rise.

On the other hand, when PFA is used in concrete mixes instead of PC, these results in decrease in thermal admittance as specific heat capacity is increasing. Similarly, as PFA content increases from 10 to 30%, and at the same time specific heat capacity increases from 3.1 to 7.9%, thermal admittance decrease by from 1.91 to 1.19 %. Additionally, in such concrete mixes, no difference in reduction of thermal admittance is observed when PFA content is increased from 20 to 30% while specific heat capacity is greater in 30% PFA content concrete mixes than 20% PFA content concrete. When silica fume is used in concrete mixes instead of Portland cement, using 10% SF results in approximately same effect in increasing thermal admittance as applying 45% GGBS when specific heat capacity is increased. However, when the amount of Silica fume content is increased such as to 15 or 20 %, greater silica fume content in the concrete mix results in slightly decrease in thermal admittance as specific heat capacity increases.

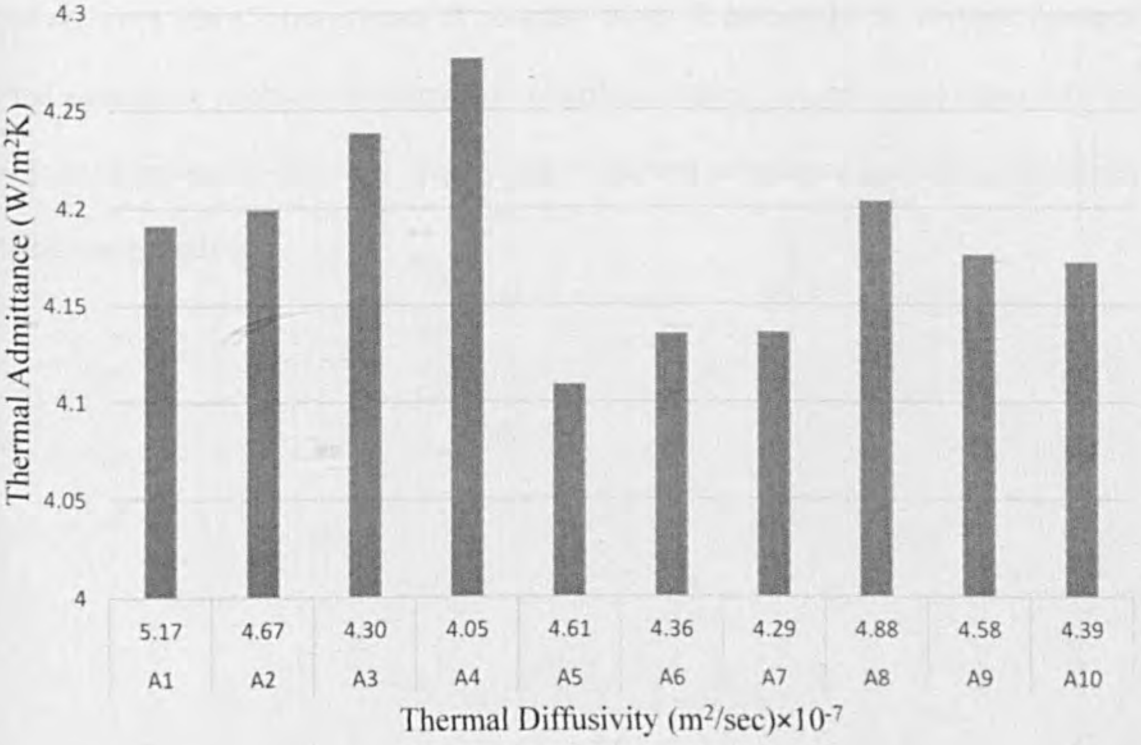


Figure 6-27 Thermal Admittance varying Thermal Diffusivity of Group A concrete mixes

Thermal Admittance is related to Thermal Diffusivity of the concrete. This is the reason that thermal diffusivity (calculated by specific heat capacity, density and thermal conductivity) is important in thermal dynamic properties of the concrete mixes.

PFA concrete mixes decrease the thermal admittance value more than others in group A. The reason for this is PFA being more effective than other cement replacement materials. Since, PFA concrete mixes have lower density and thermal conductivity than other cement replacement material concrete mixes and at the same time have greater specific heat capacity than other cement replacement material concrete mixes. PFA concrete mixes have lower thermal admittance than others.

Beside of this, GGBS concrete mixes have greater moderate thermal conductivity, density and specific heat capacity than PFA concrete mixes. Therefore, as GGBS content increase in concrete mixes, it increases the thermal admittance values. This can be shown in Appendix B. However, when silica fume content in concrete mixes is around 10 %, a slight increase in thermal admittance is observed compared to Portland cement concretes and when 20% silica fume is used in concrete mixes, a lower value of thermal admittance is obtained compared to Portland cement mixes.

6.5.3.2 Effects of using Recycled Coarse Aggregate on Thermal Admittance of Concrete Mixes

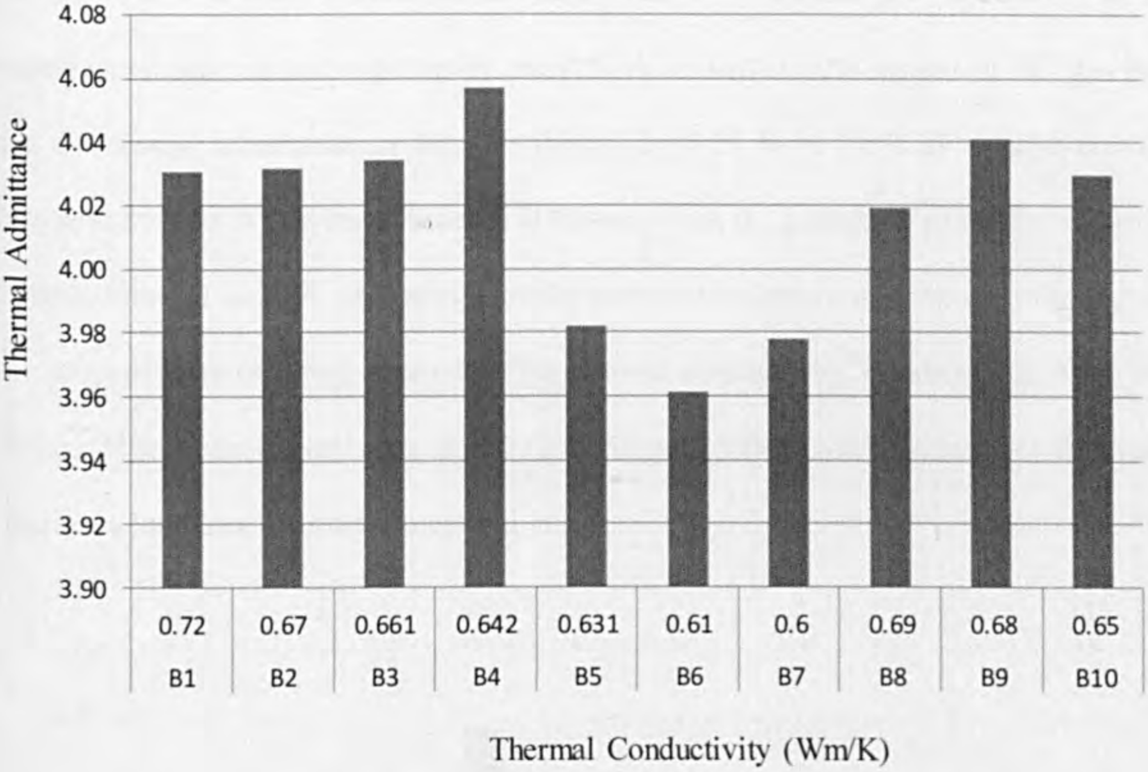


Figure 6-28 Thermal Conductivity varying Thermal Admittance Value of Concrete Mixes (Group B)

Figure 6.28 shows the change in thermal conductivity as varying thermal admittance value of Group B concrete mixes. For Group B concrete mixes, B1 (100% PC+30% RCA) concrete mix is taken as control mix and all other concrete mixes in this group are compared against B1 concrete mix. When GGBS is used instead of Portland cement, together with RCA in the concrete mixes, the increase in decreasing the thermal conductivity has shown no effect when GGBS content is 45 or 55%. However, further increase in GGBS to 65 % has slightly increased (0.74%) in thermal admittance given that the thermal conductivity of the concrete mixes is decreased further. On the other hand, decrease in thermal conductivity of PFA content concrete mixes together with 30% RCA, resulted a decrease in thermal admittance where the highest decrease in thermal admittance is observed in B6 (20% PFA with 30% RCA) concrete mix. Additionally increase in PFA content to 30% (B7 concrete mix) have resulted the same effect as having 10 % PFA (B5 concrete mix) which is observing 1.24 % decrease in thermal admittance given a 12.36 or 16.67 % decrease in thermal conductivity for 10 or 30 % PFA content concrete mixes respectively. When thermal conductivity of the concrete mixes are reduced, together by using RCA content as 30% instead of PC, this have made the thermal admittance to decrease slightly by 0.25 % in 10 % SF content concrete mixes with 30% RCA (B8 concrete mix). However, when the amount of Silica Fume content increased from 10 to 15%, an increase in the thermal admittance of concrete mix with the same proportion is observed given that the thermal conductivity is decreased. After this, additional silica fume content such as B10 (20% SF with 30% RCA) have made no difference in thermal admittance compared to control mix.

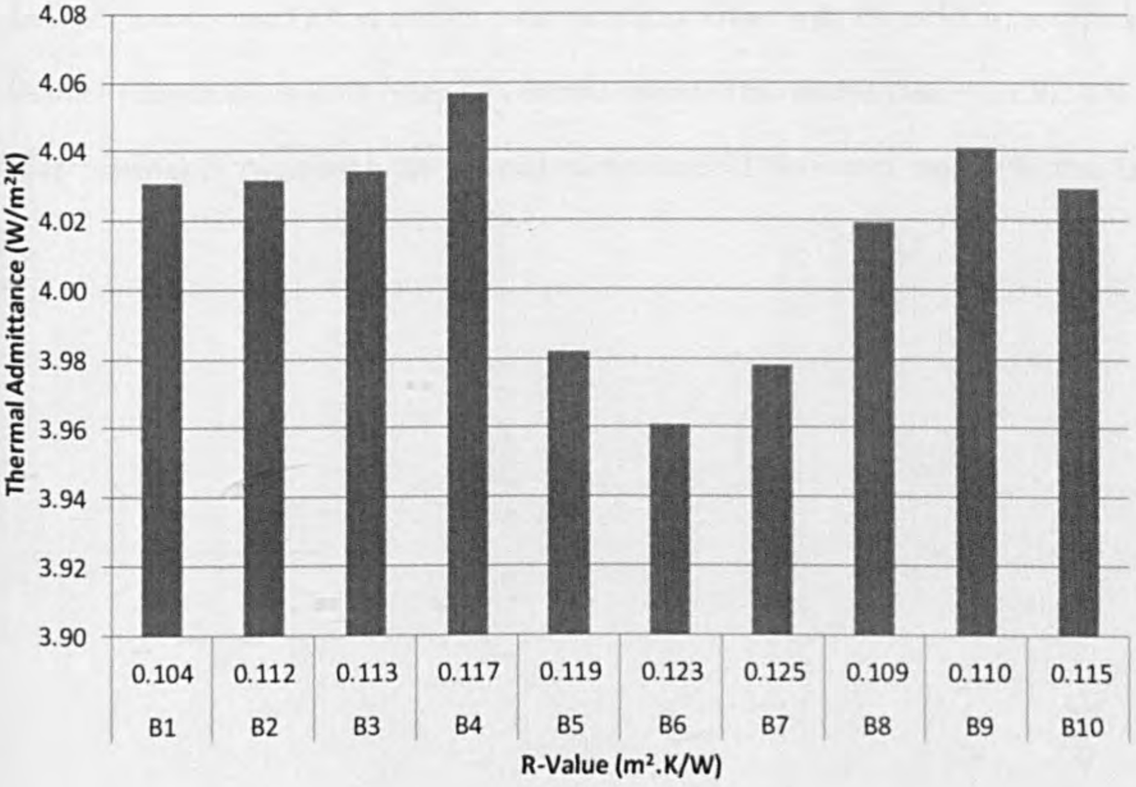


Figure 6-29 is Thermal Admittance against R-Value of Group B concrete mixes

Since RCA content concrete mixes have the lowest thermal conductivity, highest R-Value is observed in such concretes and hence this decreases the thermal admittance values. When R-Value is <0.117 m^2.K/W, thermal admittance values are observed slightly similar or little bit less than this R-Value.

Specifically, when R-Value of B8 (10% Silica fume) is 0.109 m^2.K/W, thermal admittance is observed to be 4.02 W/m^2.K and when R-Value of B1 (PC) is 0.104 m^2.K/W, thermal admittance is observed to be 4.03 W/m^2.K. When B8 is compared against B1, it is concluded that using silica fume in B8 together with RCA content increase the R-Value and decrease the thermal admittance. When silica fume is used together with PC instead of RCA, it increases the thermal admittance. This shows that RCA is more effective than Silica Fume.

On the other hand, when PFA is used in concrete mixes, either with PC or RCA, it decreases the thermal admittance in both types of concrete mixes. This means than even RCA is an effective material in decreasing the thermal admittance, PFA is even more effective than RCA.

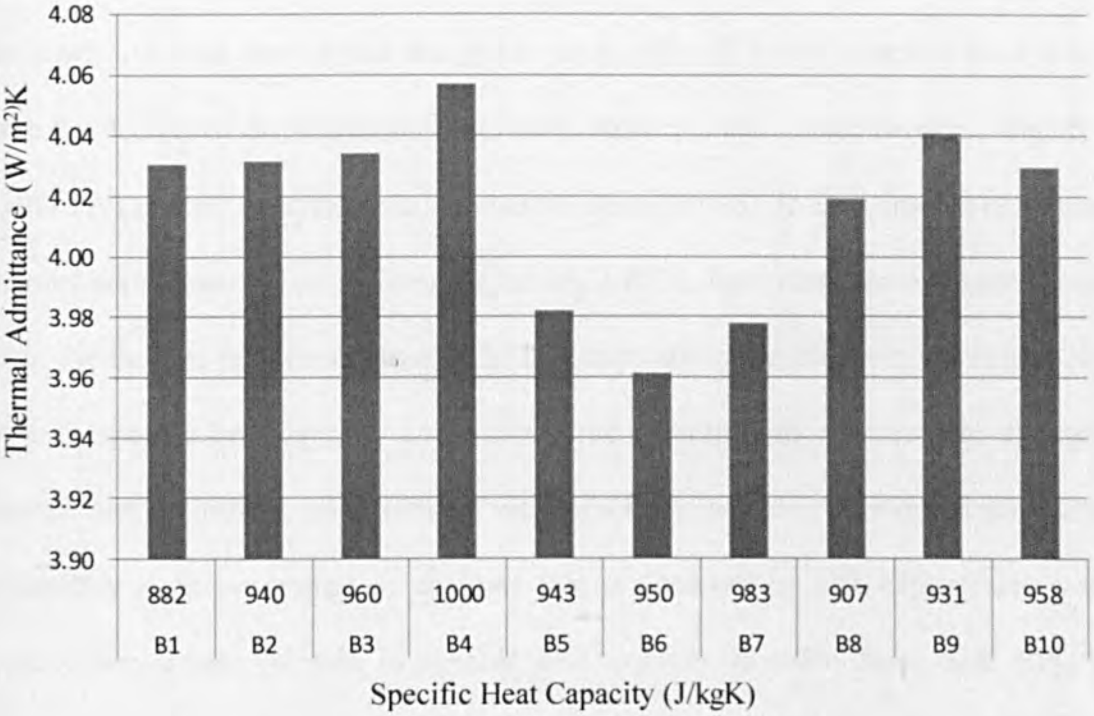


Figure 6-30 Specific heat capacity varying thermal admittance value of concrete mixes (Group B)

The figure 6.30 is described that specific heat capacity varying thermal admittance value of Group B concrete mixes. For Group B concrete mixes, the control mix is taken as B1 (100% PC +30% RCA) with specific heat capacity 882 J/KgK and thermal admittance 4.03 W/m^{2}K of concrete mix. The difference between Group B and A is instead of 100% PC, 70% NA and 30% RCA was used. The main aim in this section is to see the effect of RCA and NA in this relationship on how specific heat capacity effects the thermal admittance of the concrete mixes. The results of these mixes show that when GGBS content concrete is increased from 45% to 55%, unlike in Group A mixes, this increase does not affect the thermal admittance compared against control mix. However, increasing GGBS content to 65% have suggest a slight increase in thermal admittance given that the specific heat capacity is increased in the concrete mixes.

In concrete mixes containing PFA, similar trend as like group A mixes are observed and thermal admittance of all three concrete mixes decreases as specific heat capacity increases.

However, the greatest decrease in thermal admittance is observed when 20% PFA (B6 concrete mix) is used and beyond this point, using 30% PFA (B7 concrete mix) does not increase the decline of thermal admittance, instead thermal admittance decrease slightly less than 20% PFA content concrete mix. In concrete where 10% SF is used, instead of increasing the thermal admittance as like in Group A, having a RCA, have made the opposite effect and decrease the thermal admittance as specific heat capacity of the concrete increases. Greater increase in specific heat capacity and Silica fume content does not decrease the thermal admittance further. Instead, using 20% SF with 30% RCA increases the thermal admittance at approximately same percentage of decrease that is observed in 10% Silica Fume content concrete. Even greater increase in specific heat capacity in silica fume with 30% RCA content concrete mixes, this have resulted to have the same thermal admittance as the control mix (B1 concrete mix).

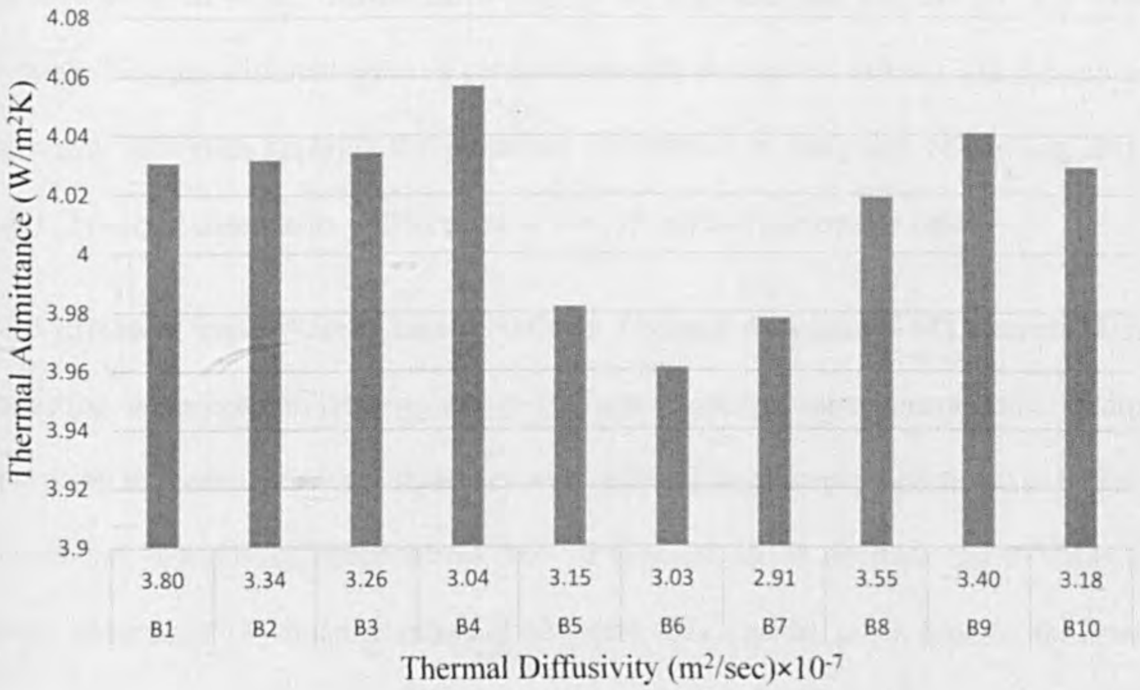


Figure 6-31 Thermal Admittance varying Thermal Diffusivity of Group B concrete mixes

RCA content concrete decrease the thermal diffusivity in all mixes in group B. This is due to RCA material being lighter than normal concretes. PFA content concrete mixes have lower thermal admittance and reasons for this depend on thermal properties of concrete. For instance, PFA directly decrease thermal conductivity and density and hence, lower thermal diffusivity and thermal admittance are observed in PFA concretes. Specifically, B7 concrete mix (30% PFA + 30% RCA) has thermal diffusivity of 2.91[m^2/sec]x10^{-7} and this is the lowest thermal diffusivity of all mixes in group B. Even B5 has thermal diffusivity of 3.14 [m^2/sec] x$10^{-7}$is different with B7. Both B5 and B7 results in same thermal admittance value which is 3.98 W/m^2K.

When GGBS content is used together with RCA, it increases the thermal diffusivity more than using either silica fume or PFA together with RCA. When GGBS is used together with 30% RCA (B2, B3), thermal admittance value obtained is the same as B1 that is PC together with 30% RCA. However, thermal diffusivity of B1 is greater than B2 and B3. It is shown that using RCA and different types of cement materials in concrete mixes make the concrete lightweight. However, applying the properties of material in designing of concrete mix is given lightweight concrete as well as same or similar thermal admittance value.

6.5.3.3 Effects of using Water/Cement Ratio on Thermal Admittance of Concrete Mixes

Minimizing water/cement ratio decreases R-Value because water/cement ratio is direct proportional to thermal conductivity and as well as this, it is indirect proportional to R-Value. It means that minimising water/cement ratio in concrete mixes decrease the R-Value and thermal admittance of concrete mixes. Comparing this against other groups, the lowest thermal admittance and R-Value is observed in group C.

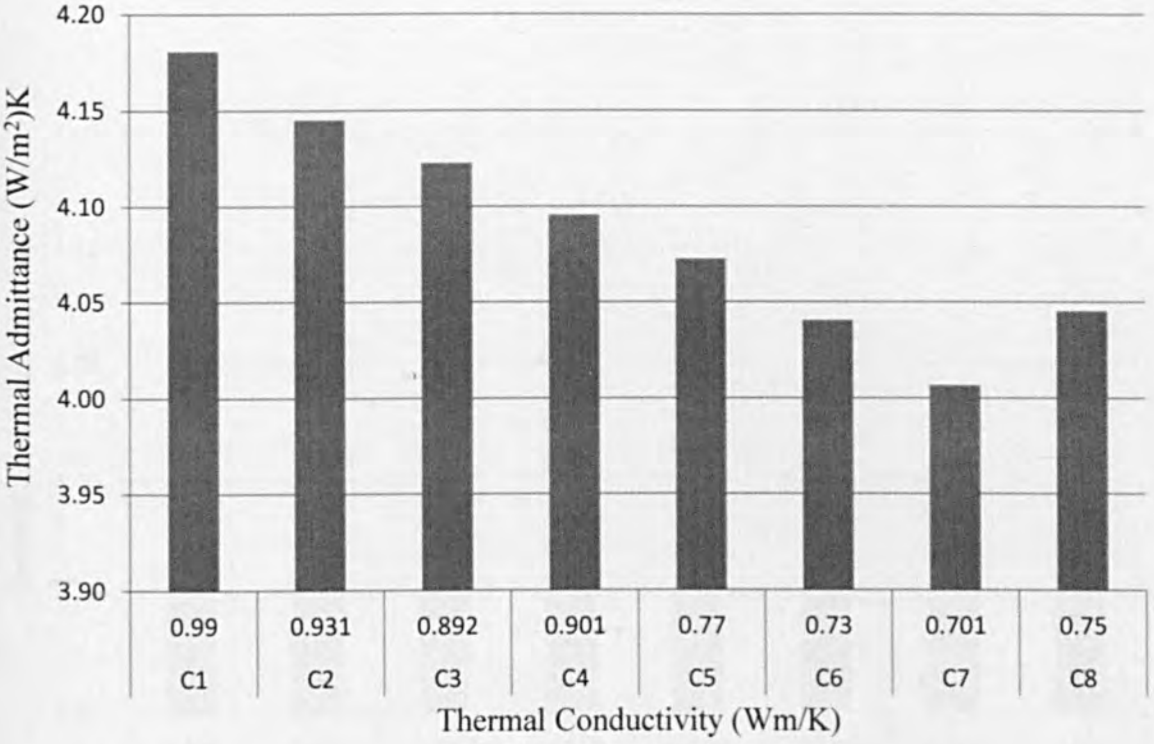


Figure 6-32 Thermal Conductivity varying Thermal admittance value of concrete mixes (Group C)

The figure 6.32 is shown that thermal conductivity varying thermal admittance value of Group C concrete mixes. For Group C concrete mixes, C1 (100% PC + 100% NA) and C5 (100% PC + 70% NA + 30% RCA) is taken as control mixes. Concrete mixes C2 (45% GGBS), C3 (20% PFA) and C4 (20% SF) are compared against control mix C1 (100% PC) where RCA is not used in such concrete mixes. From the comparison of C2, C3 and C4 against C1 conclude that 20% SF (C4) resulted the highest decrease in thermal admittance as thermal conductivity is decreasing whereas concrete mixes C6 (45% GGBS + 30% RCA), C7 (20% PFA + 30% RCA) and C8 (20% SF + 30% RCA) are compared against control mix C5 (70% PC + 30% RCA). The result of comparisons of such concretes containing RCA content conclude that when RCA is present additionally in concrete mixes, 20% PFA content concrete is resulted to show the highest decrease in thermal admittance given that the thermal conductivity of the mixes are decreasing.

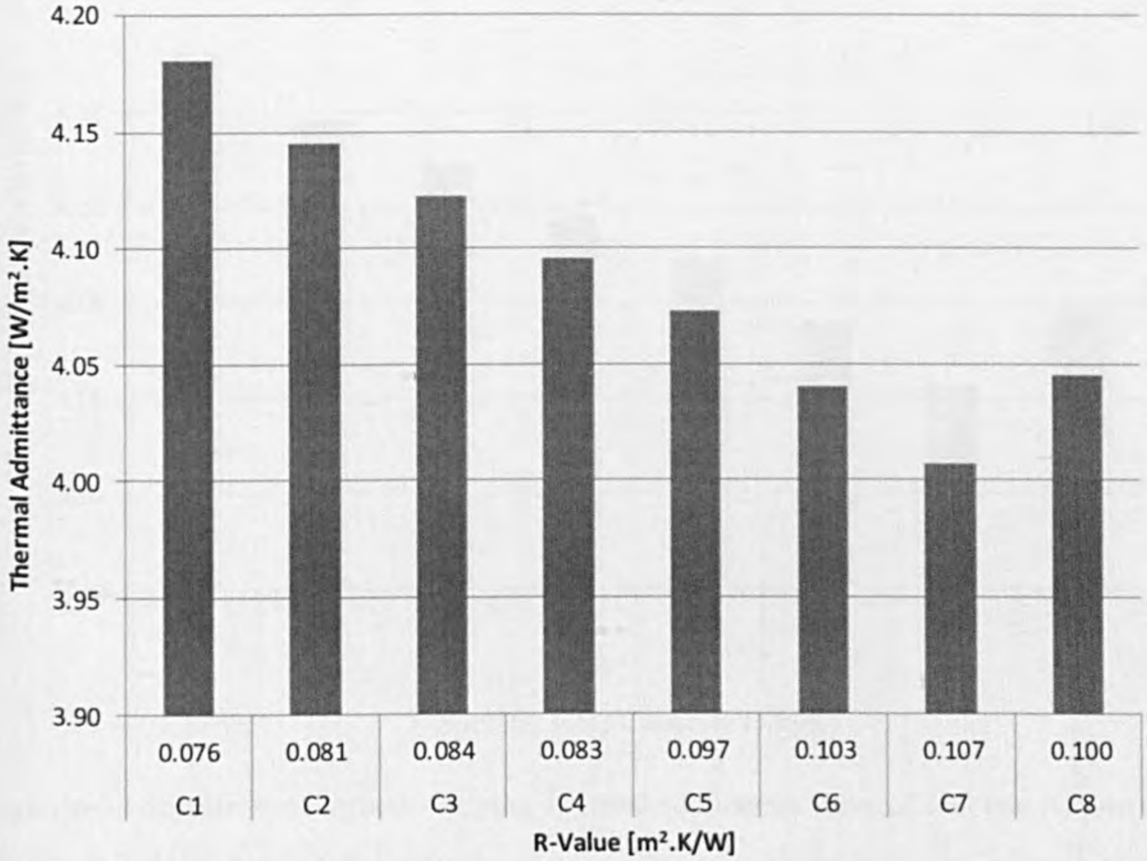


Figure 6-33 Thermal Admittance varying R-Value of Group C concrete mixes

The main reasons of group C having lowest thermal admittance and R-Value are; minimizing water/cement ratio improve thermal conductivity and density of the concrete. Therefore, in all groups, group C concrete mixes have the highest value of thermal conductivity and density. As well as this, most of the concrete mixes having lowest specific heat capacity values are present in group C. These factors are directly affecting the thermal diffusivity and hence thermal diffusivity values are increased. However, these results are provided that higher thermal conductivity is not good for the thermal admittance of the concrete mix. The important thing is using less dense concrete such as lightweight concrete to achieve same or similar thermal admittance values in the concrete mix which is more sustainable concrete.

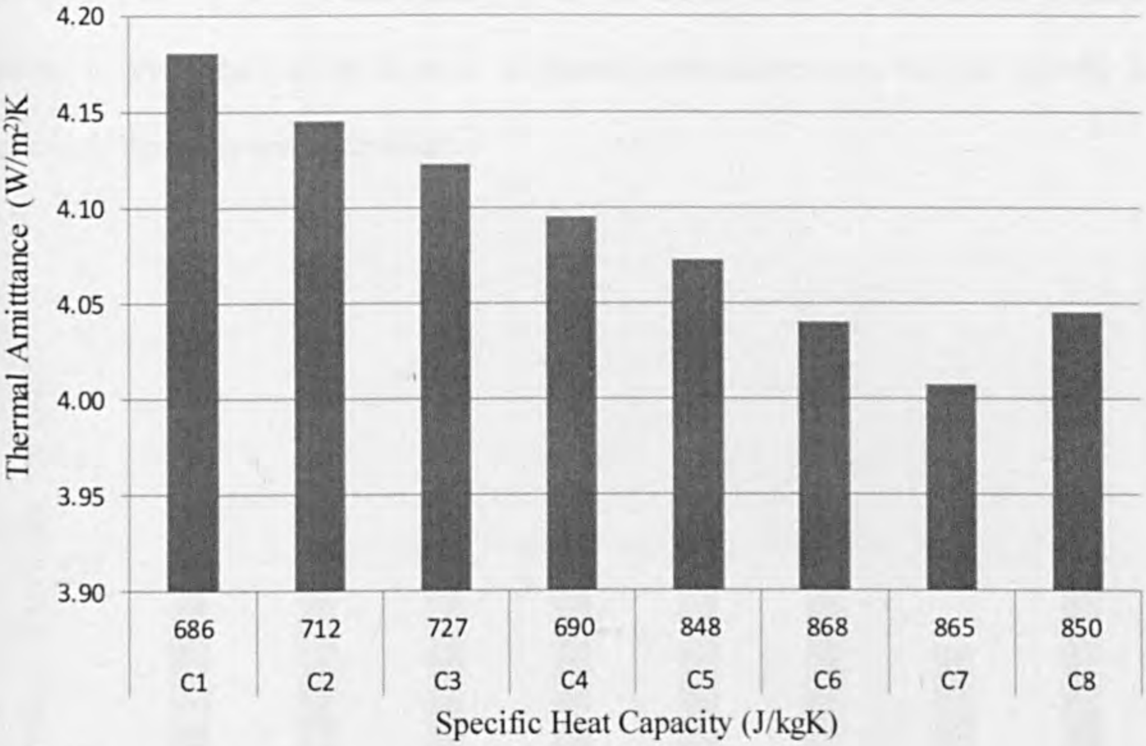


Figure 6-34 Specific heat capacity varying Thermal admittance value of concrete (Group C)

The figure 6.34 is defined that specific heat capacity varying thermal admittance value of Group C concrete mixes. In Group C concrete mixes, concrete mixes C1 (100% PC +100% NA) with specific heat capacity 686 J/KgK and thermal admittance 4.18 W/m^{2}K and C5 (100%PC + 70%NA + 30%RCA) with specific heat capacity 848 J/KgK and thermal admittance 4.07 W/m^{2}K are taken as control mixes. In this section, Group C concrete mixes are used to see the effect of minimizing water cement ratio on different types of cement materials and recycled coarse aggregate on the thermal admittance as varying specific heat capacity of the concrete mixes. Again, concrete mixes C2 (45% GGBS), C3 (20% PFA) and C4 (20% SF) are compared against control mix C1 (100% PC) where RCA is not used in such concrete mixes. From the comparison of C2, C3 and C4 against C1, it can be concluded that 20% SF (C4) resulted the highest decrease in thermal admittance as specific heat capacity is increasing whereas concrete mixes C6 (45% GGBS + 30% RCA), C7 (20% PFA + 30% RCA) and C8 (20% SF + 30% RCA) are compared against control mix C5 (70% PC + 30% RCA). The result of comparisons of such concretes containing RCA content conclude that when RCA is present additionally in concrete mixes, 20% PFA content concrete is resulted to show the highest decrease in thermal admittance given that the specific heat capacity of the mixes are increasing.

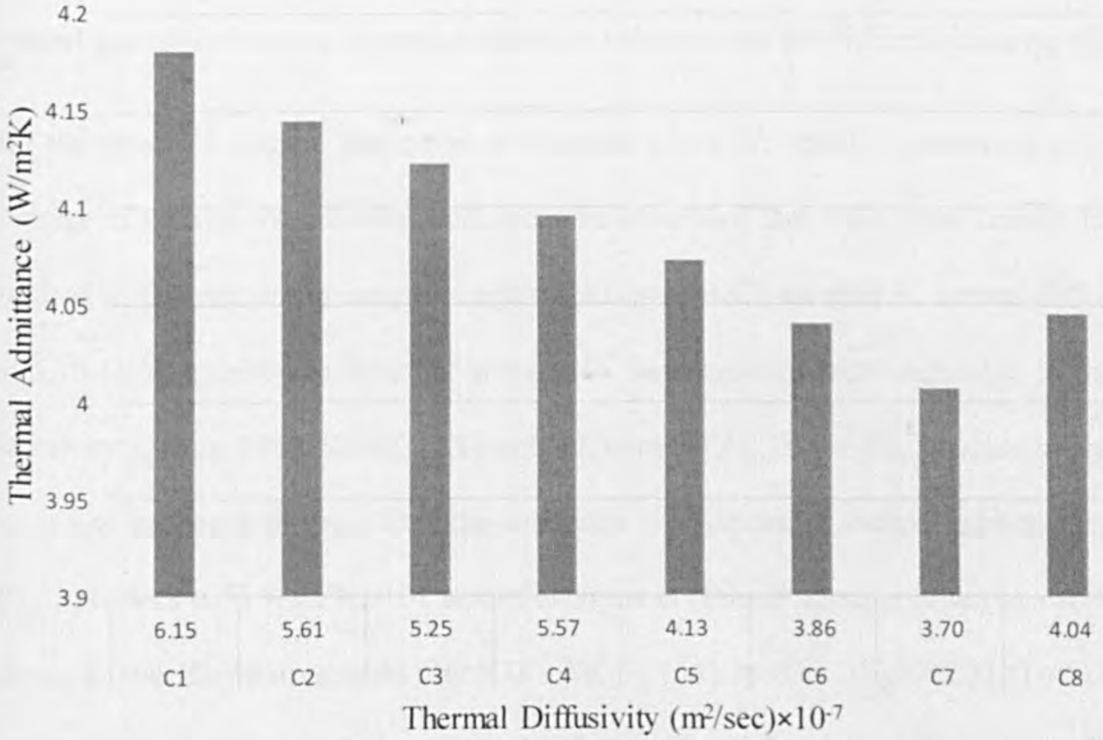


Figure 6-35 Thermal Admittance varying Thermal Diffusivity of Group C concrete mixes

In other words, achieving moderate thermal conductivity is more useful for the thermal admittance of the concrete. For instance, comparing C1 (100% PC) against C5 (100% PC + 30% RCA), the thermal diffusivity of C1 is 6.15 [m^2/sec]x10^{-7}and thermal diffusivity of C5 is 4.13 [m^2/sec]x10^{-7} but thermal admittance values of C1 and C5 are approximately same such as 4.18 and 4.07 W/m^2.K respectively. From the observations, C1 is heaviest concrete mix than all the mixes. However, C5 contains RCA content and it is lighter than some of the concrete mixes in group C and lighter than some of the concrete mixes. This results are lead to decide that the effect of materials and how these materials have to be used properly in concrete to achieve lightweight concrete with functional thermal properties.

After such comparison, since thermal diffusivity is calculated by using thermal conductivity, specific heat capacity and density values simultaneously, in the following section, the effect of minimizing water cement ratio on thermal conductivity, specific heat capacity and hence on thermal diffusivity is explained by using various concrete mixes. These effects are then compared against the varying thermal admittance values across the different concrete mixes.

When the effect of thermal properties in concrete mixes A1 and C1 containing the same percentage of PC and NA are compared, it can be concluded that when water cement ratio is minimized in C1 (w/c=0.35) compared against A1 (w/c=0.57) increase in thermal diffusivity from 5.16 [m^2/sec]xx10^{-7} to 6.15 [m^2/sec]x x10^{-7} have resulted with increasing in thermal conductivity is from 0.921 W/mK (A1) to 0.99 W/mk (C1). Hence this increase in thermal conductivity influence thermal admittance slightly by decreasing thermal admittance from 4.19 (A1) to 4.18 (C1) W/m^2K. 0.01 unit of decrease in thermal admittance might also due to decrease in specific heat capacity from 785 J/KgK (A1) to 686 J/KgK (C1). To sum up, minimizing water cement ratio improves the density, thermal conductivity and reduces the specific heat capacity of concrete. Therefore, similar results are observed in thermal admittance.

Results obtained when concrete mix A2 with thermal conductivity 0.88 W/mK, thermal diffusivity 4.66x10-7, and thermal admittance 4.14 W/m^2K, it can be seen that minimizing the water cement ratio has from 0.57 (A2) to 0.35 (C2) increased the thermal diffusivity and hence resulted an increased in thermal conductivity by 5.8% and this creates a decreased in the thermal admittance by 1.43 %. This might also be the effect of decreasing the specific heat capacity from 836 J/KgK (A2) to 712 J/KgK (C2). When concrete mixes A6 with thermal diffusivity 4.36 [m^2/sec]x10^{-7}, thermal conductivity 0.82 W/mK and thermal admittance 4.14 W/m^2K compared against C3 with thermal diffusivity 5.25 [m^2/sec]x10^{-7}, thermal conductivity 0.89 W/mK and thermal admittance 4.12W/m^2K, it is shown that minimizing the water cement ratio from 0.49 (A6) to 0.30 (C3)resulted in increase in thermal diffusivity which will then decrease the thermal conductivity by 10.98% and 0.48%. Hence decrease the thermal admittance. This decrease might due to the change in specific heat capacity of the concrete mix from 847 (A6) to 727 (C3) J/KgK.

The concrete mix C4 is contrasted with A10 and this association suggest that using minimal water cement ratio as 0.35 in C4 instead of 0.57 in A10. have improved the thermal conductivity by 9.88% with increasing thermal diffusivity from 4.39 (A10) to 5.57 (C4) $[m^2/sec]x10^{-7}$ which in turn decrease thermal admittance by 0.97%. This can be due to decrease in specific heat capacity from 850 (A10) to 690 (C4) J/KgK. Concrete mixes C5 and B1 are compared where C5 has thermal diffusivity of 4.13 $[m^2/sec]x10^{-7}$. thermal conductivity 0.77 W/mK. thermal admittance value 4.07 W/m^2K and B1 has thermal diffusivity of 3.80 $[m^2/sec]x10^{-7}$. thermal conductivity 0.72 W/mK. thermal admittance value 4.03 W/m^2K. Minimizing water cement ratio from 0.59 in B1 to 0.35 in C5. resulted a increase in thermal conductivity with increasing thermal diffusivity by 6.49% and at the same time resulted a decrease in thermal admittance by 0.98%. it is also possible that this reduction might due to decrease in specific heat capacity from 882 (B1) to 848 (C5) J/KgK. Thermal conductivity of B2 is 0.67 W/mK with thermal diffusivity 3.34 $[m^2/sec]x10^{-7}$. thermal admittance is 4.03 W/m^2K. On the other hand. thermal conductivity of C6 is 0.73 with thermal diffusivity 3.86 $[m^2/sec]x10^{-7}$. and thermal admittance is 4.04 W/m^2K. When these concrete mixes are compared with each other results have showed that. minimizing the water cement ratio from 0.59 (B2) to 0.35 (C6) have increase the thermal conductivity by 8.96% which will then increase diffusivity and simultaneously increase the thermal admittance by 0.25%. As well as this. specific heat capacity decreases from 940 (B2) to 868 (C6) J/KgK in such mixes. When concrete mix B6 with thermal conductivity 0.61 W/mK with thermal diffusivity 3.03 $[m^2/sec]x10^{-7}$. thermal admittance 3.96 W/m^2K compared against concrete mix C7 with thermal conductivity 0.70 W/mK, thermal diffusivity 3.70 [m^2/sec]x10^{-7}, and thermal admittance 4.01 W/m^2K. Using minimal water cement ratio as 0.30 in C7 instead of 0.51 in B6 has resulted an increase in thermal conductivity by 14.92% with a slight increase in thermal diffusivity as well as increasing thermal admittance by 1.26%. On the other hand, when concte mix B10 is compared C8, minimizing the water cement ratio from 0.59 in B10 to 0.35 in C8, increase in thermal conductivity by 15.38% which in turn creates an increase in thermal diffusivity has improved from 3.18 (B10) to 4.04 (C8) [m^2/sec]x$10^{-7}$from B10 to C8. As well as causing an increase in thermal admittance by 0.59% from 4.03 W/m^2K in B10 to 4.05 W/m^2K in C8 concrete mixes. from the laboratory results are shown that the specific heat capacity of concrete mix in B10 has 958 J/KgK is decreased in C8 has 850 J/KgK.

6.6 Practical Implications

The main aim of this research is measuring the thermal admittance hence thermal mass of concrete mixes. According to BS EN ISO 13786:2007 standard was used to develop the thermal dynamic calculation to use the excel spreadsheet. This research enables the use of different types of cements and aggregates efficiently in the building construction such as wall or floor in the construction industry.

The excel spreadsheet provides to calculate the thermal dynamic properties. Such as U-value or decrement factor of the concrete can be evaluated. The laboratory thermal results are used to calculate thermal dynamic properties of the research concretes. At the same time, the spreadsheet can be applied in construction industry such as block or brick manufacturing companies can be used this excel spreadsheet to calculate their products thermal dynamic properties. It can also be helped for their customers to choose right product for their buildings and also it is good for the company to sell their product more because of the product specifications are clearer.

The research concretes can be applied in the concrete construction industry for the commercial, residential and multi-storey buildings. For instance, the research concrete mixes can be used in external wall, internal partition, and party wall of the buildings. On the other hand, this research is given that 30% Recycled coarse aggregate content concrete mixes might be applied in the building structures. Such as Group B (30% RCA content mixes) concrete mixes have slightly less thermal admittance value with Natural aggregate concrete mixes. Extensive background gained from this research opens up an opportunity to improve the using recycled aggregate content in building concrete construction

The research is helped to Sustainable concrete construction industry applying the materials to build more sustainable buildings with minimizing energy consumption and providing optimal thermal comfort in the buildings for best living area.

6.7 Summary of main findings

Different types of Cement materials increase the R-value with decreasing U-value of the concrete mixes. Especially PFA content in concrete mixes has the lowest U-value and the highest R-value of the concrete mixes. The highest U-value is obtained when Cement replacement material is Silica Fume. However, GGBS content in concrete mixes have greater R-value than Silica Fume content in concretes. When R-values are reduced based on thermal mass benefits have also been published for commercial and high-rise residential buildings. ASHRAE/IES Standard 90.1-1989 (American Society of Heating, Refrigeration and Air Conditioning Engineers 1989) and DOE, 'Energy Conversation Voluntary Performance Standards for New Commercial and Multi-Family High-Rise Residential Buildings; Mandatory for New Federal Buildings'. When Recycled Coarse Aggregate content in concrete mixes is examined, it is concluded that RCA content in concrete decreased the U-value more than types of cement materials of concrete mixes. The results are defined that when both RCA and different types of cement materials are used in the concrete mix, U-value of the concrete mixes decreased more than using either of them separately. On the other hand, when water-cement ratio is minimized, all types of concrete mixes increased the U-value of the concrete mixes. In other words, low water-cement ratio helped to increase the U-value of concrete mix. That's why water-cement ratio is more vital than RCA and different types of cement materials content in the concrete mix.

The results are explained that when types of cement materials are compared with the decrement factor value, there is no significant difference between the mixes. When consideration is done by checking thermal conductivity and specific heat capacity of concrete mixes, it is found that thermal conductivity of concrete is increased with increasing the decrement factor value and specific heat capacity of concrete decreased with decreasing the decrement factor of the concrete mixes. Beyond the specific heat capacity of 750 J/Kg.K, decrement factor of the concrete mix decreased suddenly. On the other hand, RCA content in concrete decreased the decrement factor of concrete mix. When the specific heat capacity of concrete mix is greater than 850 J/Kg.K, decrement factor of the concrete is decreased significantly. However, decreasing in thermal conductivity of concrete mixes is also observed. Beside of this, minimizing water cement ratio increased the decrement factor value and minimizing water/cement ratio improved the decrement factor of the RCA and different types of cement materials content in concrete mixes.

On the other hand, when GGBS is used in concrete mix; it increases the thermal admittance more than all groups. PFA content in concrete mixes have the lowest thermal admittance value than all mixes. Silica Fume concretes has similar value of thermal admittance with Portland cement concrete mixes. RCA content in concrete mixes have the lowest thermal admittance values than other natural aggregate content in concrete mixes. Thermal admittance does not need to have high or low thermal conductivity of concrete mix. The importance is to have a moderate thermal conductivity. The results are provided that thermal admittance is increased with high specific heat capacity, high density and moderate thermal conductivity of the concrete mixes. Those factors are vital for improving thermal admittance of concrete mix.

7 Conclusion & Recommendation

7.1 Conclusion

This research is aimed to investigate effects of the different types of cement materials, recycled coarse aggregate and minimizing water cement ratio on the thermal properties of concrete mixes. These factors are taken into consideration to compare the effects of the materials on the density, specific heat capacity and thermal conductivity of the concrete. After the laboratory test results of concrete mixes are applied to calculate the Thermal Admittance, and other thermal dynamic properties such as U-value and Decrement factor of concrete mixes.

Thermal properties of concrete mixes are considered by applying thermal conductivity, specific heat capacity and density of the concrete mixes. In order to find out the effect of different types of cement materials, Recycled Coarse Aggregate [RCA] and water cement ratio on thermal properties of the concrete mixes, thermal properties of all of the concrete mixes are tested. The results are given and discussed in Chapter 4. Main points found are:

- The results are explained that different types of cement materials are affected the thermal properties of concrete. PFA is the more effective material than Silica Fume and GGBS in the concrete mix. When investigation is done by Silica Fume and GGBS, Silica fume is more affected than GGBS. It is needed to highlight that the amount of material is important. However, the material affectivity (such as chemical reaction of the material) is more important than amount of the material in concrete mixes. The laboratory results are shown that all of the different types of cement materials are decreased the thermal conductivity and thermal diffusivity of the concrete comparing with Portland cement concrete mix. On the other hand, different types of cement materials are increased the specific heat capacity of the concrete mixes.

- When RCA content in concrete mix are presented, it makes the concrete lighter than natural aggregate concrete mix. In other words, RCA concrete mixes are not denser like natural aggregate concrete mixes. Because RCA is contained other materials such as wood, cement paste and etc. as well. RCA concrete mixes are decreased the thermal conductivity and thermal diffusivity of the concrete mixes. At the same time RCA is increased the specific heat capacity of the concrete mixes. If RCA and different types of cement materials are compared, RCA is decreased the density and thermal conductivity more than different types of cement materials concrete mixes. On the other hand, RCA concrete mixes are increased the specific heat capacity more than the different types of cement materials concrete mixes. When Both RCA and different types of cement materials are used in concrete mix together, the reduction of thermal conductivity and thermal diffusivity is greater than applying both RCA and different types of cement materials concrete mix separately. The results are proofed in Chapter 4. According to research results, when RCA and different types of cement materials are used, water-cement ratio has to be considered to improve thermal conductivity and thermal diffusivity.
- Water- Cement ratio is the main actor on the thermal properties of the concrete mix. The reason is; minimizing water-cement ratio is made the concrete denser than the normal range of water cement ratio in concrete mix. Water-cement ratio is improved thermal conductivity and thermal diffusivity [Group C concrete mixes] more than other factors [Group A and B concrete mixes]. That's why the design of the concrete mix has to be considered with the water-cement ratio for improving the thermal properties of concrete mix. Minimizing water-cement ratio is provided to increase the

density and thermal conductivity of the concrete mix. The first reason is: thermal conductivity is increased with increasing the density of the concrete. The second reason is: the cement has greater thermal conductivity value than thermal conductivity of water. As well as this, minimizing water-cement ratio is helped to increase the unit weight of concrete [mass of concrete]. It means that minimizing water-cement ratio is minimised the porosity and air in the concrete mix.

After the thermal dynamic calculator is set up in excel. The concrete mixes results are used to calculate thermal admittance hence thermal mass, the U-value, and decrement factor of the concrete mixes. The calculation is made by using thermal conductivity, specific heat capacity and density of the concrete mixes. The results obtained from the calculations conclude:

- Different types of cement materials concrete mixes decreased the U-value of the concrete mix. Since U-value of the concrete mix is related with R-value of the concrete, R-value of the different types of cement materials concrete mixes are greater than other mixes. It means that the different types of cement materials concrete mixes have lowest thermal conductivity value. This is the main reason that the different types of cement materials has the highest U-value in Silica Fume concrete mixes when compared against other the different types of cement materials concrete mixes [GGBS, PFA]. On the other hand, RCA is decreased the u-value of the concrete mixes more than the different types of cement materials concrete mixes. The reason is RCA content in concrete mixes have lowest thermal conductivity of concrete more than all groups of the concrete mixes. The other factor is water-cement ratio of the concrete mix. When water-cement ratio is minimized, thermal conductivity of the concrete mix is increased with increasing U-value of the concrete mixes. Water-cement ratio is the vital for improving thermal conductivity and U-value of the RCA and the different types of cement materials concrete mixes.

- The results from the thermal dynamic calculator are defined that there is no significant difference in decrement factor of the concrete mixes. The consideration is taken by using thermal conductivity and specific heat capacity of the concrete mixes. The results are provided that thermal conductivity is increased the decrement factor. However, the specific heat capacity is decreased with reducing decrement factor of the concrete. The result is shown that when the specific heat capacity of 750J/Kg, the decrement factor is decreased slightly. On the other hand, RCA concrete mixes are decreased the decrement factor of the concrete mixes. The main reason is RCA content in concrete mixes have highest the specific heat capacity value more than other concrete mixes. However, water-cement ratio is minimized with increasing the decrement factor value of the concrete slightly as shown in Chapter 5.

- Thermal admittance value is affected by thermal conductivity, density and the specific heat capacity of the concrete mix. In other words, thermal diffusivity is taken consideration for the thermal admittance value. The calculation is shown that GGBS content in concrete mixes have highest thermal admittance value than all other mixes. PFA content in concrete mixes have lowest thermal admittance value in all groups. However, Silica Fume content concrete mixes are similar thermal admittance value with Portland cement. On the other hand, RCA content concrete mixes have low thermal admittance value. Water cement ratio is helped to increase slightly of the thermal admittance value. However, the thermal admittance is required to have high specific heat capacity and high density and moderate thermal conductivity of the concrete mixes. The chapter 5 is provided that these factors are important for developing or arranging the thermal admittance of the concrete mix.

As an application of this thesis, results obtained from laboratory section and hence the calculations carried out afterwards can help in performing conceptual design of framed buildings including options such as floor slabs and walls. Additionally, investigations of various materials used for concrete contribute in specifying which materials are more suitable to use than others in sustainable concretes. By using this thesis, awareness about sustainability in concrete is improved to make further recommendations to construction professionals. Moreover, further research on thermal mass is encouraged.

6.2 Future Recommendation

The lack of knowledge is identified about the effects of recycled coarse aggregate and different types of cement materials on thermal properties of concrete. Therefore by this thesis, it is recommended that the microstructure of such materials has to be explored. Specifically GGBS material is suggested to investigate further. Beside of analysing the microstructure of such materials, since a gap in the available knowledge about the specific heat capacities of the building materials is found, it is also acclaimed to analyse and investigate specific heat capacity. Finally this thesis proved that thermal properties of materials are very important in building construction and needed to be discussed deeply.

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9 Appendices

9.1 Appendix A- Compressive strength results

Table 9-1 Compressive strength of all groups of concrete mixes

	Compressive Strength [N/mm^2]			
Mix No.	7 Day		28 Day	
	Cube	Cylinder	Cube	Cylinder
A1	35	28	45	38
A2	27	23	42	35
A3	26	22	42	36
A4	24	20	41	35
A5	30	25	41	34
A6	29	24	41	34
A7	29	25	40	34
A8	33	29	44	37
A9	31	26	44	36
A10	30	26	43	37
B1	27	23	39	33
B2	22	19	42	36
B3	21	18	37	31
B4	21	17	40	34
B5	26	22	42	36
B6	25	21	41	35
B7	24	21	39	33
B8	28	24	42	35
B9	30	26	41	35
B10	26	22	38	32
C1	44	37	55	45
C2	41	34	51	44
C3	42	35	53	45
C4	43	37	54	44
C5	45	38	54	45
C6	40	34	49	42
C7	44	37	48	41
C8	41	35	52	44

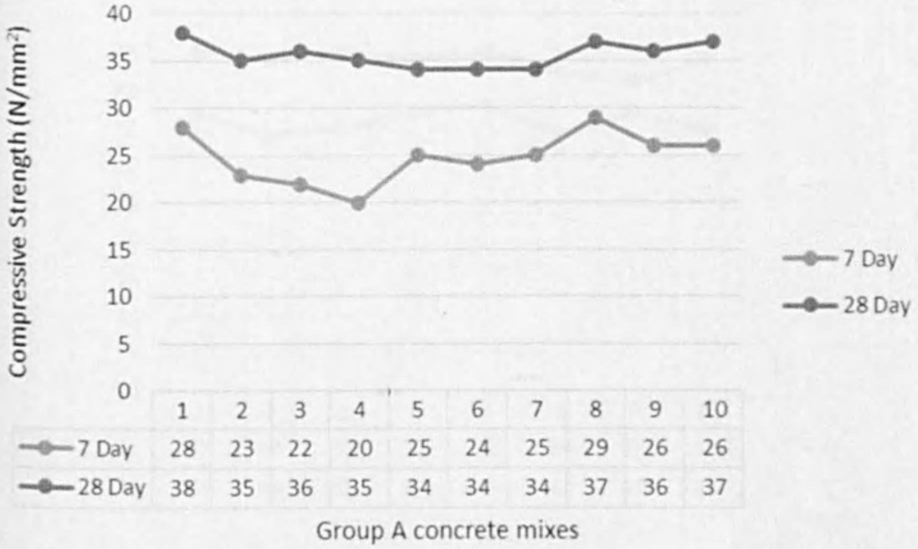


Figure 9-1 Compressive strength of group A concrete mixes (Cylinder)

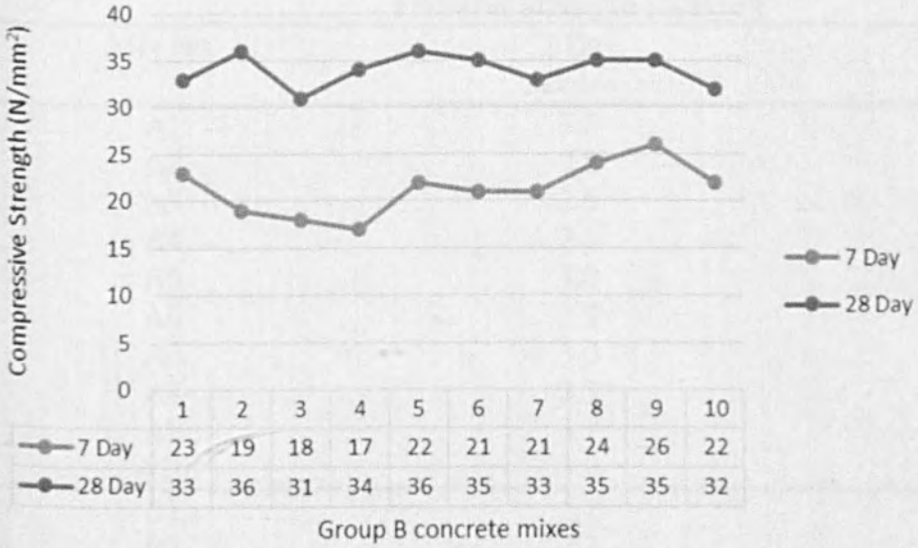
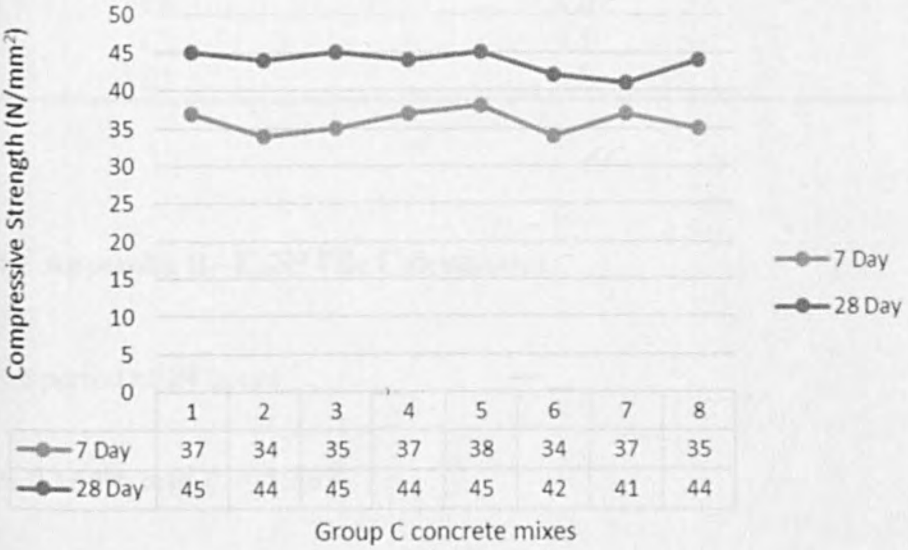


Figure 9-2 Compressive strength of group B concrete mixes (Cylinder)



	1	2	3	4	5	6	7	8
7 Day	37	34	35	37	38	34	37	35
28 Day	45	44	45	44	45	42	41	44

Figure 9-3 Compressive strength of group C concrete mixes (Cylinder)

Table 9-2 Flexural Strength of all groups of concrete mixes

Flexural Strength [N/mm²]		
Mix No.	7 Day Beam	28 Day Beam
A1	3.5	4.5
A2	2.8	4.2
A3	2.6	4.3
A4	2.5	4.2
A5	3.0	4.2
A6	2.9	4.1
A7	3.0	4.0
A8	3.3	4.4
A9	3.1	4.5
A10	3.0	4.3
B1	2.7	4.0
B2	2.3	4.2
B3	2.2	3.8
B4	2.1	4.1
B5	2.6	4.2
B6	2.6	4.1
B7	2.5	3.9
B8	2.8	4.2
B9	3.0	4.1
B10	2.6	3.8
C1	4.5	5.5
C2	4.1	5.2
C3	4.3	5.4
C4	4.5	5.4
C5	4.5	5.4

C6	4.0	5.0
C7	4.5	4.9
C8	4.2	5.5

9.2 Appendix B– Excel File Calculations

For a period of 24 hours:

$\delta = 0.144m \; and \; \xi = 1.393$

Periodic penetration depth:

From 3.1.2.7: $\delta = \frac{\lambda T}{\pi \times p \times c}$

$$= \sqrt{\frac{1.8 \times 24 \times 3600}{3.14 \times 2400 \times 1000}}$$

$$= \sqrt{\frac{155520}{7536000}}$$

$$= 0.1436556392 \cong 0.144\, m$$

ξ = ***Ratio of the thickness of the layer to the penetration depth.***

$$\xi = \frac{layer}{S\ (per\ depth)}$$

$$\xi = \frac{0.2m}{0.1436556392\, m} = 1.393$$

By using the information provided, the elements of the heat transfer matrix are needed to be calculated. The standard heat transfer matrix is in the format of:

$$\frac{\bar{Q}_2}{q_2} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \times \begin{bmatrix} Q_1 \\ q_1 \end{bmatrix}$$

Where Z_{11}, Z_{12}, Z_{21} and Z_{22} are the elements of the matrix. Detailed calculation of each element is given at below including formulas used to calculate each element.

$$Z_{11} = Z_{22} = \cosh(\xi) \times \cos(\xi) + j\mathit{sinh}(1.393) \times \sin(1.393)$$

$$= 0.3780619283 + 1.859508622j$$

$$Z_{12} = \frac{-S}{27}[\sinh(\xi)\cos(\xi)\sin(\xi) + j(\cosh(\xi)\sin(\xi))(\sinh(\xi)\cos(\xi))]$$

$$Z_{12} = \frac{-0.144}{2 \times 1.8}[\sinh(1.393)\cos(1.393) + \cosh(1.393)\sin(1.393) + j(\cosh(1.393)\sin(1.393) - \sinh(1.393)\cos(1.393))]$$

$$Z_{12} = \frac{-0.144}{2 \times 1.8}[2.438065276 + 1.769780955j]$$

$$Z_{12} = -0.09752261104 - 0.0707912382j$$

$$Z_{21} = \frac{-7}{\delta}[\sinh(\xi)\cos(\xi) - \cosh(\xi)\sin(\xi) + j[\sinh(\xi)\cos(\xi) + \cosh(\xi)\sin(\xi)]]$$

$$Z_{21} = \frac{-1.8}{0.144}[\sinh(1.393)\cos(1.393) - \cosh(1.393)\sin(1.393) + j(\sinh(1.393)\cos(1.393) + \cosh(1.393)\sin(1.393))]$$

$$Z_{21} = \frac{-1.8}{0.144}[-1.769780955 + 2.438065276j]$$

$$Z_{21} = 22.12226194 - 30.47581595j$$

$$Z_{22} = \cosh(\xi)\cos(\xi) + j(\sinh(\xi)\sin(\xi))$$

$$Z_{22} = \cosh(1.393)\cos(1.393) + j\sinh(1.393)\sin(1.393)$$

$$Z_{22} = 0.3780619283 + 1.859508622j$$

Heat Transfer Matrix

$$\frac{\bar{Q}_2}{q_2} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \times \begin{bmatrix} Q_1 \\ q_1 \end{bmatrix} \qquad Z_{ee} = Z_{s2} \times Z \times Z_{s1}$$

$$where\ Z_{s1}\ and\ Z_{s2}\ are\ heat\ transfer\ matrices\ of\ the\ boundary\ layers\ given\ by;$$

$$Z_s = \begin{bmatrix} 1 & -R_s \\ 0 & 1 \end{bmatrix} \qquad Z_{s1} = \begin{bmatrix} 1 & -0.13 \\ 0 & 1 \end{bmatrix} \qquad Z_{s2} = \begin{bmatrix} 1 & -0.04 \\ 0 & 1 \end{bmatrix}$$

So at the end of the calculations, heat transfer matrix is formed as:

$$\begin{bmatrix} 1 & -0.13 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 0.3788 + 1.858j & -0.09725 - 0.0754j \\ 22.16 - 30.55j & 0.3788 + 1.858j \end{bmatrix} \times \begin{bmatrix} 1 & -0.04 \\ 0 & 1 \end{bmatrix}$$

Internal thermal admittance is found by using the elements Z_{11} and Z_{12} from the heat transfer matrix. The formula to find internal thermal admittance is:

$$Y_{11} = \frac{-Z_{11}}{Z_{12}}$$

Detailed calculation is given as below:

$$Y_{11} = \left[\frac{-(0.508 + 3.08J)}{-0.046 - 0.545J}\right]$$

$$Y_{11} = -(5.535105519 + 1.3992933i)$$

$$Y_{11} = 5.707435\frac{w}{m^2K}$$

On the other hand, external thermal admittance is calculated by using the elements Z_{22} and Z_{12} from the heat transfer matrix. The formula used to find external thermal admittance is given as $Y_{22} = \frac{-Z_{22}}{Z_{12}}$. Detailed calculation is given as below:

$$Y_{22} = -\left(\frac{-2.502 + 5.830j}{-0.046 - 0.545j}\right)$$

$$Y_{22} = 11.59949438\frac{w}{m^2K}$$

The parameter called periodic thermal transmittance uses the Z_{12} element from heat transfer matrix to perform the formula $Y_{12} = -\frac{1}{Z_{12}}$ in order to calculate the value for this parameter. Detailed calculation is given as below:

$$Y_{12} = -\frac{1}{-0.046 - 0.545j}$$

$$Y_{12} = 1.828361339\frac{w}{m^2K}$$

The formula $K_1 = \frac{T}{2\pi}\left|\frac{Z_{11}-1}{Z_{12}}\right|$ is used to find internal areal heat capacity. For this calculation. elements of Z_{11} and Z_{12} from the heat transfer matrix. Detailed calculation is given as below:

$$K_1 = \frac{T}{2\pi} \times \left|\frac{-0.508 + 3.08J - 1}{-0.046 - 0.545J}\right|$$

$$K_1 = \frac{T}{2\pi} \times 5.707$$

$$K_1 = 86.10567197\frac{kJ}{m^2K} \; where\; T = 24x3600$$

The formula $K_2 = \frac{T}{2\pi}\left|\frac{Z_{22}-1}{Z_{12}}\right|$ is used to find external areal heat capac ity. For this calculation, elements of Z_{22} and Z_{12} from the heat transfer matrix. Detailed calculation is given as below:

$$K_2 = \frac{T}{2\pi} \times \left|\frac{-2.502 + 5.830J - 1}{-0.046 - 0.545J}\right| \qquad K_2 = \frac{T}{2\pi} \times 12.435 \qquad K_2 = 171.0527534\frac{kj}{m^2K}$$

Thermal transmittance (U) value is calculated by $U = \frac{1}{(R+rsi+rse)}$ where $R = \frac{1}{K}$.

K is the thermal conductivity and it is given as 1.8 W/mK. The information about surface resistance is given as 0.13m^{2}K/W inside which is defined as rsi and 0.04m^{2}K/W outside which is defined as rse.

L= 0.2 m. $k = 1.8\frac{w}{mK}$ $rsi = 0.13\frac{m^2K}{w}$ $rse = 0.04\frac{m^2K}{w}$ $R = \frac{0.2}{1.8} = 0.111$

$$U = \frac{1}{0.111 + 0.13 + 0.04} \qquad U = 3.56\frac{w}{m^2K}$$

<u>Decrement factor which is called as Ƒ:</u>

$$Ƒ = \frac{Periodic\ Thermal\ Transmittance\ (Y_{12})}{Thermal\ Transmittance\ (U)} \qquad Ƒ = \frac{1.83}{3.56} = 0.514$$

9.3 Appendix B – Thermal Dynamic Results

Mix No.	Thickness [mm]	Periodic Thermal Admittance [W/m^2K]	Areal Heat Capacity [KJ/m^2K]		Thermal Admittance [W/m^2K]		R-Value [m^2K/W]	U-value [W/m^2K]	Decrement Factor
			Internal	External	Internal	External			
A1	75	3.47	98976	116749	4.19	6.37	0.081	3.98	0.87
A2	75	3.38	97181	116482	4.20	6.52	0.085	3.92	0.86
A3	75	3.33	96162	117344	4.24	6.73	0.087	3.89	0.86
A4	75	3.29	95450	118237	4.28	6.91	0.088	3.87	0.85
A5	75	3.33	95477	113166	4.11	6.27	0.090	3.84	0.87
A6	75	3.30	94825	113703	4.14	6.41	0.091	3.82	0.86
A7	75	3.28	94492	113595	4.14	6.43	0.092	3.81	0.86
A8	75	3.42	98104	116899	4.20	6.48	0.083	3.95	0.87
A9	75	3.36	96432	115509	4.18	6.47	0.087	3.89	0.86
A10	75	3.32	95550	115080	4.17	6.51	0.089	3.86	0.86
B1	75	3.12	90348	108835	4.03	6.24	0.104	3.65	0.86
B2	75	3.00	87595	107433	4.03	6.35	0.112	3.55	0.85
B3	75	2.98	87071	107198	4.03	6.37	0.113	3.53	0.84
B4	75	2.92	85873	107059	4.06	6.48	0.117	3.49	0.84
B5	75	2.92	85531	104975	3.98	6.25	0.119	3.46	0.84
B6	75	2.87	84336	103736	3.96	6.22	0.123	3.41	0.84
B7	75	2.84	83649	103710	3.98	6.28	0.125	3.39	0.84
B8	75	3.06	88771	107740	4.02	6.27	0.109	3.59	0.85
B9	75	3.02	88118	107959	4.04	6.36	0.110	3.57	0.85
B10	75	2.95	86456	106716	4.03	6.38	0.115	3.50	0.84
C1	75	3.59	101806	116984	4.18	6.11	0.076	4.07	0.88
C2	75	3.51	99656	115438	4.14	6.13	0.081	3.99	0.88
C3	75	3.45	98133	114381	4.12	6.15	0.084	3.94	0.88
C4	75	3.48	98667	113668	4.10	6.00	0.083	3.95	0.88
C5	75	3.22	92727	111058	4.07	6.28	0.097	3.74	0.86
C6	75	3.14	90832	109325	4.04	6.25	0.103	3.67	0.86
C7	75	3.09	89431	107751	4.01	6.20	0.107	3.61	0.86
C8	75	3.19	91848	109917	4.05	6.22	0.100	3.70	0.86

9.4 Appendix C – "Measuring Thermal Mass of Sustainable Concrete mixes"

Measuring thermal mass of sustainable concrete mixes

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Abstract: Thermal mass is currently evaluated with "admittance" which is the ability of the element to exchange heat with the environment and is based on specific heat capacity, thermal conductivity, and density. The aim of this study is to evaluate the effect of thermal properties namely; density, specific heat capacity and thermal conductivity on thermal mass. The objective of the study is to carry out laboratory experiments by measuring such thermal properties of concrete mixes with various percentages of Ground Granulated Blast Furnace Slag (GGBS), Pulverized Fuel Ash (PFA), Silica Fume (SF) and recycled coarse aggregates [RCA]. The results obtained from these tests would contribute to the evaluation of how such thermal properties influence the thermal admittance and hence the thermal mass performance of sustainable concrete elements in a building system.

Key words: Thermal Mass, Thermal Admittance, Thermal Properties, Sustainable Concrete.

1. Introduction

One of the challenges in sustainable development is to optimize the energy efficiency of buildings during their lifespan. Modern concretes offer both low embodied CO_2 with the use of cement-replacements & recycled aggregates and reduced operational CO_2 with the intrinsic property called "thermal mass" that reduces the risk of overheating in the summer and provides passive heating in the winter [1]. Sustainable construction is becoming more popular as this sector corresponds to the world changing needs. Variations concerning global warming are the most important factor in which construction industry is exposed to. The purpose of those variations is to increase the life of the residence by lowering CO_2 emissions and to increase the use of natural resources. Environmental problems created in construction industry can be overwhelmed by decreasing both embodied and total energy usage for the construction products. Energy consumption figures in European buildings are increasing every year due to increase in air-conditioning and heating usages as a result of greater standards of living [2]. Examination of thermal mass can be used to prevent or minimize temperature swings in the building and can also be used to eliminate the need for energy consuming for air conditioning systems.

Thermal mass which is also called **thermal inertia** is related to the storage material. Storage material is the mass of the building including walls, partitions, ceilings and floors where all have high heat capacity. The most important factors associated to heat storage (i.e. thermal mass) are thermal conductivity (λ), specific heat capacity (c) and the density (ρ) of the concrete.

Thermal mass can explain the ability of the concrete to store the transferred heat/cool. Thermal mass can be determined by thermal diffusivity (α) of the building material that can be expressed as;

$$\alpha = \frac{\lambda}{c\rho} \qquad (1)$$

The higher the λ and the lower the product of ρ and c, the higher the heat storage capability of the material. As a conclusion, the usefulness of thermal storage depends on several parameters, such as materials' properties, the exposed surface area, the thickness of the storing elements and its location and orientation within the building (as an external or an internal partition) [3].

The storage capacity of the slab is determined by the thickness of the penetration depth. If a building has a natural ventilation system with a concrete of thin penetration depth (i.e. 50mm × 75mm), it is operationally efficient for heat transfer and storage.

Daily temperature cycle which is called sinusoidal cycle has a period of 24 hours. The slab reacts to variations occurred in this daily cycle. According to CIBSE Guide (1999), exchange of heat and cool over the cycle is measured by thermal admittance that can be defined as [4]:

$$\mathrm{Y} = \frac{Qswing}{Tswing} \qquad (2)$$

From the above definition of thermal admittance, it can be resulted that for a given temperature variation, heat/cool load that can be absorbed by the slab has a direct relationship with the thermal admittance.

Since heavy materials such as concrete, brick or stone have a large, internal exposed capacity, those materials were storing greater part of the daily energy cycle. High admittance of those materials results in small temperature swing in the room. The unit for admittance (Y) is W/ m^2 K. Admittance values for several construction components are given in CIBSE Guide section A3 [5].

Materials having a high density will have a high thermal conductivity and therefore these materials are classified as good for heat storage.

The aim of the admittance method is predicting indoor temperature and by this way, evaluating peak environmental temperature for any proposed building. Details about the technique of this method can be found from CIBSE guide, section A8 [6].

Performance of the system is highly affected by thermo-physical properties of the materials. Therefore, high density in a building material indicates high thermal conductivity such as having a building with poor thermal resistance. On the other hand, insulation materials have a low thermal conductivity and high thermal resistance. This indicates that those materials can be used for insulation purposes but not for heating. Efficient heat storage material should have high density, thermal capacity and thermal conductivity [7, 8].

2. Experimental & Research Methodology

By using each cement replacement material separately, such as Silica fume [SF], Pulverized Fuel Ash [PFA], and Ground granulated blasted slag [GGBS] will be illuminating the factor that how these cement replacement materials may affect the thermal properties of concrete.

2.1 Experimental Design

2.1.1 Preparation of Mixes

The mixes used in this study are described in table 1. There are 8 different specimens that can be classified in into two sections, namely; coarse aggregate and recycled coarse aggregate concretes.

Table 1. The mixes prepared for the measurement of thermal properties.

Mix No.	Definition
A1	100% Coarse Aggregate OPC concrete
A2	100% Coarse Aggregate OPC/GGBS [45%] concrete
A6	100% Coarse Aggregate OPC/PFA [20%] concrete
A8	100% Coarse Aggregate OPC/SF [10%] concrete
B1	Recycled Coarse Aggregate[30%] OPC concrete
B2	Recycled Coarse Aggregate[30%] OPC/GGBS [45%] concrete
B6	Recycled Coarse Aggregate[30%] OPC/PFA [20%] concrete
B8	Recycled Coarse Aggregate[30%] OPC/SF [10%] concrete

2.1.2 Materials

The following materials were applied to produce concrete mixes.

- Ordinary Portland cement [OPC]: A single source [Lafarge Cement] of Class 52.5 N OPC confirming to BS EN 197-1 was applied.
- Ground granulated blast-furnace slag (GGBS): A single source (Civil-Marine) of GGBS confirming to BS 6699/BS EN 197-1 was applied.
- Silica fume [SF]: A single batch of silica fume confirming to EN 13263-1 was applied.
- PFA is used according to BS-EN 450-1 (2012). PFA used in the UK is classified as CEM IV according to BS EN 197-1 (2011).
- Graded natural sand with a maximum particle size of 5 mm and complying with the requirements of BS EN 12620-1 (2009) was used as fine aggregate in the concrete mixes.
- Two types of coarse aggregate will be used in the study, Natural Aggregate [NA] and Recycled Coarse Aggregate [RCA]. Natural Aggregate used was Thames Valley gravel with a size fraction between 20 to 5mm. The RCA used was obtained from processing concrete debris from demolished concrete structures. The size of fraction of the RCA is between 20 to 5mm (the supplier for fine and coarse aggregates is Day Company [BS EN 2620:2002 Classifying Aggregates].

2.1.3 Mix Proportions

Table 2 and 3 give the mix proportions for the test concrete mixes. All of the mixes applied in the study were designed to have a slump of 60-180 mm. which is the range of acceptable slumps according to EN 206-1. As well as this, the range of the compacting factor of fresh concrete mixes was determined. All the mixes applied in the study were designed to have a compacting factor of 0-3s.

Table2. Mix proportions for natural aggregate concrete mixes.

Constituent Proportions, kg/m3					
Mix No.		**A1**	**A2**	**A6**	**A8**
FA		85	85	84	85
NA		180	180	189	180
RCA		-	-	-	-
OPC		50	27.5	43	45
CRM	**GGBS**	-	22.5	-	-
	PFA	-	-	11	-
	SF	-	-	-	5.0
FA/CA		0.47	0.47	0.47	0.47
W/C		0.57	0.57	0.49	0.57

Table 3. Mix proportions for recycled coarse aggregate concrete mixes.

Constituent Proportions, kg/m3				
Mix No.	**B1**	**B2**	**B6**	**B8**
PFA	87	87	87	87
NA	123	123	122	123

RCA		53	53	52	53
OPC		50	28	43	45
CRM	**GGBS**	-	22.5	-	-
	PFA	-	-	11	-
	SF	-	-	-	5.0
FA/CA		0.49	0.49	0.49	0.47
W/C		0.59	0.59	0.51	0.57

3.0 Sample of Testing Concrete Mixes

From this study, it is concluded that understanding the thermal properties by performing such concrete tests is vital. The most commonly used tests in this research are described as;

3.1 Specific heat capacity

Specific heat capacity is investigated as a thermal property of the concrete, so that it can be determined how much mass is needed per unit for one unit increase in temperature of the sample. By this way, specific heat capacity can be used to explain association between heat and temperature variation. Specific heat capacity is measured by performing an experimental procedure in an insulated box.

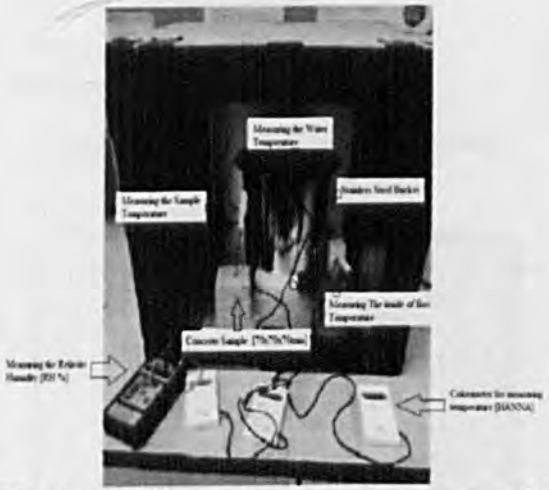

Figure 1. The apparatus to measure the specific heat capacity of concrete

The following steps should be attained one day before carrying out the test. Oven is pre-heated at suitable temperature (i.e.100°C±5°C) and the sample is placed in this pre-heated oven in order to reach a constant temperature. Since the same stainless bucket is used for all specific heat capacity experiments, mass of the stainless steel bucket is constant and it is measured only once. Then, approximately half of the bucket is filled with water and the total mass of the stainless bucket with water is measured.

After that, the mass of water can be determined by subtracting the constant mass of stainless bucket from the total mass of bucket with water. Bucket with half-filled water is placed inside the insulated box. During the overnight stay, the front of the insulated box is kept open in order to achieve constant temperature.

After this overnight stay, connect the thermometer to the bucket with water to check the temperature. If the temperature is constant, this means that the bucket with water is now ready to be used for testing. However, before the start of testing, weight of the bucket with water should be re-measured to aware of any variations in mass of water due to evaporation that might occur during overnight stay. Three different thermometers are placed inside the insulated box to measure the temperature of the concrete, water and air respectively during the testing procedure.

Beside of this, relative humidity is measured to estimate the mass of the dry air. This apparatus is specifically designed for this research in Kingston University. It can be seen from figure 1.

Observed values from the three different thermometers are used to evaluate the value for specific heat capacity by using the formula stated below;

$$Q = cm\Delta T \qquad (3)$$

The specific heat capacity is found by using the following formula and known values for the specific heat capacity of water, the stainless steel bucket and air.

$$C_C m_C \Delta T_C = C_S m_S \Delta T_S + C_W m_W \Delta T_W + C_A m_A \Delta T_A + [M_W \iota] \tag{4}$$

Where;

ι is specific latent heat of the water [$226\text{x}10^4$],

M_w is mass of water in air [evaporated water]

Table 4: Known Specific Heat Capacities

Known Specific Heat Capacities	
Material	**Specific heat capacity [$\text{Jkg}^{-1}\text{K}^{-1}$]**
Stainless Steel 18Cr/8Ni	502
Water at 20, 30, 40, & 50^{0}C	4181.6, 4178.2, 4178.3, 4180.4
Air at 20 to 100^{0}C [Dry]	1006

3.2 Thermal conductivity

According to BS EN ISO 8990: 1996 and BS EN 1934: 1998, a method called "hot-box" is developed by Dundee University in order to measure steady-state thermal transmission properties.

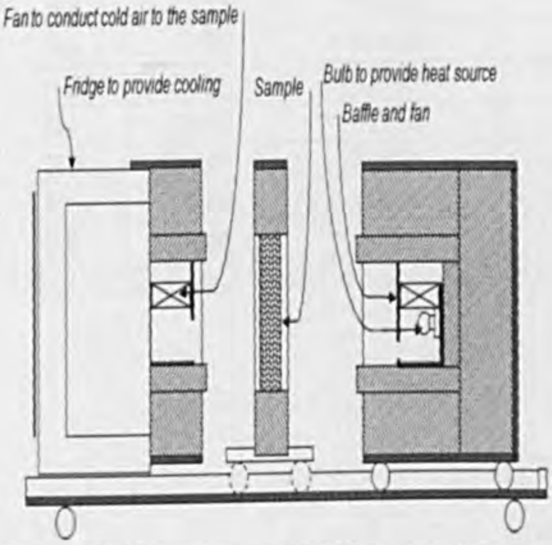

Figure 2. Schematic of hot box equipment

This equipment contains two sides; heating side and cooling side. Heating side is achieved by using 40W light bulb and cooling side is achieved by using a fridge. Both cold box from cooling side and hot box from heating side needs to be insulated. As well as this, the box which includes the sample is also insulated. This experiment with two sides are designed on a trolley where both fridge and cold box is kept fixed, while designing the hot box and sample box in a way to move towards and away from the fixed part of the apparatus. It can be seen from figure 2.

$$\Phi_p = \frac{(40 \times counter\ reading)}{(time\ between\ readings)} \tag{5}$$

By using the heating side of the equipment, total power input (Φ_p) is calculated by using the measurement obtained from thermostat of hot box and timer counting. Timer counting is used to determine the proportion of the time needed to maintain constant temperature with heat source generated by 40W light bulb and a fan that is used to circulate the air.

Insulated box is open at both ends. At one open end, a fan is attached to the fridge whereas on the other open end the sample box is presented. This sample box is designed in a way that can be opened from the top to place the sample inside the sample box.

After the sample is placed, thermocouples are sealed at both sides of the box. Same amount of thermocouples are placed on heating side and cooling side separately. The sample that will be used in this study is square shape slab with 300mm length and 75mm thickness. Temperature of the sample during the experiment is controlled by using a temperature controller at 240V/2A. The voltage and current used in the experiment is recorded by using 16 channel thermocouple data acquisition and a simple logger log system. Hence, thermal conductivity values are calculated by using the equation below:

$$\lambda = \frac{Q_1}{A \times \Delta T} \times d \qquad (6)$$

Where:

$Q_1 = Q_p - Q_3 - Q_4$

$Q_4 = (0.9763 \times Q_p) - 6.2516$

d – Thickness of the sample

$A = 0.04m^2$[Exposed Area]

ΔT - The temperature difference between the hot side of the equipment and cold side of the equipment and $d = 0.075m$ which is the thickness of the samples.

Q_P - The total heat input.

Q_1 - The heat transferred from hot side of the equipment to cold side of the equipment through the specimen.

Q_3- The heat loss from hot side of the equipment to the environment

Q_4- The flanking loss that is the heat lost through the gap between the specimen and the equipment during the experiment.

3.3 Density of Hardened Concrete

Hardened concrete density is determined either by simple dimensional checks, followed by weighing and calculation, or by weight in air/water buoyancy methods. [BS EN 12390-7, 1097-6].

The density of hardened concrete specimens such as cubes and cylinders can be quickly and accurately determined using a Buoyancy Balance.

4.0 Experimental Results & Discussions

The thermal properties of concrete mixes were measured. The values of the measured properties are summarized in table 5.

Mix No.	Density [Kg/m^3]	Thermal Conductivity [W/m.K]	Specific Heat Capacity [J/Kg K]	Thermal Diffusivity [m^2/sec)x10^{-7}	Compressive Strength [N/mm^2]	
					7 day	28 day
A1	2270	0.921	785	5.2	35	45
A2	2255	0.880	836	4.7	27	42
A6	2220	0.820	847	4.4	29	41
A8	2265	0.902	816	4.9	33	44
B1	2150	0.720	882	3.8	27	39
B2	2135	0.670	940	3.3	22	42
B6	2120	0.610	950	3.0	25	41
B8	2140	0.690	907	3.6	24	42

Table 5. Density, specific heat, thermal diffusivity and thermal conductivity of concrete.

Figure 3 shows the relationship between the thermal conductivity and density of the concrete. Ordinary Portland Cement (OPC) with natural coarse aggregate exhibits the highest value on both thermal conductivity and density.
On the other hand, the lowest thermal conductivity and density of concrete occurred at 20% of PFA replacement for ordinary Portland cement. Additions of admixtures to the concrete affect the thermal conductivity and density. Comparing PFA, GGBS and OPC, OPC concrete is slightly greater than GBBS and SF concretes.

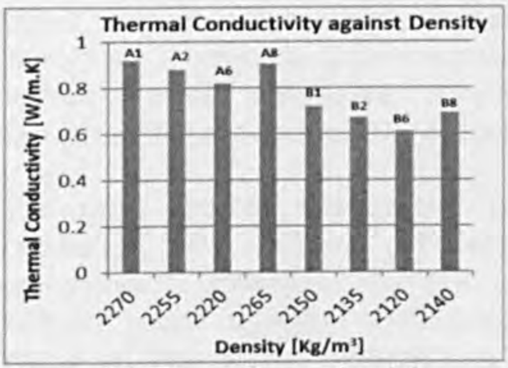

Figure 3. Thermal conductivity against density graph.

On the other hand, Recycled coarse aggregate decreased the thermal conductivity and density of the concrete. RCA concretes are the light weight aggregate concretes which have low density. In such cases, there is a lack of information about recycled aggregate concrete and admixtures.

The previous studies reported that the reduction in thermal conductivity is observed with increasing Silica Fume and PFA contents. This means that SF and PFA are probably related to the higher air content and partly to the amorphous structure of SF and PFA [9, 10, and 11].

On the other hand, the results are shown that the chemical and physical properties of admixtures are important. For instance, even the amount of PFA in the concrete mix is less than the amount of GBBS, PFA is found to be more effective than SF and GGBS. Ordinary Portland cement concrete has the highest thermal conductivity and density. However, the specific heat capacity of OPC concrete is lower than all of the mixes which is also demonstrated in previous studies in the literature.

This might be due to having low specific gravity of mineral admixtures. In other words, lower specific gravity results in porous and lower density of concrete. Decreasing in density causes a decreasing in thermal conductivity [9, 10].

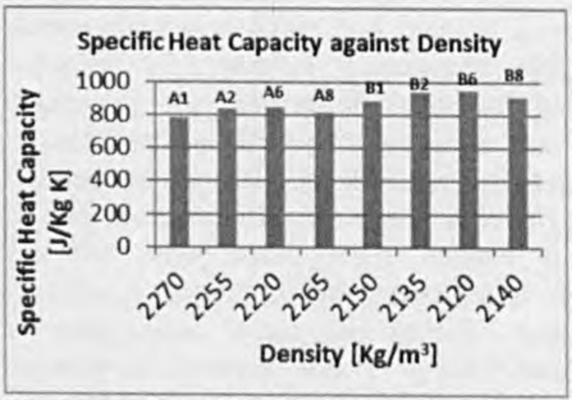

Figure 4. Specific Heat Capacity against density graph.

The admixtures increased with increasing specific heat capacity. It is observed that OPC concrete is the highest density and the lowest specific heat capacity. On the other hand, the replacement of PFA for OPC is the lowest density and the highest specific heat capacity in natural and RCA concrete mixes.

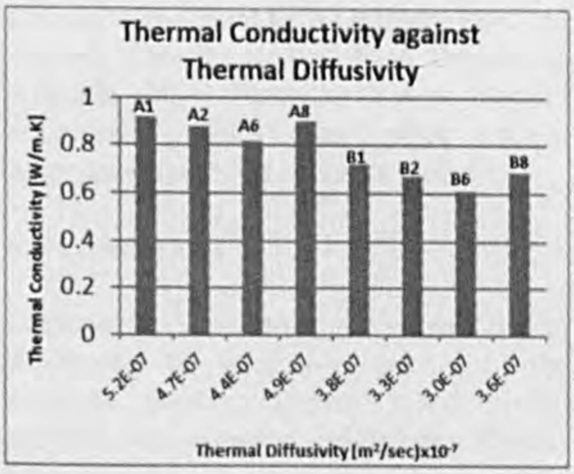

Figure 5. thermal conductivity against thermal diffusivity.

Figure 5. represents that the thermal conductivity is directly proportional with thermal diffusivity. It is observed that both of these parameters are simultaneously increasing.

5.0 Thermal Dynamic Calculation

The excel file is set up to calculate the thermal dynamic properties of concrete mixes by applying the thermal properties data (thermal conductivity, density and specific heat capacity) of the concrete mixes. Factors which affect the thermal storage are taken under examinations that include thermal admittance, decrement factor, thermal transmittance [U-value].

The main aim of this section is to understand the effects of cement replacement materials [CRM], and recycled coarse aggregate of the concrete mixes on the thermal transmittance and decrement factor of the concrete mixes. Before setting up the excel calculator, the thermal dynamic properties are calculated theoretically. BS EN ISO 13786:2007 standard is used to calculate those parameters [12]. The thickness of the samples is 0.75mm [constant]. The results are provided in Table 6.

Mix No	R-Value [m^2.K/W]	U-Value [W/m.K]	Thermal Admittance [W/m^2.K]	Decrement Factor
A1	0.81	3.98	4.19	0.87
A2	0.85	3.92	4.20	0.86
A6	0.91	3.82	4.14	0.86
A8	0.83	3.95	4.20	0.87
B1	0.104	3.65	4.03	0.86
B2	0.112	3.55	4.03	0.85
B6	0.123	3.41	3.96	0.84
B8	0.109	3.59	4.02	0.85

Table 6: Thermal Dynamic Properties of Concrete.

Especially PFA content in concrete mixes has the lowest U-value and the highest R-value of the concrete mixes. The highest U-value is obtained when Cement replacement material is Silica Fume. However, GGBS content in concrete mixes have greater R-value than Silica Fume content in concretes. When Recycled Coarse Aggregate content in concrete mixes is examined, it is concluded that RCA content in concrete decreased the U-value more than Cement replacement materials of concrete mixes. It is found that thermal conductivity of concrete is increased with increasing the decrement factor value and specific heat capacity of concrete decreased with decreasing the decrement factor of the concrete mixes. Beyond the specific heat capacity of 750 J/Kg.K, decrement factor of the concrete mix decreased suddenly. On the other hand, RCA content in concrete decreased the decrement factor of concrete mix. When the specific heat capacity of concrete mix is greater than 850 J/Kg.K, decrement factor of the concrete is decreased significantly. However, decreasing in thermal conductivity of concrete mixes is also observed.

On the other hand, when GGBS is used in concrete mix; it increases the thermal admittance more than all groups. PFA content in concrete mixes have the lowest thermal admittance value than all mixes. Silica Fume concretes has similar value of thermal admittance with Ordinary Portland Cement concrete mixes. RCA content in concrete mixes have the lowest thermal admittance values than other natural aggregate content in concrete mixes.

6.0 Conclusions

Laboratory experiments are carried out to determine the thermal properties of the concrete namely; thermal conductivity, specific heat capacity and density. Results obtained from these tests are used to make inferences on how each of the thermal properties affect the thermal admittance and hence the thermal mass of the concrete. Main findings are reported as:

The results obtained proved that cement replacement affected the density and thermal conductivity of the concrete. For instance, when the cement is replaced by PFA, it is found to decrease the thermal conductivity in a direct proportional manner and thermal diffusivity of the concrete. As well as this, all cement replacement materials are increased with increasing the specific heat capacity of the concrete. The results also showed that CRM content is important in considering the effect of thermal properties of the concrete. However, the chemical and physical properties of the material are more important than the amount of material in the concrete such as PFA. Thermal properties are also affected by the types of aggregate. In this research Natural Aggregate is replaced by Recycled coarse aggregate. The results are described that RCA content affect the thermal properties of concrete. RCA content increased with decreasing the density, thermal conductivity and thermal diffusivity of the concrete. On the other hand, RCA content increased with increasing of the specific heat capacity of concrete. The laboratory tests showed that RCA content decreased the density and thermal conductivity of concrete more than CRM content. Beside of this, when RCA and admixture content increased in the concrete mix, this increases the specific heat capacity of the concrete.

It is concluded that cement replacement materials increase the R-value with decreasing U-value of the concrete mixes less than RCA content concretes. The results obtained explain that when Cement Replacement materials are compared in terms of decrement factor value, no significant difference is found between the mixes. When the value of thermal admittance is concerned, it is found that this value does not need to have high or low thermal conductivity of concrete mix. The importance is to have a moderate thermal conductivity. The results are provided that thermal admittance is increased with high specific heat capacity, high density and moderate thermal conductivity of the concrete mixes. Therefore, those factors are found to be vital for improving thermal admittance of concrete mix.

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