DEVELOPING A ROOF SLAB INSULATION SYSTEM FOR TROPICAL CLIMATIC CONDITIONS

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Thesis submitted in partial fulfillment of the requirements for the degree of
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Declaration

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Abstract

Global Warming is proven to be one of the biggest issues that the current world is facing. Greenhouse gas emission due to the extensive energy usage has been identified as the primary cause for that. Hence, the world is on its path to investigate ways and means of reducing energy consumption in the world.

On the other hand, due to the rapid urbanisation took place in recent history, land prices have escalated significantly. Hence, flat roof slabs become popular day-by-day due to the possibility of land recovery by that. Further, it has many additional advantages like cyclonic resistance, the possibility of future vertical extension and the possibility of utilising as an extra working space. However, a serious matter of concern is its thermal discomfort, for which air-conditioning the corresponding spaces is the most common remedy used. However, it has led to extensive use of energy, increasing the operational cost of the buildings and contributing to global warming, which is the issue that the world is attempting to mitigate. Hence, the current trend is to go for passive techniques. In this process, insulating roof slabs has been identified as a better passive way to make buildings thermally comfortable.

In this study, several existing roof slab insulation systems and their performances were investigated, and the most efficient system for tropical climates was identified. Since that system had an issue in durability as it had poor drainage arrangement, an optimised system with a structural arrangement of discontinuous strips was found out by computer simulations. A physical model developed to verify the results showed that the newly developed system could withstand a point load of 4MT at its most critical locations.

A comparison of thermal performance between the new system and the existing system was carried out by small-scale model testing. It resulted in finding that the newly designed system performs better than the most recent and efficient existing insulation system. An actual scale model testing was carried out to check its performance under real conditions. The results suggested that this newly developed system performs well in thermal aspects under actual conditions, and performs better than even a calicut tiled roof with a timber ceiling. Results suggested that this system can produce a peak cooling load reduction of about 20%.

The performance of an air gap as an insulator was checked in the process of trying to replace the insulation material and found out that air gap is marginally less effective than polystyrene. Further, it was proven that the thickness of the air gap does not have a significant effect on the thermal performance. Further, a confined air gap with bamboo strips was also proven to have a similar thermal performance. An added vegetation layer on these systems further enhanced the thermal conditions of the building.

A life cycle cost analysis suggested that the overlaid vegetation performs slightly better than the cases without vegetation in economic aspects. But the life cycle costing values lie in the same order, proving that all the systems considered are almost equally effective in terms of economic performance. However, due to the advantages like local and natural availability, bamboo, as an insulation material, is very favourable to be used in local context.

Keywords: Global Warming, Thermal Comfort, Energy Efficiency, Strength, Durability, Rooftop Vegetation

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Chapter 1

Introduction

1.1 General

Greenhouse gas emission has increased rapidly for a couple of centuries now, causing the major issue that the current world is facing, Global Warming. Now, the world has begun to feel the degree of this threat, and the concern of researchers has been increased on the ways and means to mitigate it.

Meanwhile, climate change has become an inevitable consequence of global warming, increasing the intensity and severity of natural disasters, particularly cyclones (Halwatura & Jayasinghe, 2007, 2008; Isobe, 2013). Hence, the degree of damages caused by them is increased significantly. One of the best ways of minimising this impact is to make the structures robust, as it increases the durability.

In the process, the use of roof slabs has been identified as a good strategy (Halwatura, Mallawarachchi, & Jayasinghe, 2007). Its suitability is further emphasised as it possesses many additional advantages like low maintenance cost, ability to create greener environments and the possibility of using as a working space. (Halwatura & Jayasinghe, 2009).

However, this has made its way to the issue of the higher energy requirement for thermal comfort (Halwatura & Jayasinghe, 2008). Roof slabs act as heated bodies, and emit long-wave radiation to the underneath spaces, leading to discomfort. The roof contributes to about 70% of total heat gain (Vijaykumar, Srinivasan, & Dhandapani, 2007), and in the case of a concrete slab, it is even more.

Consequently, in Malaysia, which is a tropical country and of which most of the residences are multi-storied buildings and high rises with roof slabs, 75% of the population relies on air conditioning (Al-Obaidi, Ismail, & Abdul Rahman, 2014). This is not a good statistic at all and is an issue to be addressed soon.

In this context, passive techniques have begun to play a major role in modern designs. They are the techniques that are used in the design phase itself so that the structures use a minimum amount of energy in their operational phase, particularly for thermal comfort. Insulation of the building envelope is such a popular technique. Since 'roof' is the major contributor to internal heat gain, insulating that is very common in practice, and proven to be effective (Vijaykumar et al., 2007).

There are numerous roof insulation systems tried out in the world, and a few of them are for flat slabs. However, most of those systems have focused on their respective thermal performance, paying little attention on its strength. Further, some of the systems have failed due to a variety of reasons in long run, emphasizing the significance of considering durability as a parameter in designing as well. Further, there's another set is not economically viable to an extent to be penetrated into the industry.

Hence, there is a necessity to develop a new roof slab insulation system for tropical climatic conditions that is performing well in all the structural, thermal and durability aspects.

1.2 Objectives

The main objectives of this study can be enlisted as follows;

1. To explore the roof slab insulation systems prevailing in the world and their benefits and drawbacks
2. To find out the optimum structural arrangement so that any practical load applied on top of the roof (an imposed load of $5kN/m^2$) can be withstood

3. To compare the thermal performance of the system with existing insulation systems and to quantify the thermal benefit obtained by the system
4. To find out a naturally available insulation material to replace traditional insulation materials
5. To carry out a life cycle cost analysis to compare the different options considered in the study

1.3 Methodology

The following methodology was adapted to achieve the above objective;

1. A literature survey and a field study were carried out to identify the existing roof slab insulation systems and their benefits and drawbacks.
2. A Questionnaire survey was performed to collect the information on the public perception towards roof slabs, and to figure out the measures to be taken to make it more public.
3. An optimum structural arrangement was determined by computer simulations and actual scale casting so that the developed system does not impose any restriction on any practical loading.
4. Small-scale models of existing roof slab insulation systems and the proposed system were constructed and their thermal performances were analysed and compared with computer simulations. Further, the obtained results were verified by an actual scale model.
5. The insulation layer was replaced by a layer of bamboo trunks cut and laid in the transverse direction, and its performance was analysed and compared wit conventional insulation material.
6. The effect of laying a vegetation layer on top of the slab with the insulation was analysed by physical model testing and computer simulations, and the feasibility of this was commented.

7. A Life-cycle cost analysis was performed to compare the different alternatives considered in the study.

1.4 The Main Findings

This thesis is based on a development of thermal insulation system for roof slabs in tropical climatic conditions that is structurally sound, durable and thermally effective.

A questionnaire survey has pointed out that the major reason that roof slabs are not so popular among the general public is the thermal discomfort associated with it.

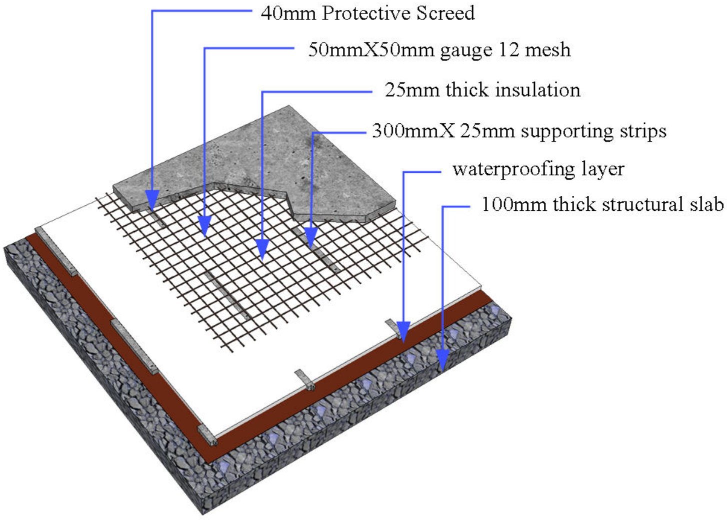

Figure 1.1: Isometric View of the Developed System
(Nandapala & Halwatura, 2016)

The major task was to develop an optimum structural arrangement so that it can carry any practical load on a roof. The developed system is shown in Figure 1.1. That has a structural slab of 100mm, on which laid a waterproofing layer to prevent water leakages. On top, there is a layer of low-conductive material of $25mm$, with a set of $300mm \times 25mm$ concrete strips with $300mm$ clear spacing and $400mm$ transverse spacing within. They are there to transfer the load on top. The topmost layer is a layer of supportive screed to protect the layer below (Nandapala & Halwatura, 2014).

A thermal performance analysis has shown that this particular system is thermally resistive than the existing systems. Further, it has been proven that this system performs even better than a traditional calicut-tiled roof in thermal aspects.

An alternative for traditional insulation materials was tried out with bamboo, and the life-cycle cost assessments have proven that this system, is economically feasible. With the other advantages like availability and the contribution to the mitigation of global warming, this was a significant achievement.

The effect of laying a vegetation layer on top of the roof with the insulation system was analysed by small-scale physical model testing. It has been found out that a vegetation layer enhances the performance of the system, both thermally and economically.

1.5 The Arrangement of the Report

The breakdown of the chapters in this thesis is as shown below;

Chapter 2 presents the detailed literature review carried out to find out the background of this research.

Chapter 3 elaborates the results of the questionnaire survey carried out to find out the public perspective towards roof slabs.

The analysis of the proposed structural arrangement and the results of the testing performed to check the structural performance of the system are given in Chapter 4.

Chapter 5 presents the detailed analysis of the experiments conducted to evaluate the thermal performance of the newly designed system. This chapter contains a comparison of the thermal performances of this system and other similar systems. Further, it has the results of the fulfilment of this system in an actual context.

An insulation layer with bamboo strips cut in the transverse direction was proposed as a replacement to polystyrene in Chapter 6. Further, the performance of the systems with a vegetation layer on top was analysed and compared with the systems without it.

Chapter 7 gives a comparison life-cycle cost analysis of the different alternatives considered.

Finally, Chapter 8 describes the conclusions and future works related to this research.

Chapter 2

Literature Review

2.1 General

This research focuses on developing a roof slab insulation system for tropical climatic conditions.

Use of flat-concrete-roof slabs should be encouraged due to its disaster resistance possessed due to self-weight, particularly with the unpredictable nature of the climate. It provides an additional robustness due to the self-weight and the structural integrity(Halwatura et al., 2007). However, it has not been made popular sufficiently. One of the principal reasons identified by the researchers is the thermal discomfort in the immediate underneath space. The slab gets heated during the daytime and emits long-wave radiation downwards, causing the discomfort.

Consequently, most of the multi-storied buildings use active means of cooling, particularly in the form of air-conditioning, to negate this effect. Thus, an unaffordable amount of energy is consumed by buildings to cater the thermal comfort requirements of the occupants, aggravating the biggest issue that the current world is Facing, ‘Global Warming’.

The subsequent action by the researchers is to develop passive strategies to minimise the energy consumption in the operational phase of a building. Insulating the building envelope is such a popular technique, roof in particular, as it is the element that contributes to the largest portion of the heat gain into buildings

(Vijaykumar et al., 2007).

There are numerous roof slab insulation techniques developed in the world, with different arrangements and different insulation materials.

This chapter contains a detailed literature background of the key aspects described above, according to the following criteria;

1. Global Warming and its effects
2. Thermal comfort in tropical countries
3. Energy consumption to make buildings thermally comfortable
4. Use of passive techniques
5. Roof insulation
6. Life-cycle cost analyses of the insulation systems

2.2 Global Warming and Its Effects

Global warming is one of the most alarming issues that the current world is placing. There is hardly any field in which there's no impact of climate change. Every living being on this earth has to face the repercussions of global heating.

As far as the researching community is concerned, this is an area that is under the telescope of the researchers in a variety of fields. It has been scientifically proven that a global rise in temperature is evident (Macilwain, 2000). Quantitatively, global average temperature has increased between 0.4^0C - 0.8^0C during the 20th century, which is alarming that it was kept balance in equilibrium at 13.6^0C for millions of years till then (Nordell, 2003). A graphical representation of the global mean temperature rise is shown in Figure 2.1 (Pachauri, Mayer, & Intergovernmental Panel on Climate Change, 2015). It clearly indicates that the global mean temperature is on its rise in an alarming manner.

The rise of the sea level has been identified as the major issue emerged due to global warming. It is estimated that the sea level could rise by approximately 18 -

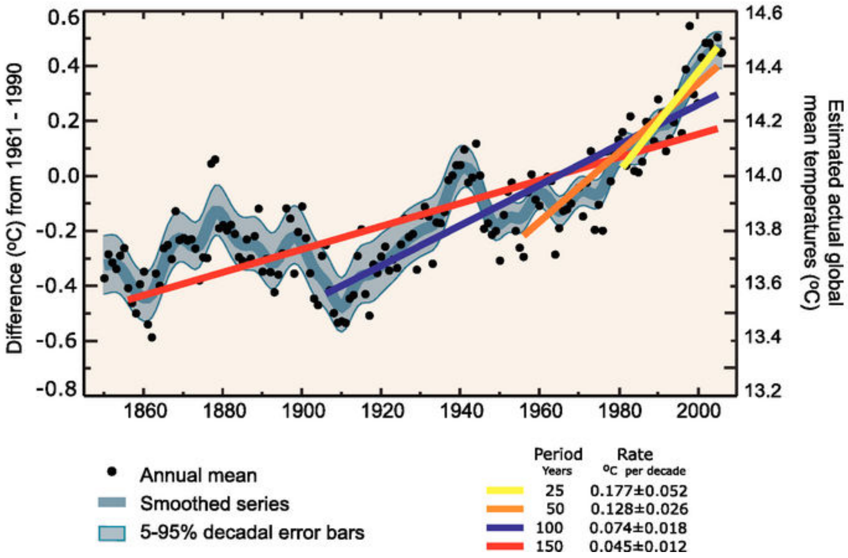

Figure 2.1: Global Mean Temperature Rise in Last 150 Years
(Pachauri et al., 2015)

59 cm by the end of 21st century. It is estimated that it would causing a land loss of approximately 6000 - 17000 km^2 in Japan, forcing 1.6 - 5.3 million people to migrate, costing US $300 - $1000 for migration only (Hinkel et al., 2013).

Also, global warming has various indirect effects as well. Intergovernmental Panel on Climate Change (IPCC) emphasises that high evaporation of sea water increases the energy levels in cyclones, increasing the degree of destruction caused by them (Pachauri et al., 2015). Furthermore, it has been found out that, due to carbonation and chlorine ingress, the failure life of structures can be reduced by about 30% and service life by about 15 years (Bastidas-Arteaga, Schoefs, Stewart, & Wang, 2013). These scenarios increase the necessity of virgin materials, leading us back to another issue of higher consumption of scarce resources.

Due to such effects, the scientific community has figured out that immediate action must be taken to mitigate global warming.

The primary cause that promotes global warming is the extensive emission of greenhouse gases, dominantly due to the excess usage of energy. It has been proven that there is a statistically significant positive correlation between economic growth, energy use and Carbon emissions (Lean & Smyth, 2009). Further, It has been estimated that the emission of greenhouse gases has increased from about 275ppm to

370ppm since 1800 AD (Boden, T.A., Andres, R.J., & Marland, G., 2016). A 35% growth in greenhouse gas emission in 200 years in a world which was in the perfect balance for millions of years is incontrovertibly overwhelming.

Carbon Dioxide has its fair share in the set of Greenhouse gases. The annual carbon dioxide concentration growth rate has increased from 1.4ppm per year during the period 1960-2005 to 1.9ppm per year during the period 1995-2005 (Hinkel et al., 2013). At this rate, the environmental Carbon Dioxide concentration could increase from 379ppm in 2005 to over 1000ppm by the year 2100 (Bastidas-Arteaga et al., 2013).

Chinese statistics suggest that during 1978-2010, its total primary energy requirement (PER) increased from about 570 to over 3200 Mtce (million tonnes of coal equivalent), an average annual growth of 5.6%. And it is predicted that PER would increase to 6200 Mtce in 2050, of which fossil fuels would account for more than 70%. The corresponding emissions could reach 10 Gt of Carbon Dioxide equivalent (Chan & Chow, 2013).

Therefore, the current trend is not healthy at all and needs to be addressed soon. The best method of dealing with this is to minimise the energy consumption. An overwhelming amount of electricity is consumed for making buildings thermally comfortable, of which a quantitative analysis will be shown in Section 2.4. It is necessary to define the term ‘Thermal Comfort’ in advance.

2.3 Thermal Comfort in Tropical Countries

2.3.1 Climate in Tropical Countries

Several different types of classifications are available in the world and are used for various purposes. One such classification is shown in Figure 2.2 (*Internet Geography*, n.d.). The tropical region is the region near the equator, the area between the Tropic of Cancer and Tropic of Capricorn to be more precise. It is considered uncomfortable due to the significant amount of solar radiation, high temperature, high humidity and extended periods of sunny days throughout the year (Al-Obaidi et al., 2014).

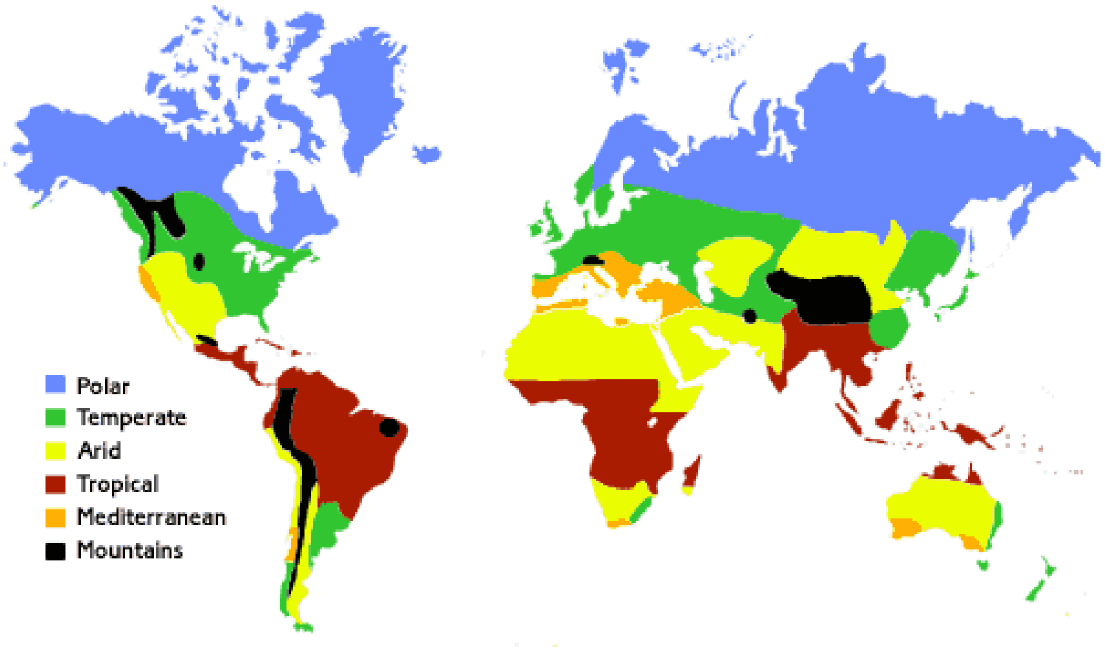

Figure 2.2: The Climate Zones in the World

It does not experience a seasonal variation as in the countries away from the equator. It experiences the direct sun almost throughout the year and has ample amount of rain as well due to the higher evaporation took place. March and September are considered the driest months as the sun is directly above the equator.

There is a diurnal temperature variation as well. In the daytime, the temperature rises to 33^0C - 36^0C during the daytime, and cools down by about 8^0C - 10^0C. A higher temperature cannot be observed as the cloud cover formed by the evaporated water blocks the path of the air.

However, all these conventional patterns are being changed due to the climate change taking place in the world. The temperatures are on the rise, and the time gaps and the magnitude-gaps of temperature and rain are in the process of increasing. Thus, defining comfort conditions has become a challenge.

2.3.2 Comfort Models Developed in the World

Nevertheless, some thermal comfort models have been formulated in the world to determine general thermal comfort conditions in buildings. There are two basic types of models: heat balance models and adaptive models. Predictive Mean Vote (PMV)

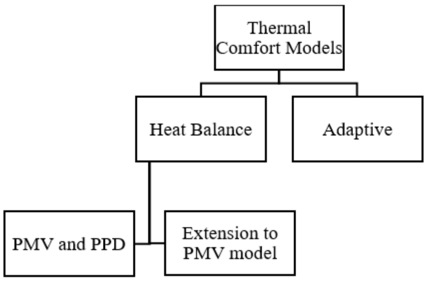

Figure 2.3: Comfort Models Developed in the World

and Predicted Percentage of Dissatisfied (PPD) are the most common forms of heat balance models used. PMV model is sometimes modified according to the conditions. A graphical representation of the comfort models employed in the world is shown in Figure 2.3 (L. Yang, Yan, & Lam, 2014).

Heat balance models assume that human body's thermoregulatory mechanism always tries to keep the body at a constant temperature to maintain the normal functions running. Hence, the body will adjust physiologically to respond any thermal imbalance in the environment, for instance, sweating, and the comfort is measured as a degree of the magnitude of those responses (L. Yang et al., 2014).

PMV is a result of an effort to develop an index for HVAC Engineers to decide on a suitable degree of comfort that they are willing to obtain for a certain building so that most of the occupants feel comfortable. Some relationships were developed between mean skin temperature, activity level and sweat secretion and were substituted into heat balance equations. Subsequent comfort equations were assumed to give the conditions that a majority of occupants feel thermally neutral. PMV is an index developed to have practical applications of those comfort equations. Hence, PMV is a function of seven variables mentioned below; (Fanger, 1970).

1. Air temperature
2. Mean radiant temperature
3. Relative air velocity
4. Air humidity

5. Activity Level

6. Clothing

7. Insulation

It should be noted that first four of these variables are environmental variables, and the rest of them are subjective. PMV models mainly focus on the four environmental variables.

Even though this gives the comfort conditions for the majority to be satisfied, it is important to note that a certain percentage would be dissatisfied with these conditions. PPD is this unsatisfied percentage under the conditions derived by PMV and is calculated by the following equation (L. Yang et al., 2014).

$$PPD = 100 - 95 \times EXP(-0.03353 \times PMV^4 - 0.219 \times PMV^2)$$

This equation indicates that even when PMV is zero, about 5$\%$ of the people will still be unsatisfied.

Therefore, the focus has been shifted from trying to achieve optimum thermal condition to exploring a range of thermal comfort. Further, it has been observed that PMV model works well in HVAC environments, but not that well in free-running buildings. In free-running buildings, the indoor neutrality temperature was observed to change with the climatic conditions of the region. To cater this, PMV model was extended to include an expectancy factor (Halawa, van Hoof, & Soebarto, 2014).

Both the PMV and PPD models were developed in climate chambers, and hence are more suitable for buildings with controlled conditions. It has not taken the occupants' behaviour into account in developing that. People are active elements in the environment and do respond and adapt to the changes in the immediate surroundings (de Dear & Brager, 2002).

This adaptation occurs in three different categories: physiological, behavioural and psychological. Physiological adaptation does not account for much in this context since it is only capable of adjusting slightly before feeling it. The psychological adaptation refers to cognitive, social and cultural variables, which has a significant influence, but not as much as behavioural adaptation.

Behavioural adaptation is the dominant factor among those three categories as it contributes to a huge variation in comfort conditions even if all the other parameters are kept constant. It includes the activity, clothing, opening or closing windows and switching on fans (Nicol & Humphreys, 2010).

One of the major characteristics of adaptive models is that it takes a dynamic neutrality temperature (T_n) based on the mean outdoor temperature (T_0) in that particular area. There are several relationships developed by different researchers.Some of them are depicted below;

For free-running buildings,

$T_n = 13.2 + 0.534T_0$ (Humphreys, 1981)

$T_n = 13.5 + 0.546T_0$ (de Dear & Brager, 2002)

$T_n = 17.6 + 0.310T_0$ (Szokolay, 1991)

For HVAC, heated or cooled buildings,

$T_n = 20.1 + 0.0077T_0^2$ (Humphreys, 1981)

$T_n = 22.2 + 0.003T_0^2$ (de Dear & Brager, 2002)

These models were observed to have a good relationship with free-running buildings, but the variation for HVAC buildings was high as the comfort conditions in such cases were observed to be high.

A chart has been developed to mark the comfort conditions on all the environmental variables to be considered. It considers following factors and mark all those variables in a single graph:

- Absolute humidity
- Relative humidity
- Wet bulb temperature

- Dry bulb temperature
- Specific volume
- Enthalpy
- Sensible heat
- Latent heat

Figure 2.4 shows a typical psychrometric chart containing all the variables specified above. Each point on the graph corresponds to a condition with a value of all the specified parameters.

Comfort conditions for 80%- satisfaction level corresponding to Colombo, of which the neutrality temperature is 26^0C is shown in Figure 2.5 (Jayasinghe, Attalage, & Jayawardena, 2002). Here, the neutrality temperature has been calculated using szokolay's equation mentioned above (Szokolay, 1991).

Then it has been proven that this comfort zone can be expanded with increased air velocity. The comfort conditions for different velocities spanning from less than $0.25ms^{-1}$ to $0.6ms^{-1}$ for a neutrality temperature of 26^0 is shown in Figure 2.6. It indicates that the comfort zone can be expanded significantly by increasing the air velocity within the occupied zone using fans.

However, the affordable energy consumption to make the surrounding thermally comfortable is a variable of many factors. It has now reached a level that immediate actions need to be taken to prevent this. Section 2.4 focuses on that aspect in detail.

2.4 Energy Consumption and Thermal Comfort

2.4.1 Energy Consumption in Tropical Countries

Nowadays, the occupants tend to pay high attention to the comfort conditions that they have to live. Comfort has many complexions in the forms of visual comfort, acoustic comfort, thermal comfort and indoor air quality. But thermal comfort seems to be dominant among them (Frontczak & Wargocki, 2011). The essence of comfort has

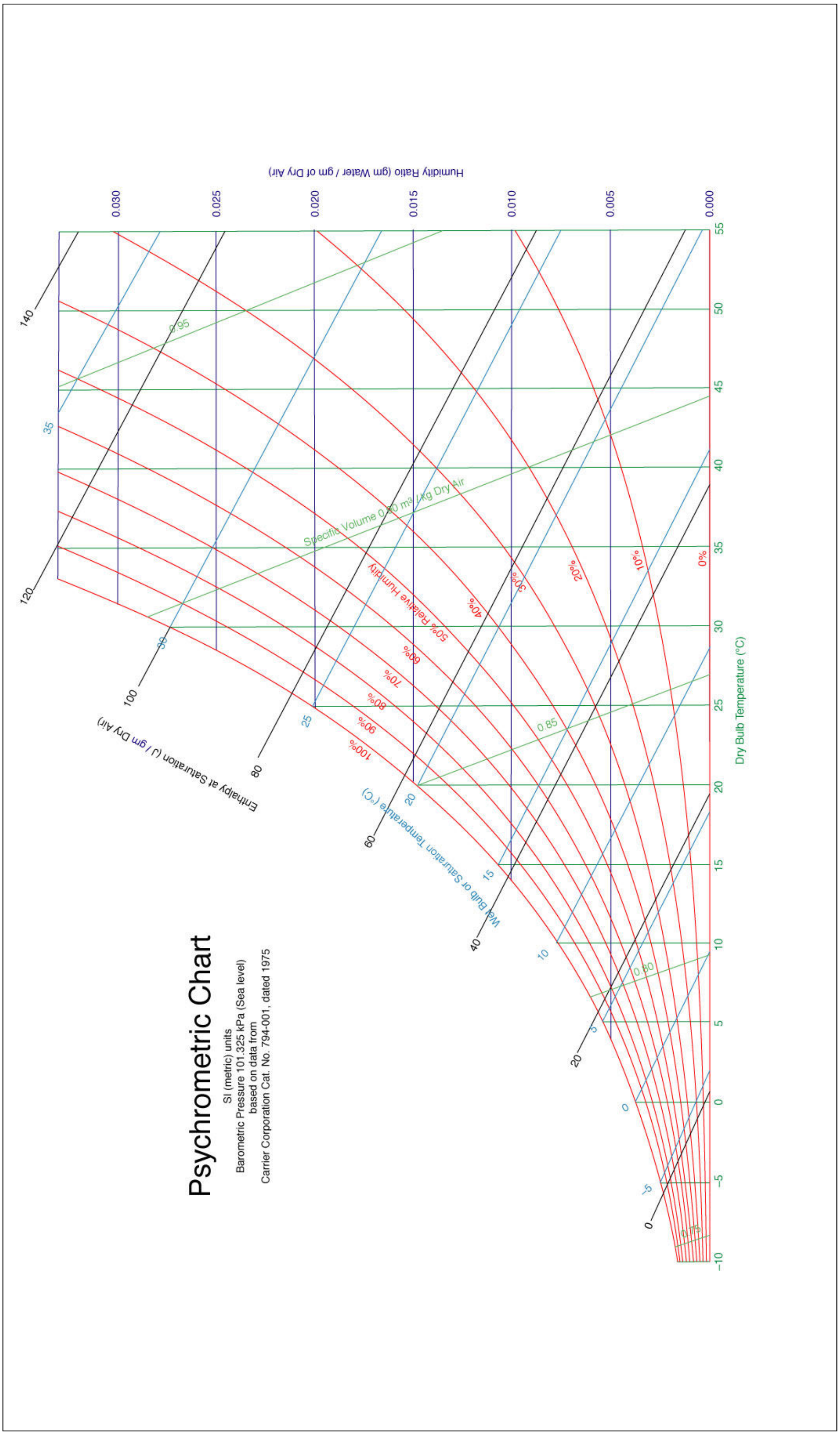

Figure 2.4: A Typical Psychrometric Chart

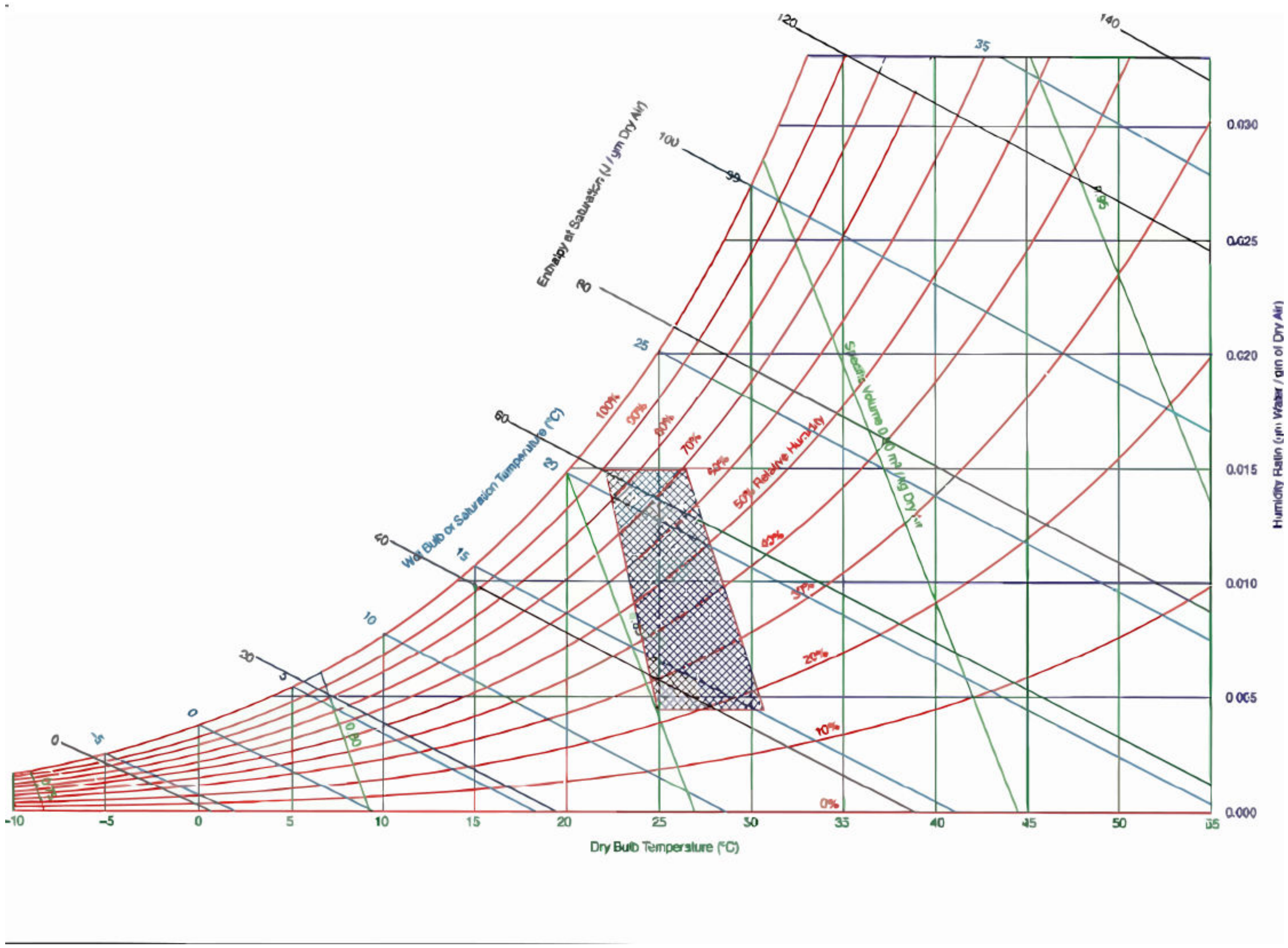

Figure 2.5: Comfort Zone for a Building without HVAC for a Neutrality Temperature of 26^0C

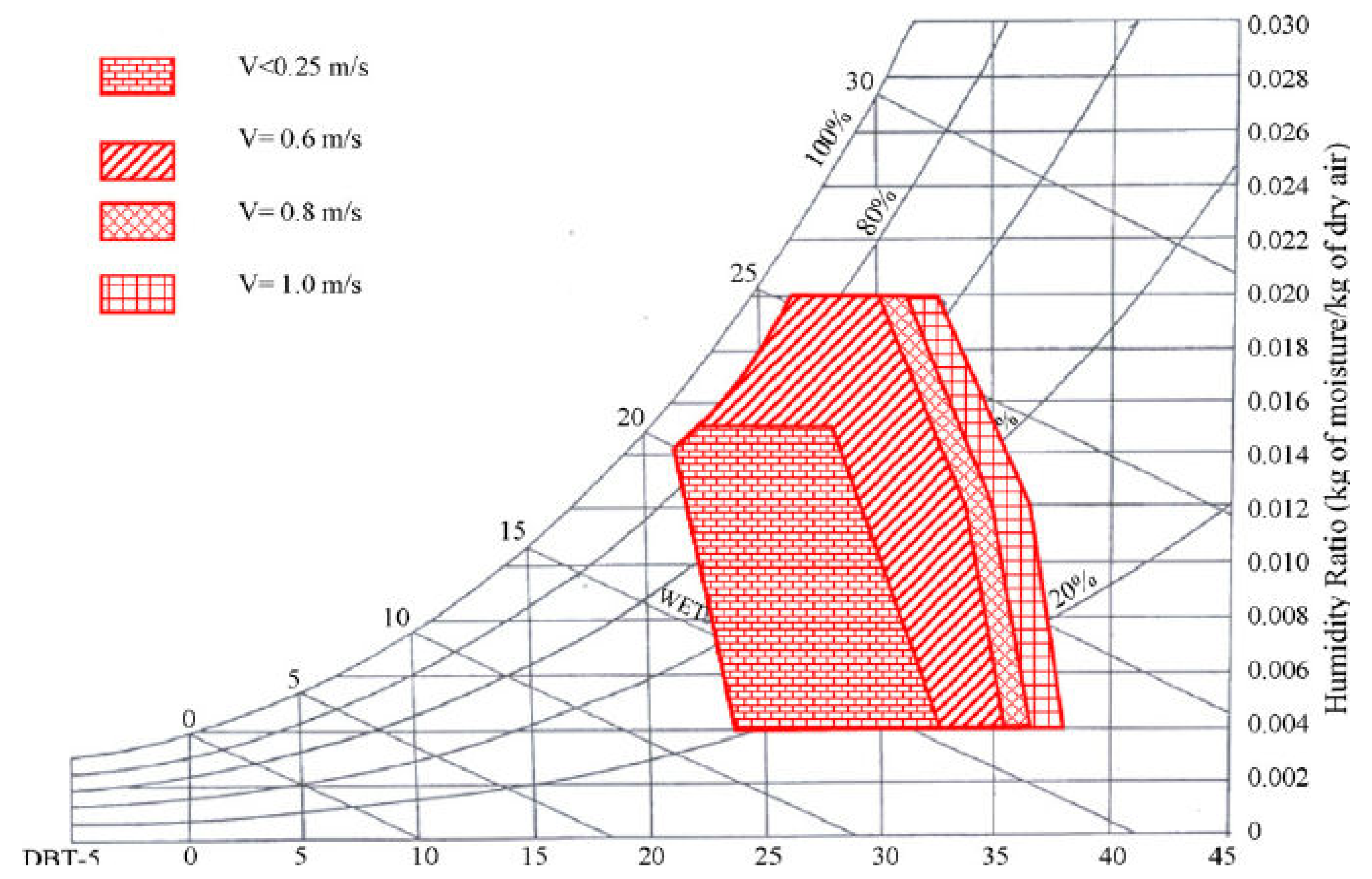

Figure 2.6: Comfort Zone for a Building with Different Air Velocities for a Neutrality Temperature of 26^0C

now reached an alarming level that it needs to reconsider degree of offer up that is affordable for that, as this has raised serious concerns over the depletion of natural resources (Kwong, Adam, & Sahari, 2014).

The current major contributors of this process are the developed countries like North America, Japan, Australia and New Zealand. However, it is predicted that developing countries in South-East Asia, Middle-East, South America and Africa will take this over by 2020 (Prez-Lombard, Ortiz, & Pout, 2008). It has been proven that there is a significant positive association between economic growth, energy use and Carbon emissions (L. Yang et al., 2014).

However, energy comes with a significant cost. Hence, the reduction in energy usage is of an essence to reduce the energy cost, particularly in developing countries (Kwong et al., 2014). It is the economic perspective of the issue. The damage that it does to the balance of the world is unquantifiable in exact monetary terms.

Statistics of China state that during 1978-2010, its Primary Energy Requirement (PER) has increased from an approximate value of 570 Mtce (Millions of tonnes of coal equivalent) to around 3200 Mtce, at an average annual growth of 5.6%. It is predicted that it would increase to 6200 Mtce by 2050. It is noteworthy that around 70% of this corresponds to fossil fuel, making these statistics much worse, since greenhouse gas emission is higher when fossil fuel is used (Chai & Zhang, 2010).

The energy usage in buildings plays a major role in this process, which is described in Section 2.4.2.

2.4.2 Energy Consumption in Buildings

Buildings, transportation and industry are the three top energy users in the current world. However, buildings have become dominant among them (Kwong et al., 2014; L. Yang et al., 2014). One of the major reasons identified for that is the subsidisations provided by governments for domestic electricity consumption. Currently, this has reached a status that this issue needs to be addressed now itself (Kwong et al., 2014).

There is literature available quantifying the energy usage in buildings. In 2004, the building sector consumed 40%, 39% and 37% of the primary energy consumption in USA, UK and the European Union respectively (J. Yang, Yu, & Gong, 2008). In China, this amount was reported as 24.1% in 1996 and has increased up to 27.5% in 2001. It is predicted that the portion of energy used up by the buildings will increase to about 35% by 2020 (Yao & Steemers, 2005).

The primary source of this vast growth in energy usage is the air-conditioning and mechanical ventilation systems. A research study in Malaysia has proven that almost 60% of the total energy usage in buildings is for active cooling (Kwong et al., 2014).

2.5 Insulation as a Passive Technique

2.5.1 Passive Techniques in General

As it has been stated earlier, heating and cooling consume about 20% of the global energy usage. In tropical climatic conditions, it is cooling that consumes most of the energy.

In this context, passive cooling is an emerging area that has interested the researchers. Those are the techniques used at the design stage itself to make the buildings comfortable with a minimum use of energy.

It has been found that there are three basic approaches to passive strategies regarding thermal comfort (Al-Obaidi et al., 2014).

1. Passive cooling strategies to prevent heat gain inside the buildings (using insulation, solar shading of faade, and outer surface properties of the building envelope)

2. Heat gain modulation by effective solar control (striking a balance between obtaining sufficient natural light and minimising heat gain inside the building)

3. Reducing heat inside the building (for instance, using air filtration inside surface properties)

There are an extensive number of passive techniques available in the world. A classification of them is depicted in Figure 2.7. Insulation is one key element of passive cooling strategies used.

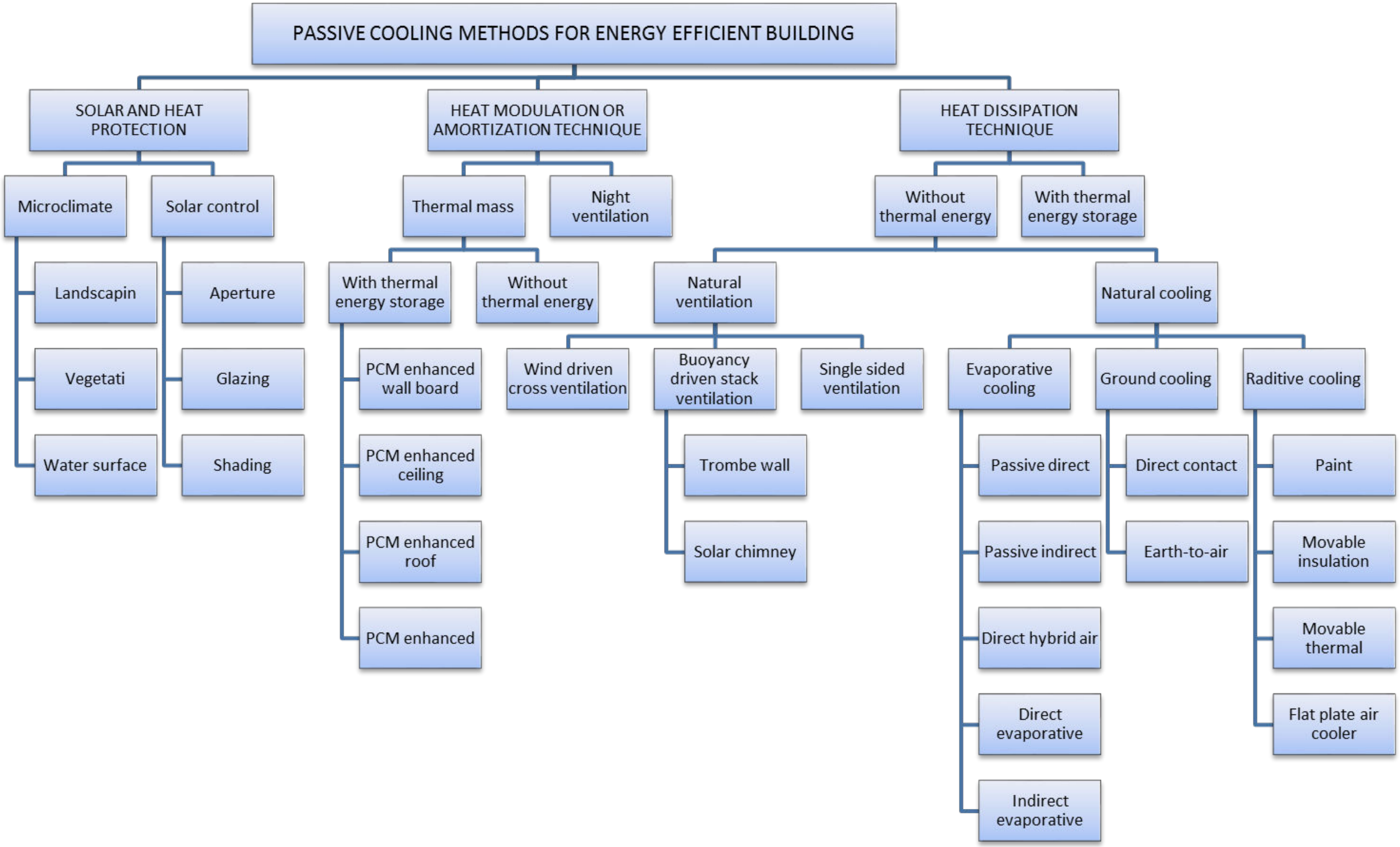

Figure 2.7: A Summary of Passive Techniques Used in Buildings

2.5.2 Insulation as a Passive Strategy

Advantages of insulation

Researchers have proven that insulation can be effectively used to prevent heat gain inside and in turn, to reduce the cooling load of the building (Tong et al., 2014). Other than this, there are many advantages of thermal insulation in general, Al-Homoud has enlisted some of them as follows; (Al-Homoud, 2005).

- **A matter of principle**- Nowadays, most of the buildings rely on mechanical and electrical means of cooling. It is gradually reaching a level that almost every building depends on fans and air-conditioners. Disturbing this trend is essential. Insulation is a good strategy to do that.
- **Economic benefits** - Even though that insulation involves an additional initial investment, reduction of electricity consumption pays that cost back within a reasonable time span. Further, it contributes to a significant decrease of initial cost by reducing the load of HVAC equipment required.
- **Customer satisfaction** - Increased use of thermal insulation in buildings will result in energy savings, which will decrease the operational cost of the customers to a great extent.
- **Thermally comfortable buildings** - insulation extends the periods of indoor thermal comfort, especially in between seasons, while reducing the reliance of mechanical cooling.
- **Reduced noise levels** - Insulation can reduce disturbing noise from neighbouring spaces or from outside and will enhance the acoustic comfort of insulated buildings.
- **Building structural integrity** -Keeping buildings with minimum temperature fluctuations helps in preserving the integrity of building structures and contents.
- **Fire protection** - Insulation can help in retarding heat and preventing flame immigration into building in case of fire.

Different Types of Insulation Systems

The heat gain reduction in insulation is achieved by three basic methods(Bastidas-Arteaga et al., 2013).

- Absorptance: fraction of incident radiation absorbed by the material
- Reflectance: fraction of incident radiation reflected by the material
- Transmittance: fraction of incident radiation transmitted through the material

Absorptance depends basically on the colour of the surface exposed to the sun. The darker the surface, higher the absorption is.

Reflective insulation is particularly suitable for tropical climatic conditions, and can be used with walls and roofs. They come as rolled foil, reflective paint, reflective metal shingles or foil-faced plywood sheathing. However, this is not recommended for rooftops as there's a possibility of creating a vapour barrier in cold seasons.

Transmission barriers minimise the heat transmission along the building envelope to the building interior. Its best performance is achieved in tropical climatic conditions when the barrier is placed outside the construction element, directly facing the sun.

There are many insulation techniques and insulation materials found and tried out for different building elements. From now on, this chapter will focus on various roof insulation techniques available and their performances.

2.6 Roof Insulation

2.6.1 Different Roof Slab Insulation Systems

The roof is the element, which contributes to most of the heat gain inside buildings. Hence, it is worth trying to prevent the heat flow from the roof. Insulation is proven to be a useful method of achieving this.

Some of the insulation techniques that are tried out throughout the world are shown in Table 2.1. By those figures, it is evident that significant energy reductions can be obtained by roof slab insulations. In countries like Greece, Italy and the USA, which

Table 2.1: Insulation Techniques Tested throughout the World

Country	Insulation technique	Results
Florida, USA	Applying a cool paint	19% of energy saved on average, Saved up to 38% on peak (Parker & Barkaszi Jr., 1997)
Italy	Applying a cool paint	Indoor temperature is reduced by 2.5^0 C in comparison with outdoor (Romeo & Zinzi, 2013)
Greece	6 cm of ventilated air gap	Daily heat gain is reduced by 56% (Dimoudi, Androutsopoulos, & Lykoudis, 2006)
Sri Lanka	25 mm thick polyethylene insulation on a concrete roof	9^0 C reduction in slab soffit temperature, About 75% reduction of heat flow (Halwatura & Jayasinghe, 2008)
A laboratory experiment	Combined application of Aluminium reflector and Polyurethane insulation	Heat flux reduction of 88% (Alvarado, Terrell Jr., & Johnson, 2009)
A laboratory experiment	10 cm plastic waste thermal insulation	About 70% effective insulation in comparison with ordinary insulation materials, However, considering the economic aspects, this is viable (Megri, Achard, & Haghighat, 1998).

are closer to the tropic of cancer, energy saving is around 40% - 60%. However, in tropical climatic conditions in Sri Lanka, a reduction of 75% of heat flow has been observed (Halwatura & Jayasinghe, 2008).

2.6.2 Roof Insulation with a Vegetation Layer on Top

The advantages of a roof insulation system can be further enhanced by adding a layer of rooftop vegetation. Some of the benefits are as follows;

- **Decrease of the heat island effect**(Zhang, Shen, Tam, & Lee, 2012; Ng, Chen, Wang, & Yuan, 2012; Lazzarin, Castellotti, & Busato, 2005; H. Chen, Ooka, Huang, & Tsuchiya, 2009; Smith & Roebber, 2011; J. K. W. Wong & Lau, 2013; Susca, Gaffin, & DellOsso, 2011; Speak, Rothwell, Lindley, & Smith, 2013; Li et al., 2010; Ihara, Kikegawa, Asahi, Genchi, & Kondo, 2008; Kosareo & Ries, 2007; Takebayashi & Moriyama, 2007; Rosenzweig et al., 2005; Oberndorfer et al., 2007; C.-F. Chen, 2013)

- **Reduction of carbon footprints**(Li et al., 2010; C.-F. Chen, 2013; Feng, Meng, & Zhang, 2010; Weng, Lu, & Schubring, 2004)
- **Mitigation of air pollution**(Zhang et al., 2012; Oberndorfer et al., 2007; Rowe, 2011; Bianchini & Hewage, 2012)
- **Stormwater management**(Oberndorfer et al., 2007; C.-F. Chen, 2013; Fioretti, Palla, Lanza, & Principi, 2010; VanWoert et al., 2005; Villarreal & Bengtsson, 2005; Getter, Rowe, & Andresen, 2007; Tabares-Velasco, Zhao, Peterson, Srebric, & Berghage, 2012; Chan & Chow, 2013)
- **Enhanced runoff quality**(Kosareo & Ries, 2007; Berndtsson, Bengtsson, & Jinno, 2009; Vijayaraghavan, Joshi, & Balasubramanian, 2012)
- **Improved use of rainwater**(Bianchini & Hewage, 2012; Fioretti et al., 2010; T. Sun, Bou-Zeid, Wang, Zerba, & Ni, 2013)
- **Enhancement of urban hydrology**(C.-F. Chen, 2013)
- **Sound insulation and noise absorption**(Connelly & Hodgson, 2011; Van Renterghem & Botteldooren, 2011, 2009; Van Renterghem, Hornikx, Forssen, & Botteldooren, 2013)
- **Reduction of habitat loss**(Oberndorfer et al., 2007; C.-F. Chen, 2013; Bianchini & Hewage, 2012; Francis & Lorimer, 2011; Blanusa et al., 2013)
- **Biodiversity and improved landscape**(Chan & Chow, 2013; Whittinghill, Rowe, & Cregg, 2013; Baik, Kwak, Park, & Ryu, 2012; Ksiazek, Fant, & Skogen, 2012; Schweitzer & Erell, 2014; Nagase & Dunnett, 2010; Wolf & Lundholm, 2008; MacIvor, Margolis, Puncher, & Carver Matthews, 2013)

Table 2.2: A Summary of Literature on Heat Gain Reduction of Rooftop Vegetation

Country	Literature on heat gain reduction by rooftop vegetation
Japan	Rooftop lawn reduced peak air temperature by 3 - 4^{0}C in summer (N. Zhou, Gao, Nishida, Kitayama, & Ojima, 2004).
Greece	Indoor temperature is reduced by 0.6^{0}C (Sfakianaki, Pagalou, Pavlou, Santamouris, & Assimakopoulos, 2009).
Singapore	A maximum heat reduction of more than 60% has been obtained (N. H. Wong, Chen, Ong, & Sia, 2003).
Hong Kong	Green roofs have 75% lower heat storage than bare roofs (Tsang & Jim, 2011).
Brazil	Reduces heat gain by 92% - 97% compared with ceramic and metallic roofs (Parizotto & Lamberts, 2011).
Taiwan	Decreases ambient air temperature by 0.3^{0}C in winter, 0.5^{0}C in spring, and 1.2^{0}C in summer (C. Y. Sun, n.d.).

Some of the publications on thermal gains from rooftop vegetation are enlisted in Table 2.2. It is notable that most of the research on rooftop vegetation have been carried out in tropical climates, particularly in South-western and far Asian regions. Hence, it is not completely fair to compare those figures with the values in Table 2.1. However, it is possible to compare the research carried out in Sri Lanka (Halwatura & Jayasinghe, 2008) and Brazil (Parizotto & Lamberts, 2011) as both are tropical climates and since they represent the upper bounds of the energy savings that can be obtained. It is apparent that adding a rooftop vegetation layer can almost nullify the heat gain through the roof whereas the use of insulation layer of polystyrene itself too can significantly reduce the heat gain.

2.7 Economic Feasibility of the Systems

2.7.1 General

Cost is one of the most important parameters that has to be taken into account in making these passive techniques popular. There is an inevitable additional initial investment associated with insulation and green roofs. However, it is necessary to consider the payback due to the reduction in operational cost. There are many types of research carried out to study the same.

Many parameters should be considered in selecting a technique of thermal insulation, including durability, cost, compressive strength, water vapour absorption and transmission, fire resistance, ease of application and thermal conductivity. However, the thermal resistance of insulation materials is the most important property that is of interest when considering thermal performance and energy conservation issues (Al-Obaidi et al., 2014).

Before carrying out a detailed analysis of this, it is important to understand the factors affecting the initial cost and the benefits and barriers along the long run. Table 2.3 presents the economic benefits and barriers to be considered in an analysis.

Life cycle costing is identified as one of the best methods to quantify the effect of these. According to the National Institute of Standards and Technology life cycle costing is defined as follows (Fuller & Peterson, 1996);

"The total discounted dollar cost of owning, operating maintaining and disposing of a building or a building system over a period. Life cycle Cost Analysis (LCCA) is an economic evaluation technique that determines the total cost of owning and operating a facility over a period of time."

In this context, thicker insulation does not necessarily mean better. Optimum economic thickness of insulation can be defined as the thickness of insulation for which the cost of the added increment of insulation is just balanced by increased energy savings over the life of the project.

On the other hand, the same thermal insulation does not always have the same effectiveness for all types of buildings. Its efficiency and economic value are to be

Table 2.3: Economic Benefits and Barriers to be Considered in Life Cycle Cost Analysis

Economic Benefits	Economic Barriers
Reduce energy consumption	High construction cost
Increase thermal insulation in retrofitting	High maintenance cost when irrigation is required for greenery
Reduce maintenance cost of the roof due to lengthening of life	Complexity of construction
Reduce costs of water run-off and urban infrastructure	Risks of failure
Improve market price of buildings	Expensive integration in existing buildings if adjustments to the structure are needed
Increase usable surface of the building	

determined by an LCCA. The factors that need attention in analysis are as follows (Al-Homoud, 2005);

- The building type, function, size, shape, and construction
- The building component to be insulated (wall, roof and the other elements in the envelope.)
- The local weather conditions at the building site
- The type of insulation used
- The local climatic conditions at the building site
- The cost of insulation (material and installation costs)
- The type and efficiency of the air-conditioning system used
- The type and cost of energy used (the value of energy saved)
- Maintenance cost

Building service life is a key parameter in performing a life cycle cost analysis. In a study that Islam et al. has carried out, it is stated that there is a broad range of 35-70 years of service lives assumed in different studies, of which the mean is taken as 50 years (Islam, Jollands, & Setunge, 2015). This figure has been justified by some other researchers as well. (Hendrickson, Lave, & Matthews, 2006; Adalberth, 1997; Huberman, Pearlmutter, Gal, & Meir, 2015).

However, it does not imply that all the elements have that service life. If a roof is considered for an example, Hoff says that the life of a roof varies from 5-30 years depending on the material used (Hoff, 2007). Halwatura & Jayasinghe and Kumar & Kaushik have used 10-20 years as the service life (Halwatura & Jayasinghe, 2009; Kumar & Kaushik, 2005). Lamnatou and Chemisana say that Photovoltaic-green roofs last for about 30 years (Lamnatou & Chemisana, 2014). Chenani et al. say that a membrane of a green roof lasts 40 years (Bozorg Chenani, Lehvvirta, & Hkkinen, 2015). These imply that even though the life of a building is taken to be 50 years, different elements have different service lives. The studies in this particular area have so far missed the impact of insulation / green roof to the service life of buildings.

2.7.2 Life Cycle Costing of Slab Insulation Systems

These can be broadly categorised into two sections: studies on slab insulation systems as a whole, and studies on materials that can be used as insulation.

Life Cycle Costing of Roof Slab Insulation Systems as a Whole

Not many comprehensive studies have been carried out in this area regarding life-cycle cost analysis. However, there are some which are sufficient to understand the potential.

As it has been mentioned above, there are many factors to be considered when carrying out a life cycle costing analysis. The major expense is the initial cost, and the primary income is the energy saving potential. According to Al-Homoud, the initial cost is about 5% of the total cost of the building, and which too can be reduced by using A/Cs with less load due to the reduction in requirement, many research findings show that significant energy savings can be obtained by the above (Al-Homoud, 2005).

As a technique of insulation, Halwatura and Jayasinghe have performed a detailed analysis of a slab insulation system in the tropical climatic conditions in Sri Lanka. They have considered five options (Halwatura & Jayasinghe, 2009);

- A 25 mm polystyrene insulation on top of the slab
- A 38 mm polystyrene insulation on top of the slab
- A 50 mm polystyrene insulation on top of the slab
- Sloping roof with reflective insulation mounted on 3 mm resistive insulation layer
- Sloping roof with reflective insulation mounted on 25 mm resistive insulation layer

In this study, they have considered several parameters; initial cost, the component of initial cost that can be recovered by land recovery and the reduction of the sensible load of the air conditioning. In the case of calculating the initial land recovery, two options have been considered for the land price: $1000 per perch and $2000 per perch. Three options have been reviewed for the discounting factor: 8%, 10% and 12% and two for the service life: 10 years and 20 years.

It concludes that insulated roof slabs recover its initial capital cost by the extra benefits gained, emphasising the fact that it has a lower life cycle cost than a conventional roofing system. Furthermore, it has additional benefits such as better cyclone resistance, low maintenance and ability to create a greener environment with rooftop gardens (Halwatura & Jayasinghe, 2009).

Life Cycle Costing of Insulating Materials

Many types of insulation materials are available which fall under different basic materials and composites; inorganic materials, fibrous materials such as glass, rock, and slag wool, fibrous materials such as cellulose, cotton, wood, pulp, cane, or synthetic fibres and cellular materials such as cork, foamed rubber, polystyrene, polyethylene, polyurethane and other polymers (Al-Homoud, 2005).

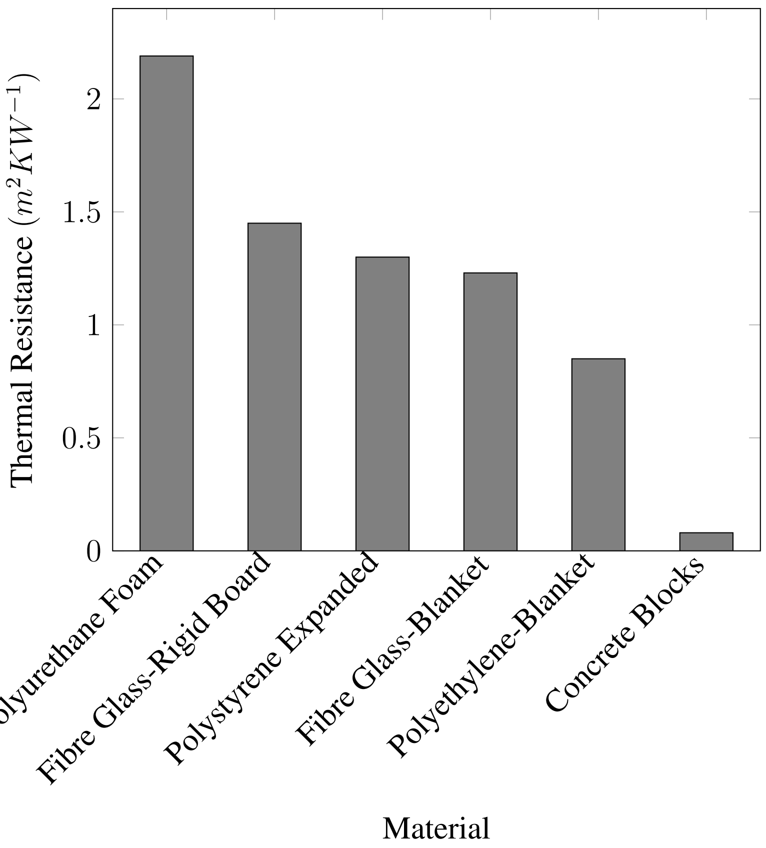

Figure 2.8: Thermal Resistances of 5 cm Thickness of Common Building Insulation Materials

Figure 2.8 shows a graphical comparison of the thermal resistances of 5 cm thickness of common building insulation materials. Concrete block is not considered as an insulating material but is included in the figure as a reference (no insulation case) for comparison purposes only. Table 2.4 illustrates a comprehensive study that has been carried out on performance characteristics of different heat insulation materials. Thermal conductivity, durability and cost per R- value (cost per a unit thermal resistance) can be identified as the parameters essential to perform a life-cycle cost analysis. Here, health aspects are also taken into account as it has a significant effect in the long run (Al-Homoud, 2005).

Polyethylene and polystyrene are two of the most common materials used as insulators, due to their availability and low cost. It has proven to be effective as a thermal insulator alone. However, both these materials are found to be emitting toxic substances.

Fibreglass can be identified as a better alternative to the above materials as a thermal insulator. Its thermal conductivity is almost same as that of polyethylene, but has no toxic emittance. But the durability in loose form is a matter of concern as the effectiveness of thermal insulation reduces with time. The rigid boards are relatively expensive.

Waste paper (in the form of cellulose) too is tested as a material for insulation. But since it is not an excellent insulator, the cost per resistance value is higher, making it relatively less viable in comparison with other materials.

Table 2.4: Properties of Different Insulation Materials

Material	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Durability	Cost per *R*-Value	Fire resistance	Potential health risks
Fiberglass (sand & recycled glass) (Al-Homoud, 2005)	0.033-0.04	Compression reduces *R*-value	Medium	good	Inorganic (organic binders), Irritating dust during installation
Rockwool (natural rocks) (Al-Homoud, 2005)	0.037-0.04	Compression reduces *R*-value	Low	excellent	Inorganic (organic binders), Irritating dust during installation

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Table 2.4 – *Continued from the previous page*

Material	Thermal conductivity (W m^{-1} K^{-1})	Durability	Cost per *R*-Value	Fire resistance	Potential health risks
Polyethylene (Al-Homoud, 2005)	0.041	*R*-value decreases w/time	Low	poor	Organic (off-gassing toxic smoke)
Cellulose (ground-up waste paper) (Al-Homoud, 2005)	0.046-0.054	Comp.& moisture degrade *R*-value	Low	poor	organic. Irritating dust during installation

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Table 2.4 – *Continued from the previous page*

Material	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Durability	Cost per *R*-Value	Fire resistance	Potential health risks
Expanded Polystyrene (closed cell foam) (Al-Homoud, 2005)	0.037-0.038	*R*-value decreases w/time	Lower of rigid board types	poor	Organic (uses pentane gas as the expanding agent, toxic)
Extruded Polystyrene (Closed cell foam) (Al-Homoud, 2005)	0.032-0.030	*R*-value decreases w/time	High	poor	Organic (uses HCFC or CFC gases as the expanding agent, toxic fumes)

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Table 2.4 – *Continued from the previous page*

Material	Thermal conductivity (W m^{-1} K^{-1})	Durability	Cost per *R*-Value	Fire resistance	Potential health risks
Aluminized thin sheets (Al-Homoud, 2005)	Reduces only radiant heat transfer			good	
Ceramic coating (Al-Homoud, 2005)	Radiant control	High (Rust proofing)			Requires protective clothing and eye protection when applied

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Table 2.4 – *Continued from the previous page*

Material	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Durability	Cost per *R*-Value	Fire resistance	Potential health risks
Kenaf (Asdrubali, D'Alessandro, & Schiavoni, 2015)	0.034-0.043	(Not Specified)	(Not Specified)	good	(Not Specified)
Sheep wool (Asdrubali et al., 2015)	0.038-0.054	(Not Specified)	(Not Specified)	good	(Not Specified)

Table 2.5 shows some unconventional building insulation materials used throughout the world. Some of those materials have as low thermal conductivity as polyethylene or polystyrene. It is worth to seriously consider replacing those natural materials with existing synthetic materials.

Table 2.5: Properties of Natural Insulation Materials

Natural Material	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)
Banana and polypropylene(PP) fiber(Annie Paul et al., 2008)	0.157-0.182
Bagasse(Manohar, Ramlakhan, Kochhar, & Haldar, 2006; Manohar, 2012; Panyakaew & Fotios, 2011)	0.046-0.055
Corn cob(Pinto et al., 2012; Paiva et al., 2012)	0.101
Cotton(stalks)(X.-y. Zhou, Zheng, Li, & Lu, 2010)	0.058-0.081
Date palm(Agoudjil, Benchabane, Boudenne, Ibos, & Fois, 2011; Chikhi, Agoudjil, Boudenne, & Gherabli, 2013)	0.072-0.085
Durian(Khedari, Charoenvai, & Hirunlabh, 2003)	0.064-0.185
Oil palm(Manohar, 2012)	0.055-0.091
Pecan(Yarbrough, Wilkes, Olivier, Graves, & Vohra, 2005)	0.088-0.103

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Table 2.5 – *Continued from the previous page*

Natural material	Thermal conductivity (W m^{-1} K^{-1})
Pineapple leaves(Tangjuank, 2011)	0.03-0.04
Rice(Yarbrough et al., 2005)	0.046-0.056
Sunflower(cake from biorefinery)(Manohar et al., 2006; Manohar, 2012; Panyakaew & Fotios, 2011)	0.046-0.055
Sunflower(pitch)(Vandenbossche, Rigal, Saiah, & Perrin, 2012)	0.038-0.050
Straw bale(Goodhew & Griffiths, 2005; Pruteanu, 2010)	0.038-0.067

It is worth comparing the effectiveness of the materials checked above. The material used in the experiment in section 2.7.2 is expanded polystyrene and its thermal conductivity was taken to be 0.035. Since the above-mentioned materials are of the same order, they are easily comparable. Hence, any other material except cellulose or natural mineral can have the same life cycle costing results, hence, are viable insulating materials.

2.8 Summary of the Literature Survey

Extensive use of energy has led to Global Warming, and the researchers try to find ways to mitigate it. Reducing the energy consumption for thermal comfort is a feasible method to implement, which can be achieved by incorporating passive techniques in the design stage. Insulation of building envelope is a passive strategy as such. Insulation of roof is the most efficient method as the roof of a building is the highest contributor to the heat gain inside buildings.

Several roof insulation techniques were tried out, and proven to be very effective in tropical climatic conditions. It and can be further enhanced by having a vegetation on the roof as well, obtaining many other advantages.

However, an additional initial cost is associated with insulation, which is around 5% of the total cost of a building. However, this cost is proven to be easily recovered within the lifespan of the building by the reduction of energy usage. Furthermore, the initial cost too can be significantly reduced by lowering the air-conditioning load of the building.

Life Cycle Cost Analyses are performed to quantify the net effects of those aspects. They have proven that insulation roof is economically feasible.

Polyethylene and polystyrene are the most common insulation materials used in the industry. The effectiveness of them is proven by the facts that they are thermally resistant, durable and cost effective. However, it emits a toxic substance, which is very harmful in the long run, and they are by-products of the petroleum industry, which itself contributes to Global Warming.

Fibreglass does not have the toxicity involved. However, it has durability and cost issues in comparison with traditional insulation materials. Waste paper, in the form of cellulose, is found to be relatively ineffective solution considering all the aspects.

There are some natural insulation materials which are as effective as polystyrene Replacing them in insulation systems will increase the effectiveness and the popularity of the systems.

To conclude, it can be stated that whatever the material that is used, insulation is a viable passive option for mitigation of global warming.

Chapter 3

Public Perception on Roof Slabs

3.1 General

‘Shelter’ became one of the most significant basic needs of a human being from the era that the civilisation started to take place. Caves were the first form of shelter they had. However, with the evolution of human life, several types of roofs were used. ‘Thatch’ can be considered one of the earliest materials used as a shelter. It was used to get protection from adverse weather.

Gradually, ‘luxury’ began to take over the core essences and different types of structures started to take place. With that development, several roofing materials were used as a shelter. Metal sheets, calicut tiles and asbestos sheets are used depending on the affordability of the occupants. Sloping roofs made out of those materials adds aesthetics to the buildings.

However, with the rapid development and urbanisation taking place in the world, ‘land’ has become one of the most expensive commodities in the world. Hence, vertical construction has gained its popularity as it provides a higher floor-area-ratio. In this context, concrete slabs have become inevitable in intermediate floors. Further, the option using a flat concrete roof slab is seriously considered by most of the builders as it recovers the land loss due to the building by converting the roof slab to a working space.

Also, it creates the possibility of future vertical extension of buildings, which is a unique advantage of flat slabs as retrofitting a sloping roof uses up an extensive additional investment. Hence, most of the occupants who prefer to construct their residences stage-by-stage tend to go for flat concrete roof slabs.

Most importantly, the additional robustness that roof slabs provides buildings a cyclonic resistance, which is a significant characteristic due to the increase in the intensity and the severity of natural disasters taking place in the world due to climate change (Halwatura et al., 2007). Despite, the public is reluctant to go for flat concrete roof slabs. According to the statistics of Census Department of Sri Lanka in 2015, 54.8% of the buildings have calicut tiled roofs. This figure for asbestos sheets and metal sheets are 18.3% and 14.1% respectively. Concrete roof slabs is a portion of the rest. A graphical representation of this is shown in Figure 3.1.

Hence, it is necessary to investigate the reasons behind this. A questionnaire survey was performed to achieve following objectives;

- To identify the preferred roofing material and the reasons for that choice
- To find out the reasons that the roof slabs are not popular among the general public
- To prioritise the issues to be addressed to make roof slabs more public
- To identify the problems associated with roof slabs
- To find out the effect of roofing material used to the energy usage for thermal comfort in buildings

3.2 The Selected Sample

The Questionnaire shown in Appendix A was distributed in both printed and electronic forms, and an effective sample of 165 was selected for the analysis. The distribution of the field of work of the selected sample is shown in Figure 3.2. Different areas of work were chosen to obtain an unbiased set of responses. The sample of Civil Engineering, Construction and Architecture (approximately 40% of the selected sample) was taken

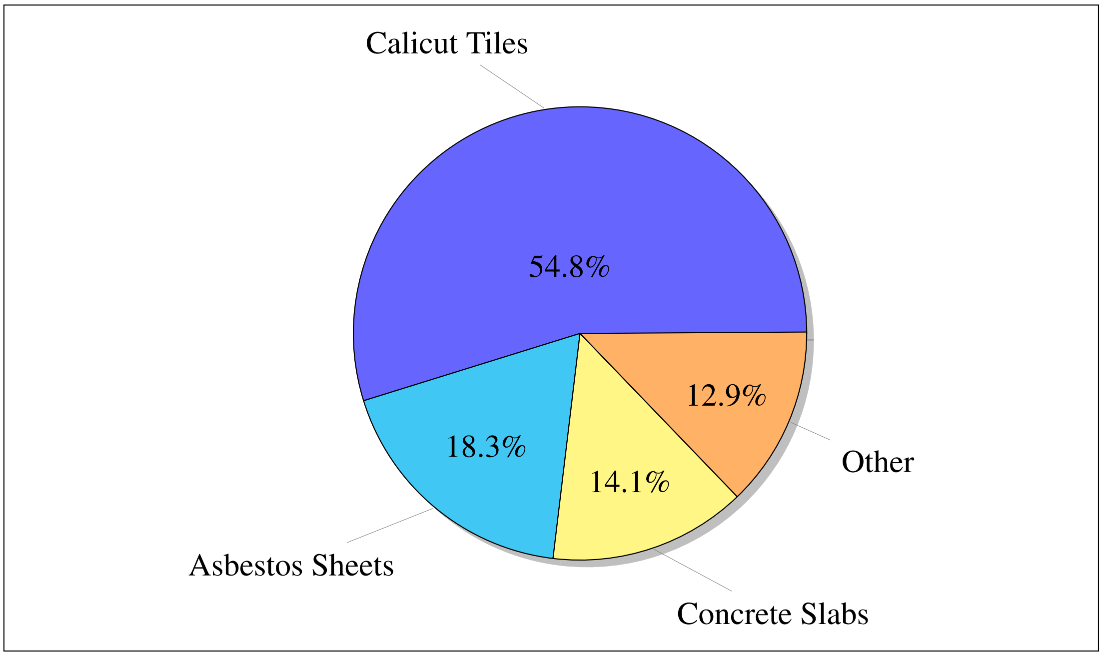


Figure 3.1: The Distribution of the Existing Roofing Materials in Sri Lanka (2015)

as professional responses as they are directly involved in the field, and the others were taken to be the general public. However, there was hardly any discrete difference of the results of the responses they are presented together. The distribution of the existing roofing materials of the selected sample is shown in Figure 3.3. It has a bias in comparison with the statistics of Department of Census which was intentionally incorporated since this research focuses on roof slabs, and the current trend is to go for either calicut tiles or asbestos sheets.

3.3 Results Obtained by the Questionnaire Survey

The first question was, “Are you satisfied with your available roofing material?”. The answers were analysed for each roofing material separately.

Figure 3.4 indicates the degree of satisfaction of calicut tile users. It shows that 80% of the calicut tile users are satisfied with their roofing material and that percentage is reduced to 53% in the case of asbestos roofs as shown in Figure 3.5. An overwhelming 86% are unsatisfied with the use of roof slabs (Figure 3.6), proving that there is an issue in roof slabs which needs to be addressed in the process of

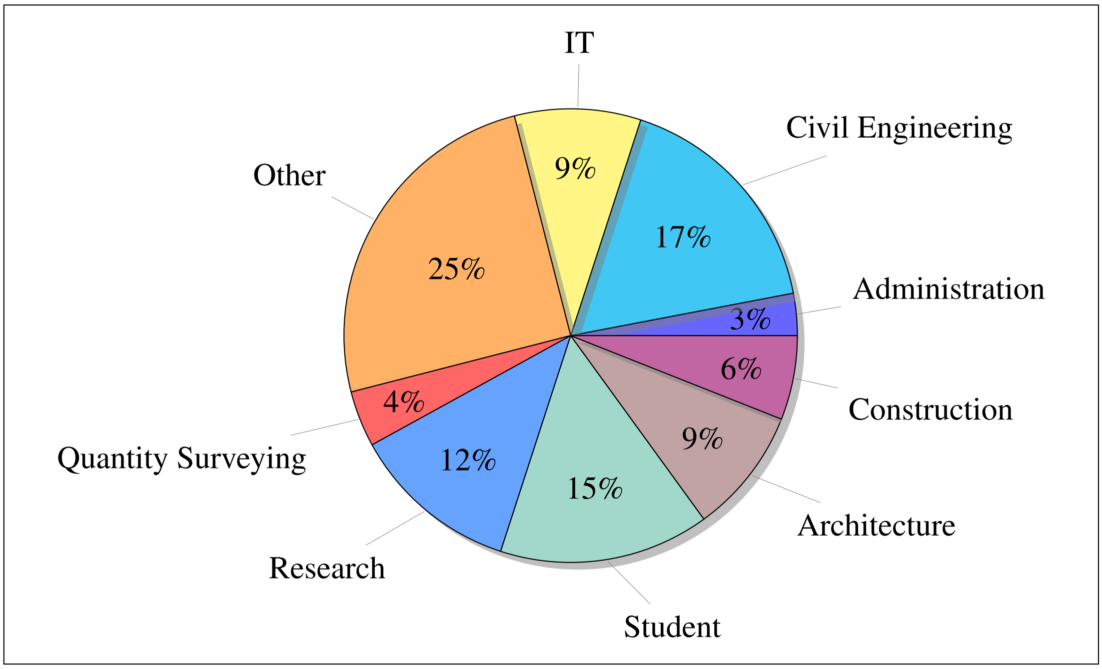


Figure 3.2: The Distribution of the Field of Work of the Selected Sample

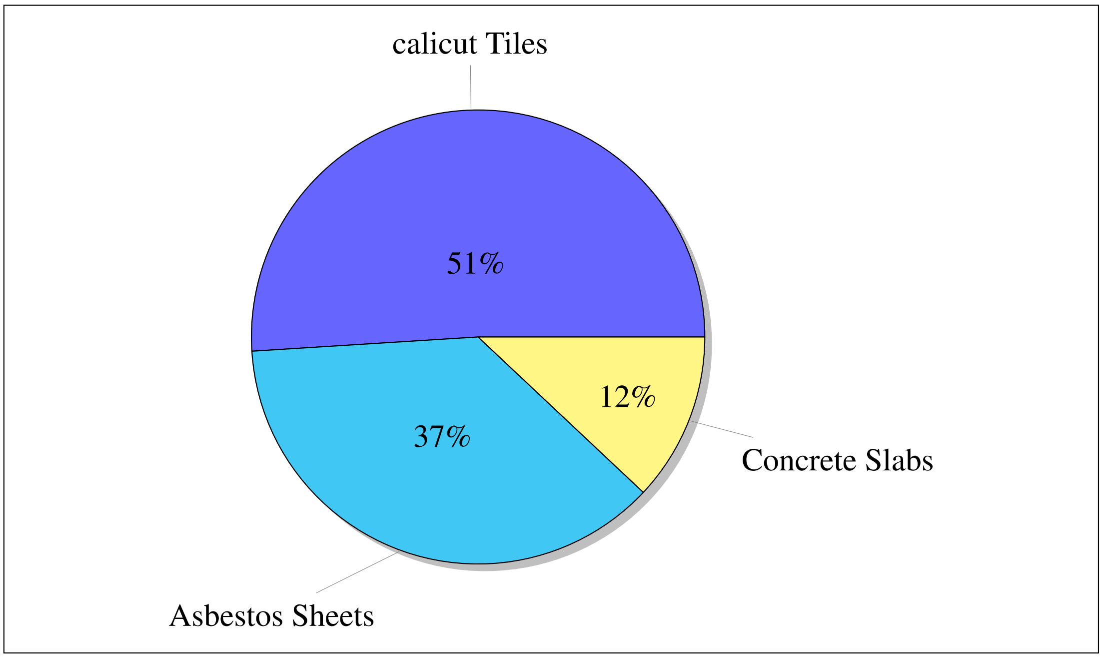


Figure 3.3: The Distribution of the Existing Roofing Materials of the Selected Sample

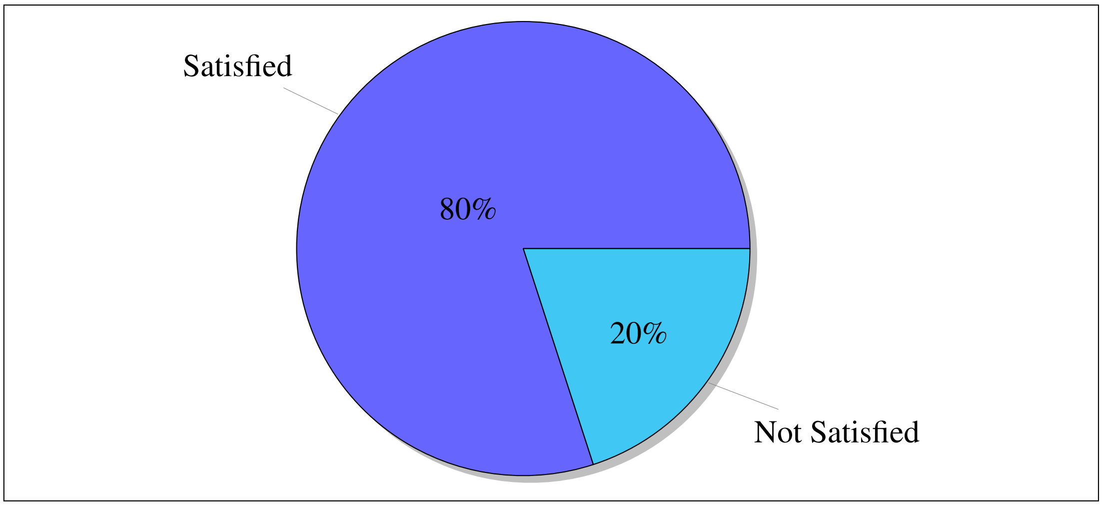


Figure 3.4: The Satisfaction Levels of the Calicut Tile Users on their Roofing Material

making roof slabs popular.

The next question was on the preferred roofing materials of which the results are shown in Figure 3.7. Almost 75% of the responders preferred calicut tiles. Even though concrete slabs show a higher preference over asbestos sheets, it is less than 15% as a percentage. 1% of the responders have stated wood as their preferred material, which may be not so popular due to high initial cost and durability concerns.

Then it was worthwhile to find out the reason for their respective preferred material, for which the responses are shown in Figure 3.8. It clearly depicts that the comfort is the major concern of the occupants. The concerns of roughly a 25% of the occupants were the cost and aesthetics each.

Then the asbestos sheet users were further enquired on the reasons to not to go for a concrete slab. According to Figure 3.9, around 60% of the sample have stated that it is due to the thermal discomfort. A major portion of the rest has the high initial cost as a concern. The same question from calicut tile users has resulted more-or-less a similar result, having thermal discomfort as a major concern (See Figure 3.10).

The next step was to figure out the problems associated with roof slabs. There were two issues pointed out by the users: thermal discomfort and serviceability issues in the form of cracking (shown in Figure 3.11). It is noteworthy that thermal discomfort, as an issue, has a clear dominance over the other.

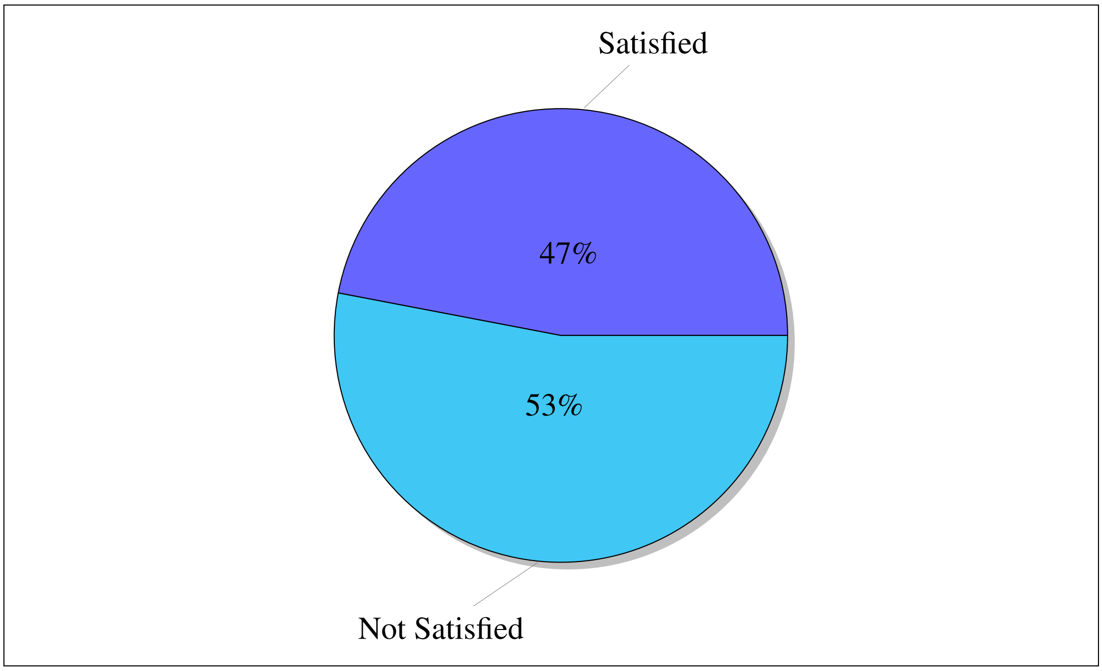


Figure 3.5: The Satisfaction Levels of the Asbestos Sheet Users on their Roofing Material

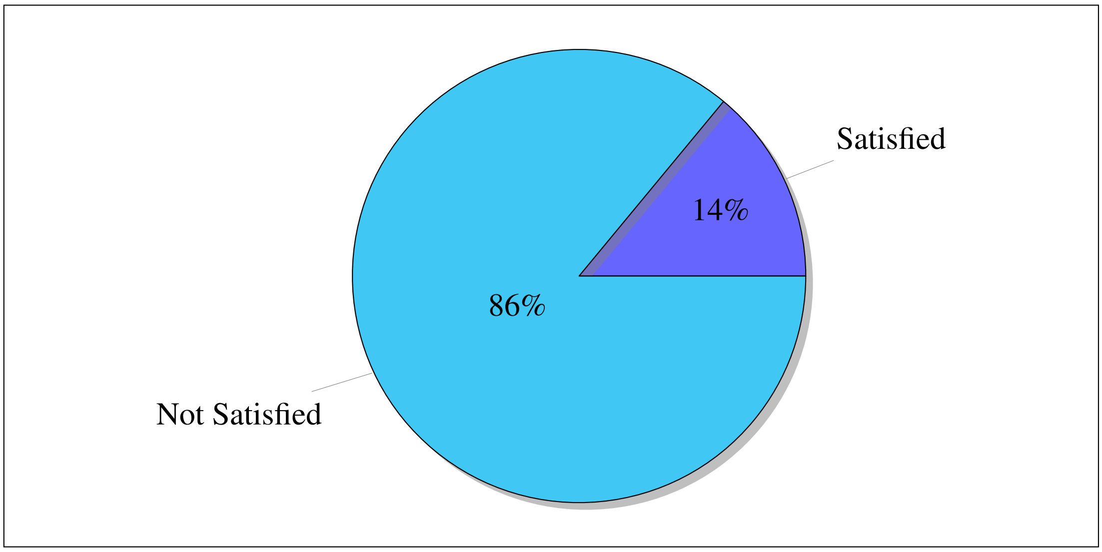


Figure 3.6: The Satisfaction Levels of the Concrete Slab Users on their Roofing Material

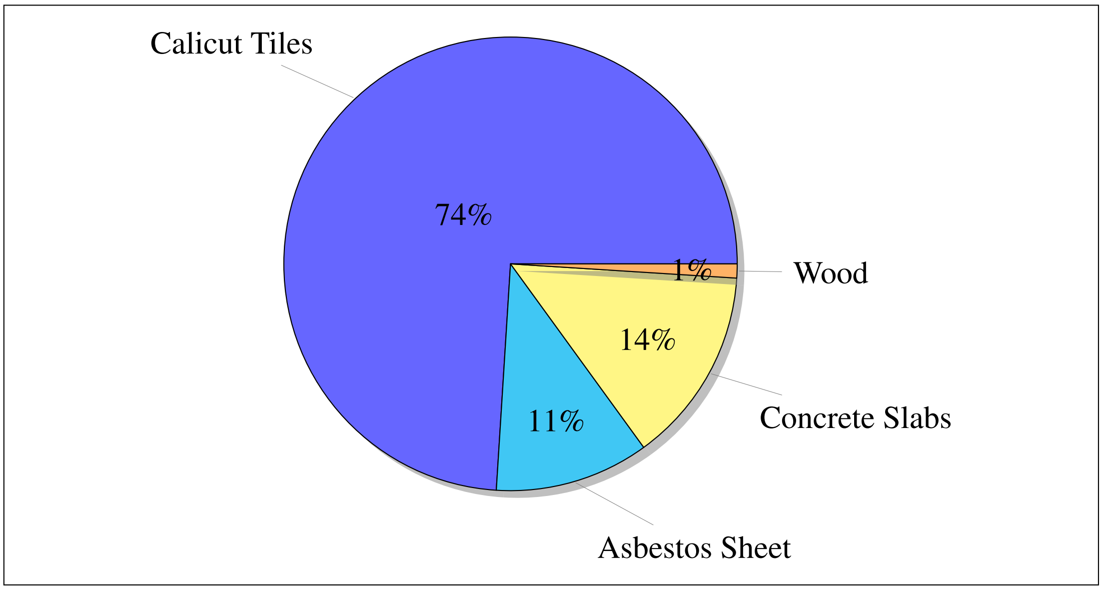


Figure 3.7: The Preferred Roofing Material of the Selected Sample

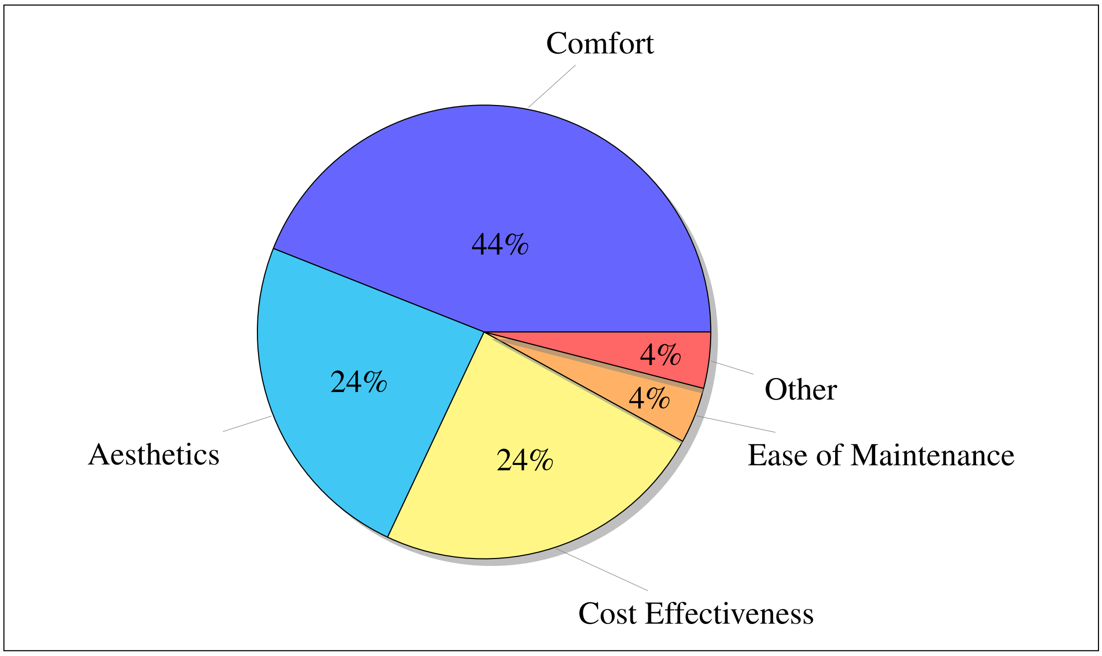


Figure 3.8: The Reasons Expressed to the Choice of Preferred Roofing Material

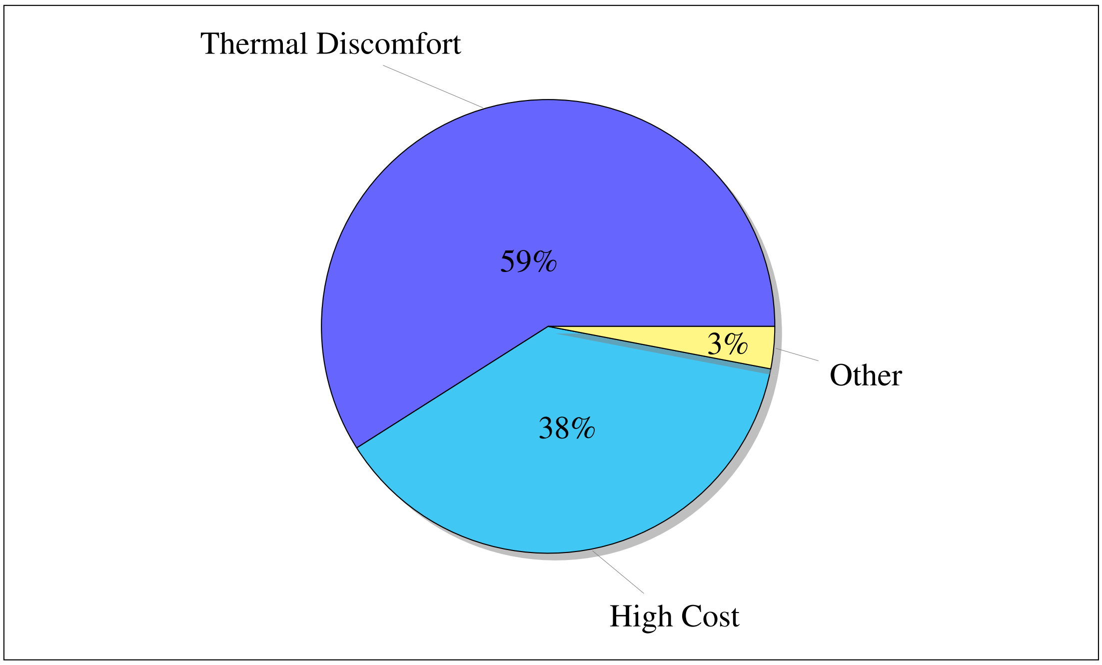


Figure 3.9: Users of Asbestos Sheets: Reasons for not Choosing a Concrete Slab as a Roof

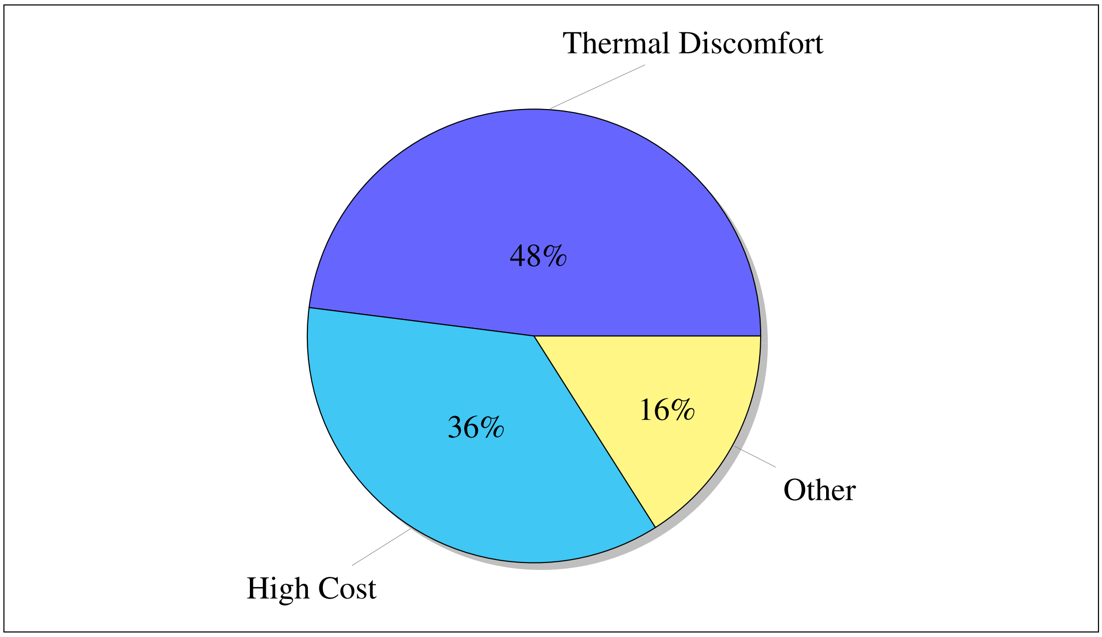


Figure 3.10: Users of calicut Tiles: Reasons for not Choosing a Concrete Slab as a Roof

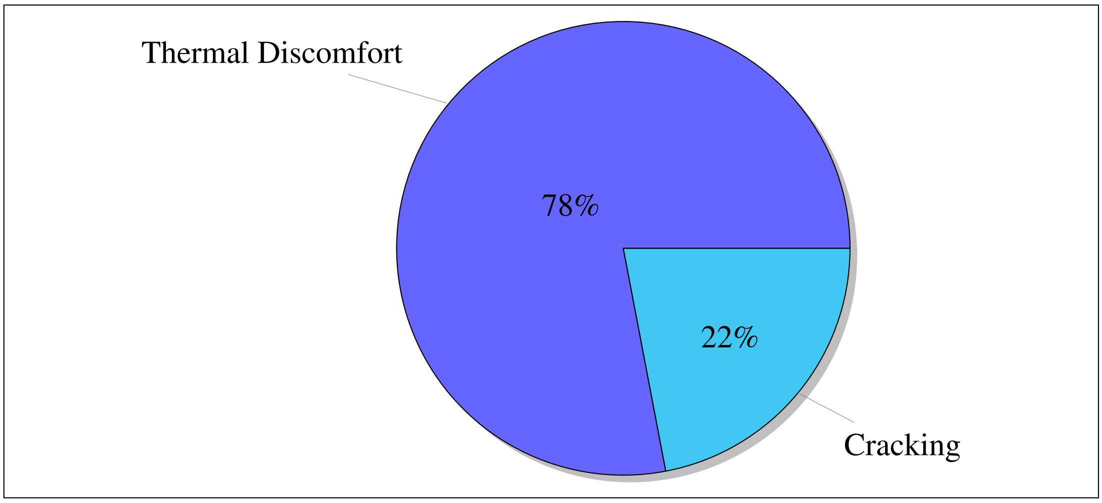


Figure 3.11: Users of Concrete Slabs: Issues Associated with Roof Slabs

One of the primary intentions of the main study is to reduce the energy usage while aiding the process of mitigating global warming. Hence, the remedies taken by the occupants when it is thermally uncomfortable were enquired to obtain an idea on the usage of energy with each type of roofing material.

Figure 3.12 shows that around 60% of the calicut tiled house owners only open their windows to make the indoor environment thermally comfortable. This does not affect the energy consumption of the building and is the most favourable action as far as the sustainability is concerned. A major proportion of the rest use fans, which is an active means of cooling, but much favourable than using Air-Conditioners. Conclusively, calicut tiled users do not consume much energy to make a thermally comfortable interior.

The results obtained for the same question of the asbestos-sheet-users is depicted in Figure 3.13. The results are similar to the calicut tile users, with a little bias towards active cooling.

In contrast, only one-third of the concrete roof slab users believes that opening the windows would solve the issue (See Figure 3.14). Almost 60% use active cooling techniques in the forms of fans and Air-conditioners. This supports our initial hypothesis that concrete roof slabs do increase the energy consumption for thermal comfort in buildings.

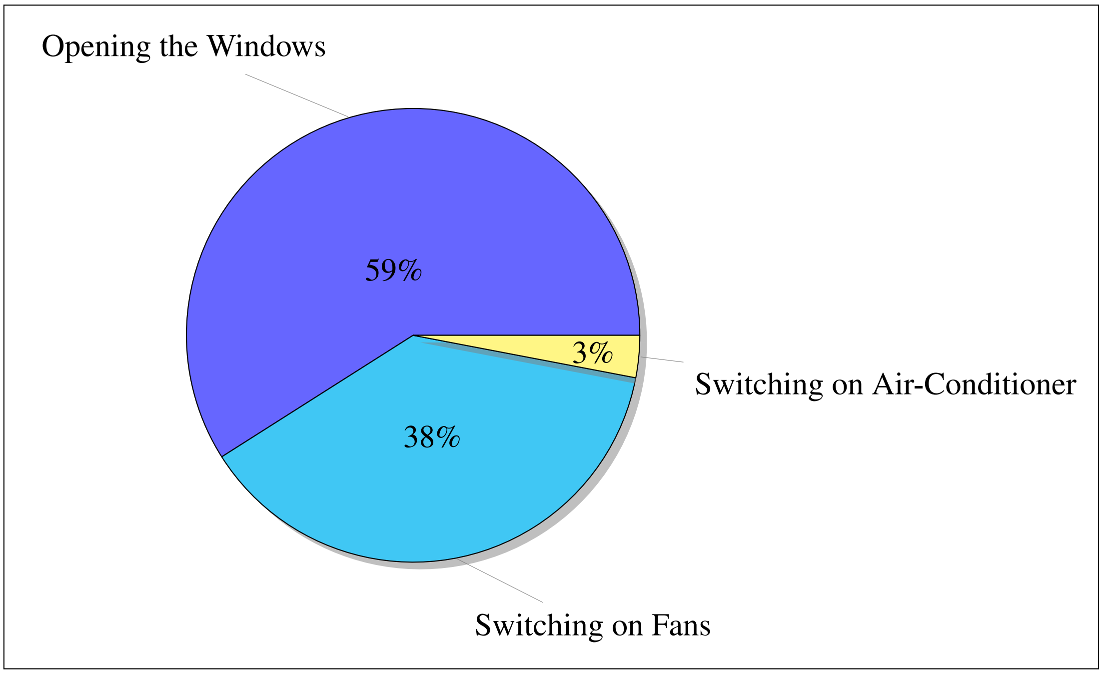


Figure 3.12: Actions for Thermal Discomfort of those who have calicut Tiles as the Roofing Material

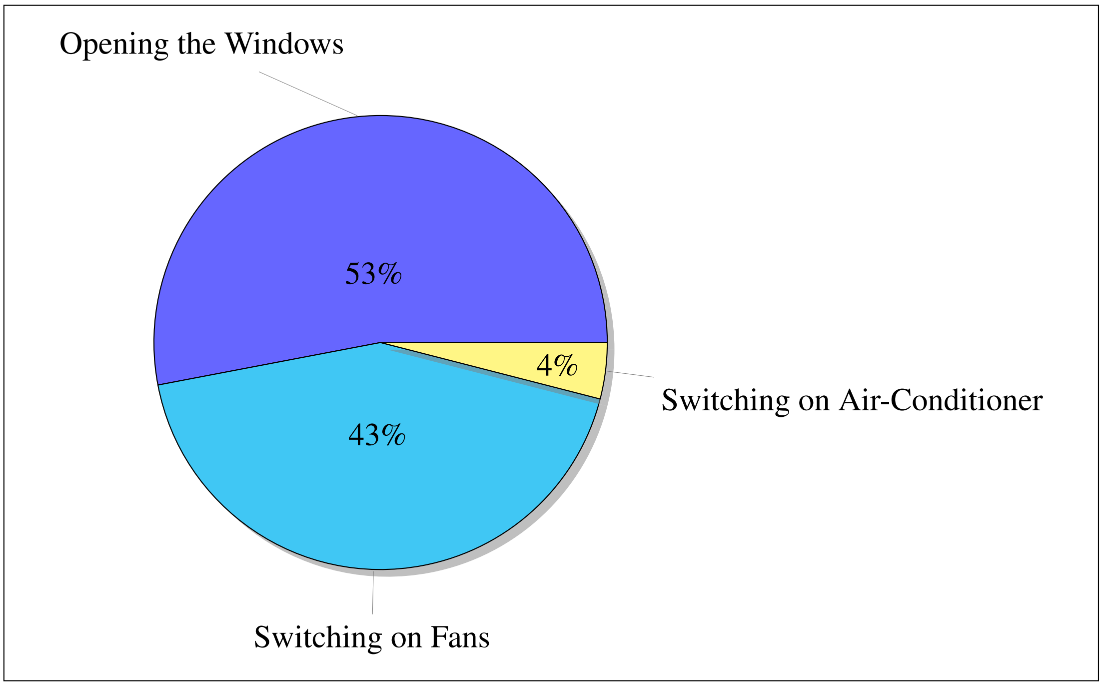


Figure 3.13: Actions for Thermal Discomfort of those who have Asbestos Sheets as Roofing Materials

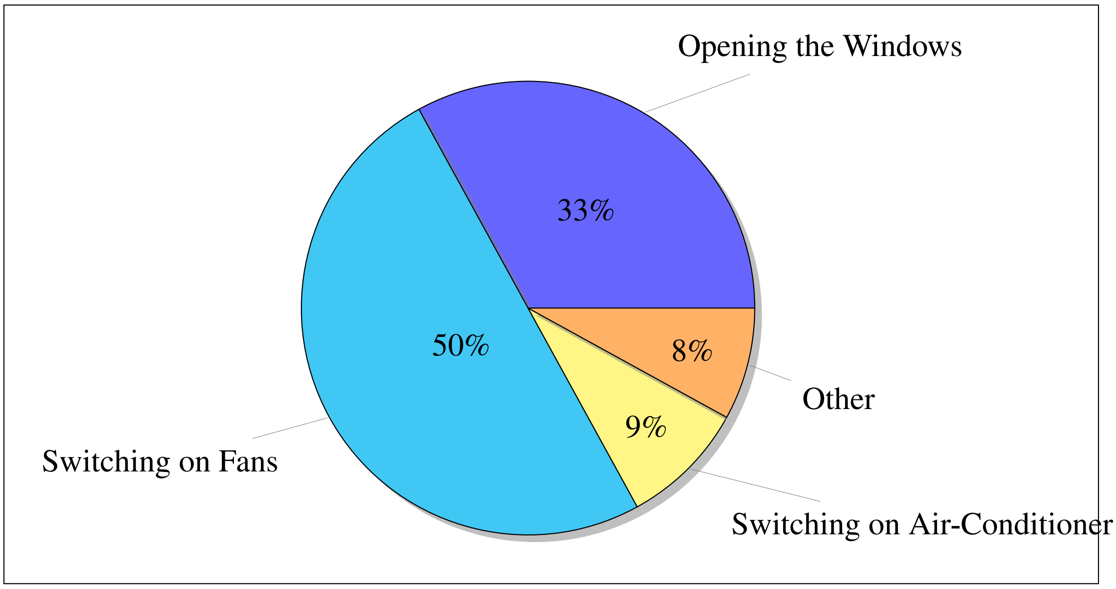


Figure 3.14: Actions for Thermal Discomfort of those who Concrete Roof Slabs

This result was verified by a quantitative analysis of the next question in the questionnaire survey, which is shown in Figure 3.15. The question was on the number of hours that they use fans per day and the results were analysed for each roofing material.

The responses clearly show that the majority of calicut tile users hardly use fans, whereas most of the asbestos sheet users use it for 1 - 3 hours. However, the concrete slab users use fans almost throughout the day that the occupy those spaces.

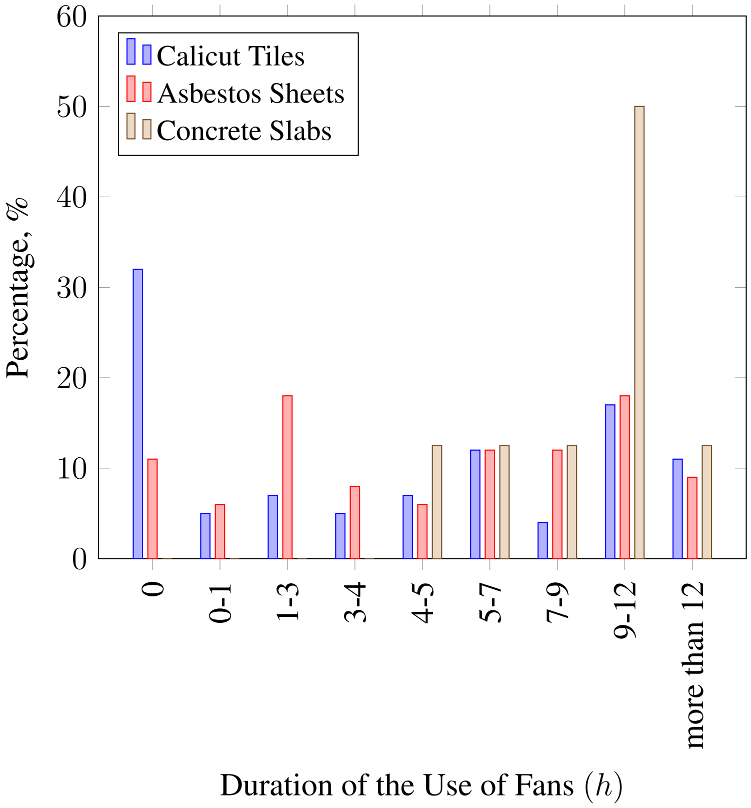


Figure 3.15: Durations that Fans are Used in Residences with Different Roofing Materials

3.4 Summary of the Questionnaire Survey

The major objective of carrying out a questionnaire survey was to find out the reasons for concrete roof slabs being not-so-popular among the general public and its effect on the energy consumption in buildings. The sub-objectives defined to achieve this was presented in Section 3.1.

The final remarks of the questionnaire survey performed can be enlisted as follows;

- Calicut tile users are satisfied with their roofing materials, whereas the users of asbestos sheets as a roofing material presented mixed responses. However, concrete slab users are unsatisfied with the roof's performance.
- Despite the roofing material they have, most of them prefer to have a calicut tiled roof.
- The thermal environment underneath the roof is the major reason pointed out by the responders for their preferred choice of roofing material. However, aesthetics and the initial cost have a significant influence as well.
- The thermal discomfort is the major reason pointed out by calicut tile users and asbestos sheet users as the major reason to not to go for concrete roof slabs.
- Further, thermal discomfort itself is the major issue associated with roof slabs, according to the occupants.
- Passive cooling seems sufficient for the buildings having calicut tile roofs and asbestos sheet roofs. However, concrete slabs demand active cooling to satisfy the comfort requirements.
- The buildings with either calicut tiles or asbestos sheets as the roofing material do not require a larger span of duration of active cooling. Meanwhile, the buildings with concrete slabs require continuous cooling when they are occupied.

Addressing the issue of thermal discomfort is the best way to make roof slabs more public.

Chapter 4

Structural Arrangement and Performance

4.1 General

Due to the extensive demand, urban land has become one of the most expensive commodities all around the world. Even though urbanisation is not favourable and has to be discouraged, its growth is not likely to be stopped in near future. Hence, the best option is to adapt to the changes occurred due to that.

Consequently, multi-storey construction has become popular as it provides a higher floor-area ratio, resulting an inevitable popularity of concrete floors. The current trend is to construct the roof too as a concrete slab itself as it results in an almost null effective land consumption for the buildings. Also, there are some other advantages of flat concrete roof slabs such as cyclonic resistance, the possibility of future vertical extension and the possibility of utilising as a rooftop garden.

Despite all those advantages, it is not as popular as it should be, mainly due to the thermal discomfort it possesses in the immediate underneath floor, as discussed in Chapter 3. Since active cooling in the form of fans and Air-Conditioners increase the energy consumption and contributes to global warming significantly, it has to be discouraged as far as sustainability is concerned.

As a result, there are numerous passive cooling techniques developed in the world,

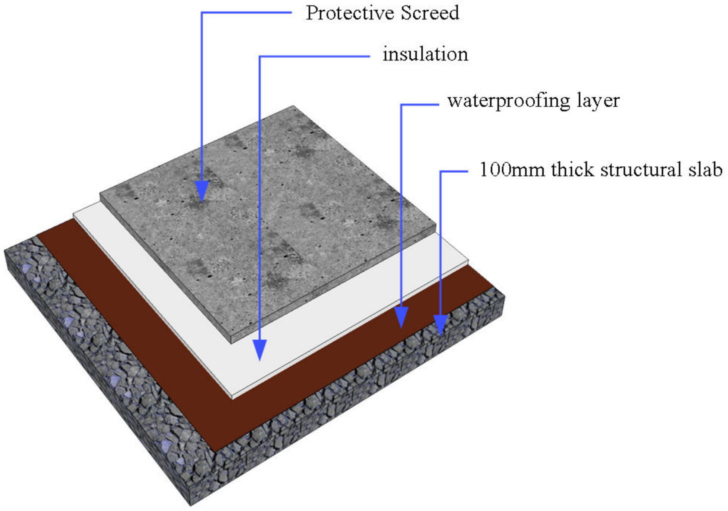


Figure 4.1: One of the Most Common Insulation Systems Used in Tropical Countries

and insulation is one of the most popular among them. Since roof is the element that is under consideration in this study, several roof insulation techniques were investigated and presented in Section 2.6.

One of the most commonly used systems in tropical conditions is shown in Figure 4.1. It has a low-conductive material on top of a waterproofed structural slab and a protective screed on top of it to protect that layer. This system has been tested under practical conditions and proven to be effective in thermal aspects.

Amid the thermal performance, the performance of this arrangement is in contrast to the initial objective of implementing a roof slab. The intended land recovery cannot be achieved with this system as it imposes a restriction of loading on the system, because that an insulation material which is not designed to carry load is sandwiched in the system and the load has to pass through it. Hence, the entire system has been categorised as structurally unsound.

As a remedy, a system has been developed with a supporting arrangement within the insulation layer, of which a perspective view of this system is shown in Figure 4.2 (Halwatura & Jayasinghe, 2008). This system maintains the same basic structure as the system illustrated in Figure 4.1, but with a few alterations. A set of concrete strips has been introduced into the system within the insulation layer to take the load acting on the roof. Further, the protective concrete layer has been reinforced by a layer of

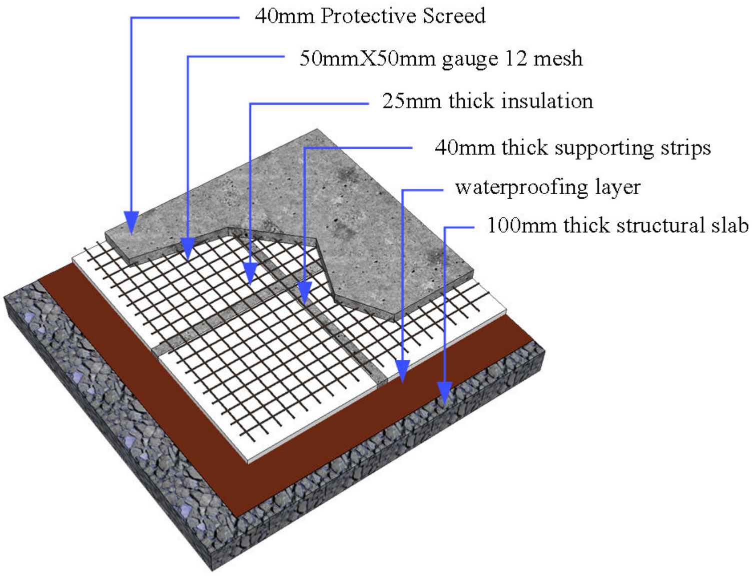


Figure 4.2: The System with Continuous Concrete Strips
(Halwatura & Jayasinghe, 2008)

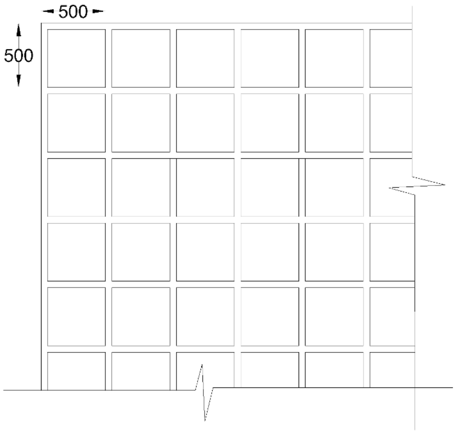
$50mm \times 50mm$ steel net of gauge 12.

This system too has been implemented and tested practically, and proven to be effective enough to be utilised regarding thermal and structural aspects. The structural arrangement is strong sufficiently to take an imposed load of $5kN/m^2$ (which is the maximum practical value specified for a roof), and in thermal aspects, a 75%-heat flow reduction has been achieved (Halwatura & Jayasinghe, 2008).

Nevertheless, this system was observed to have a durability concern as some water patches were found in slab-soffits in the long run. A thorough study resulted in finding that water is stagnant in the pores of the insulation material. This phenomenon can be elaborated as follows;

The plan view of the supporting arrangement of this system is shown in Figure 4.3. If water is passed through the top concrete layer, it fills up in the pores of the insulation layer. Thereafter, there's no path for it to flow out as the insulation material is covered by a set of concrete strips. Gradually, a water head is developed, reducing the effectiveness and the lifespan of the waterproofing layer drastically.

In this study, it was intended to develop a system which is thermally effective, structurally sound and durable.



(Dimensions are in Millimetres.)

Figure 4.3: The Plan View of the Supporting Arrangement of the System with Continuous Concrete Strips

4.2 Methodology

4.2.1 General

As it has been reiterated, durability is the major concern in the existing system drawn up by Halwatura and Jayasinghe. Providing a drainage path in the insulation layer has been identified as the obvious remedy.

Further, this new system developed was intended to be structurally sound, with the ability of carrying any practical load applied on that. The requirement was defined as that the system should be able to carry an imposed of $5kN/m^2$ as it is the maximum specified in BS6399 Part 1:1996 (Code of Practise for Dead and Imposed Loads) (British Standards Institution, 1996).

Since the protective concrete layer was to be designed as a load-bearing slab itself, different reinforcing arrangements were tried out. After an initial trial analysis, hogging bending moment has been identified as the critical parameter. First, the moment carrying capacity for each reinforcing arrangement was calculated as mentioned in Section 4.2.2, then the moments due to the applied loads were calculated by computer simulations (elaborated in Section 4.3). The optimum arrangement was finalised by minimising the concrete area in the insulation layer.

4.2.2 Finding the Moment Capacity

BS 8110 Part 1 (Structural Use of Concrete: Code of Practise for Design and Construction) (British Standards Institution, 1997), was used as the referring document in this process. Equation 4.1 was used to calculate the lever arm of the elements of which the constant $'K'$ was taken to be 0.156 since no redistribution was considered (British Standards Institution, 1997).

A reverse calculation of Equation 4.2 was used to calculate the bending moment capacity for each of the reinforcing arrangement considered ($M = 0.95 \times A_s \times f_y \times Z$). As it has been mentioned earlier, only hogging bending moments the slab for each case was considered as it was the critical parameter.

$$Z = d\left(0.5 + \sqrt{0.25 - \frac{K}{0.9}}\right) \tag{4.1}$$

$$A_s = \frac{M}{0.95 f_y Z} \tag{4.2}$$

Where,

Z = Lever Arm

d = Effective Depth

K = A Constant Based on the Degree of Redistribution Used

M = Corresponding Bending Moment

f_y = Tensile Strength of Reinforcement Used

4.2.3 The optimisation Process

Step 1: Removing Strips in One Direction

Providing a proper drainage path is the major intention of this process as it was the issue to be addressed in the system with continuous concrete strips. As the first option, a drainage path in one direction was tried out by removing strips in one direction. A typical plan view of this supporting arrangement is shown in Figure 4.4.

In this context, there were four variables to be considered;

1. An optimum spacing between strips
2. A suitable width of the strips
3. Strength and a mix proportion of the concrete to be used
4. A Reinforcing arrangement in the protective concrete layer

The first variable was the spacing between strips. The system could structurally fail if the strips are placed too far apart to each other, and the thermal performance could be adversely affected if they were placed too closer to each other.

A suitable size of the strips was to be determined. The area of concrete was to be minimised to obtain the maximum thermal effectiveness of the system. Meanwhile, it had to be made sure that the selected size of the strips could withstand the target load on that.

The concrete used was supposed to be compacted within an area of $40mm$ thick layer. Hence, it was decided to use a concrete with lower maximum aggregate size (chip-concrete). However, the protective concrete layer was to be designed as a load-bearing slab itself. Therefore, a mix design was performed to obtain the required strength.

The last of the variables mentioned was the reinforcing arrangement. The bottom reinforcement was fixed to be a $50mm \times 50mm$ gauge 12 mesh, considering the convenience in construction. Four options were considered for the top reinforcing arrangement: no top reinforcement, 6mm mild steel bars near supports, 10mm tor steel bars near supports and a $50mm \times 50mm$ mesh (double nets). Then the optimum arrangement was found by the results obtained from the computer simulations.

Step 2: Discontinuing the Strips in Longitudinal Direction

After finalising the above system, it was further optimised by varying the spacing between strips while discontinuing them in their longitudinal direction as well. A

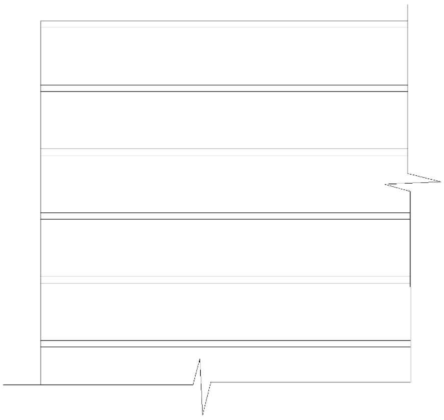


Figure 4.4: A Typical Plan View of the Supporting Arrangement after Removing strips in One Direction

typical plan view of this arrangement is shown in Figure 4.5. Three more variables were to be finalised in further analysis of this case;

1. Spacing between the strips (Number 1 in Figure 4.5)
2. Longitudinal spacing between the supports (Number 2 in Figure 4.5)
3. Length of the supports (Number 3 in Figure 4.5)

Several finite element models were developed by varying the above variables, and optimum arrangements for each spacing between strips were found out.

Then the system with a minimum concrete area within the insulation layer was selected as the best arrangement.

A graphical elaboration on the process followed to optimise the system is depicted in Figure 4.6.

Step 3: Flat Slab Arrangement

When the supporting strips are discontinued in the longitudinal direction, some stress concentrations were observed on two ends of supports as it can be seen in Figure 4.7. When the lengths of the supports are reduced gradually, these concentrations become almost concentric. In this case, this acts as a flat slab. Since the design of such a scenario uses a different methodology, this case was analysed separately.

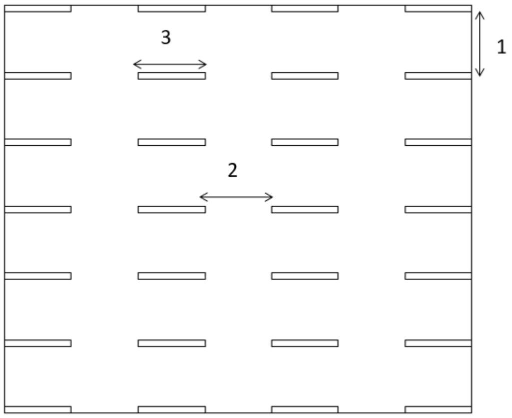


Figure 4.5: Variables to be Considered in Optimising the Strips in Longitudinal Direction

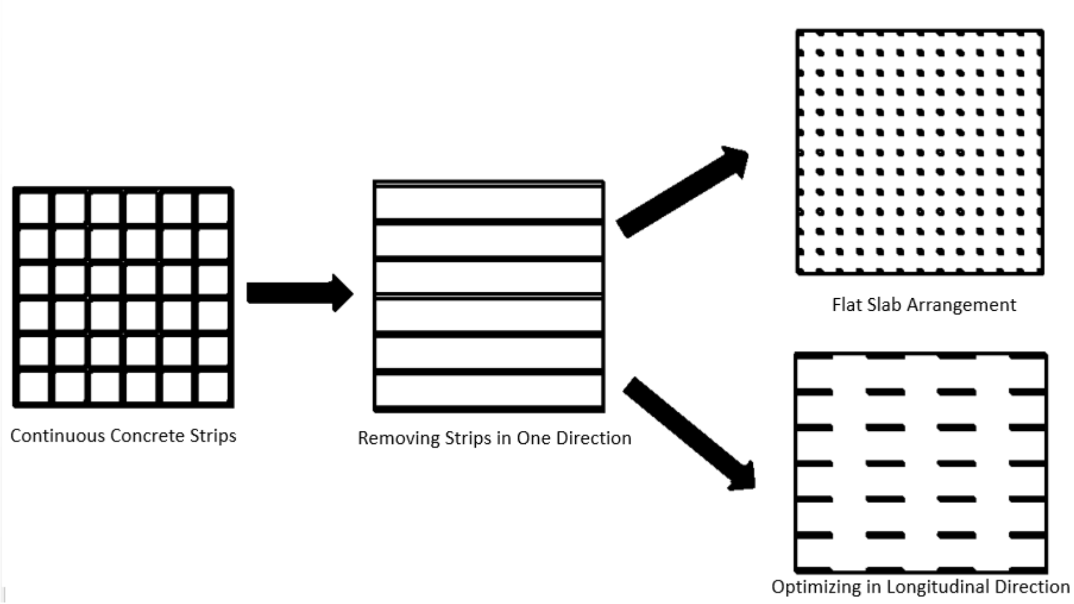


Figure 4.6: The Process Followed to Optimise the System

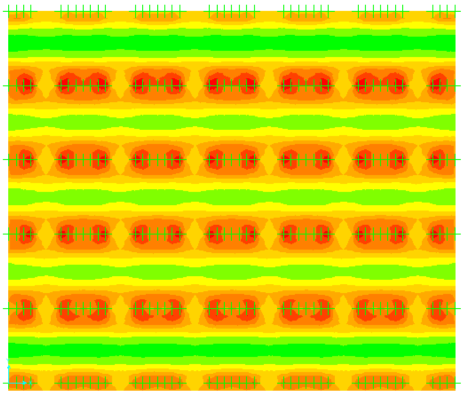


Figure 4.7: A Typical Bending Moment Diagram for an Arrangement of Discontinuous Supports

4.3 Results Obtained by Numerical Modelling

4.3.1 Step 1: Removing Strips in One Direction

In this case, a drainage path was provided in the system by removing strips in one direction from the system developed by Halwatura and Jayasinghe. There were four variables to be finalised as mentioned in Section 4.2.3.

Hence, the width of the strips was fixed to $50mm$, and the concrete used was assumed to have a strength of $15N/mm^2$ in initial trial calculations. Then the optimum spacing was found out by computer simulations for four reinforcing arrangements mentioned in Section 4.2.3.

A typical model developed by SAP2000 is shown in Figure 4.8. The moment resistance capacity was calculated by the procedure mentioned in Section 4.2.2.

The obtained results are shown in Figure 4.9. It indicates that the strip spacing can be increased significantly if some form of top reinforcement is provided. However, providing two layers of reinforcement within a 40mm thick concrete layer is not economical and inconvenient in construction.

Nevertheless, Figure 4.9 further shows that the system can be implemented without a top reinforcement layer if the strips are spaced at less than $540mm$. Hence, it was used for further analysis.

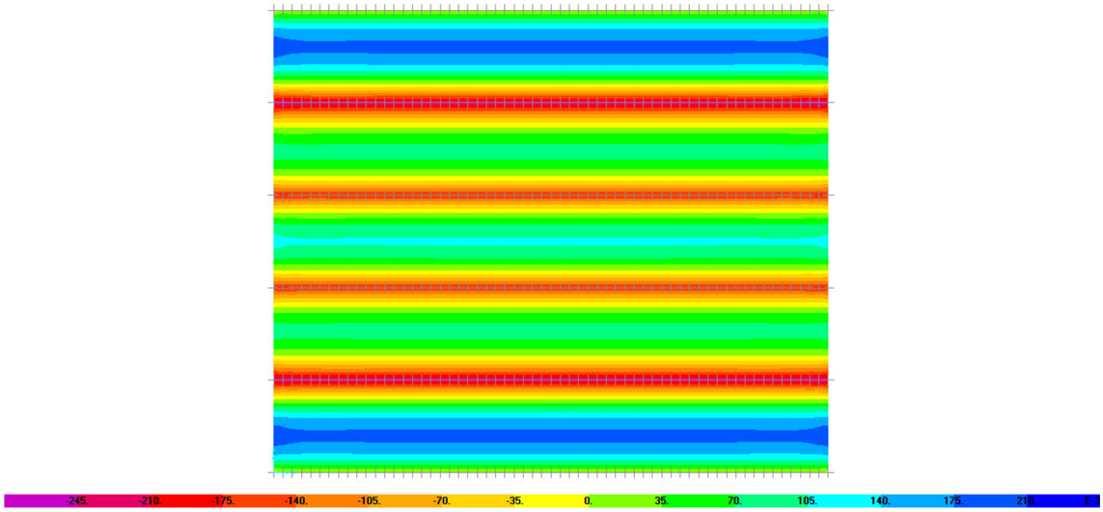


Figure 4.8: A Typical Model Obtained by Computer Simulations with Strips Only in One Direction

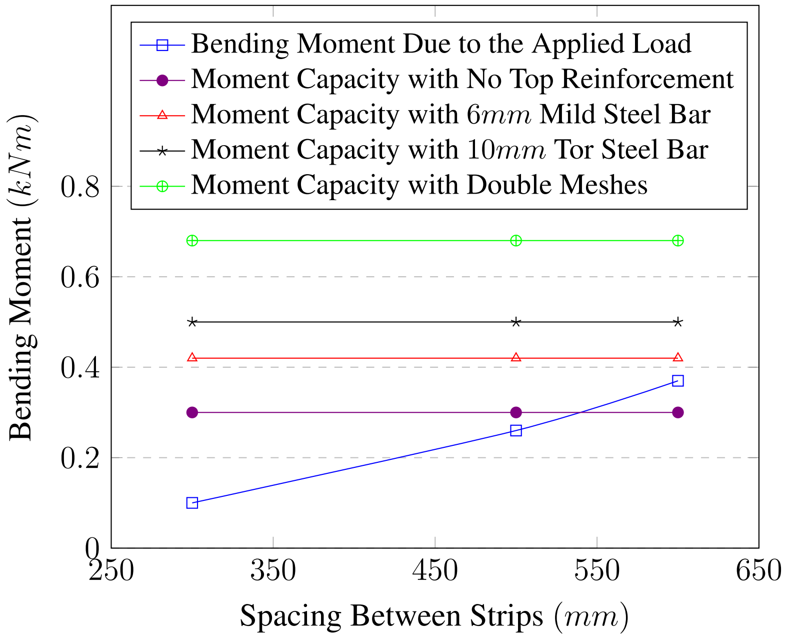


Figure 4.9: Actual Bending Moments and Moment Capacities of Different Reinforcing Arrangements When the Strips in One Direction is Removed

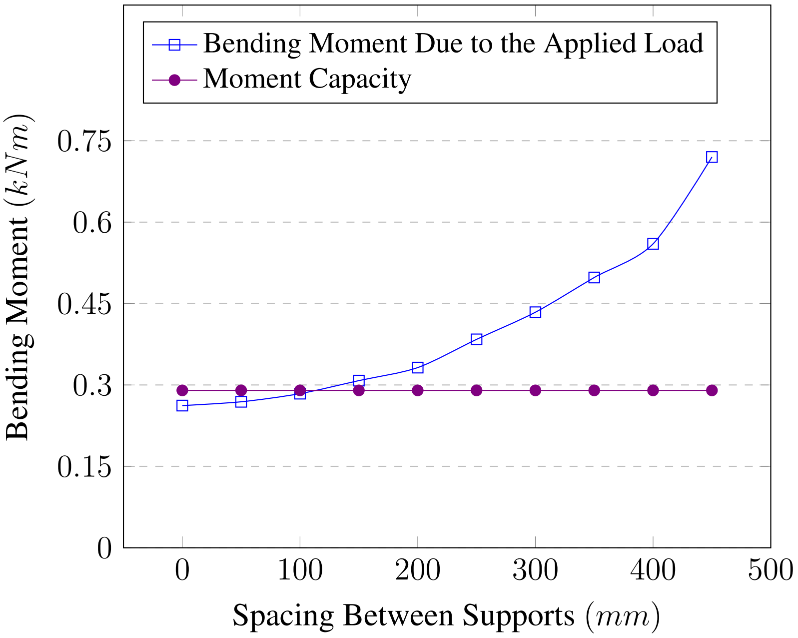


Figure 4.10: Bending Moments and Moment Capacities of the Protective Concrete Layer for a Discontinued Strip Arrangement with a Strip Spacing of 500mm

4.3.2 Step 2: Discontinuing the Strips

The next phase of the optimisation process is to discontinue the strips in their longitudinal direction as well. Several options were considered by varying the spacing of the strips (shown as number ‘1’ in Figure 4.5.

Since it was determined that it was possible to construct the system without any top reinforcement, the discontinuation process was started by a spacing of $500mm$ (less than $540mm$, which is the maximum spacing of strips without discontinuing).

Initially, the support length (number ‘3’ in Figure 4.5) was also fixed at $500mm$, then the clear spacing between the supports (number ‘2’ in Figure 4.5) was varied. Then the moment capacity was calculated by the method described in Section 4.2.2.

The obtained results, in this case, are shown in Figure 4.10. It reveals that supports can be spaced at $100mm$ to withstand the applied moment.

Then it was tried to finalise a suitable length of supports for this obtained spacing of $100mm$. Several computer models were developed by varying this variable. The results achieved in this process is shown in Figure 4.11. It indicates that a $150mm$ length of supports would marginally satisfy the requirement. However, it is

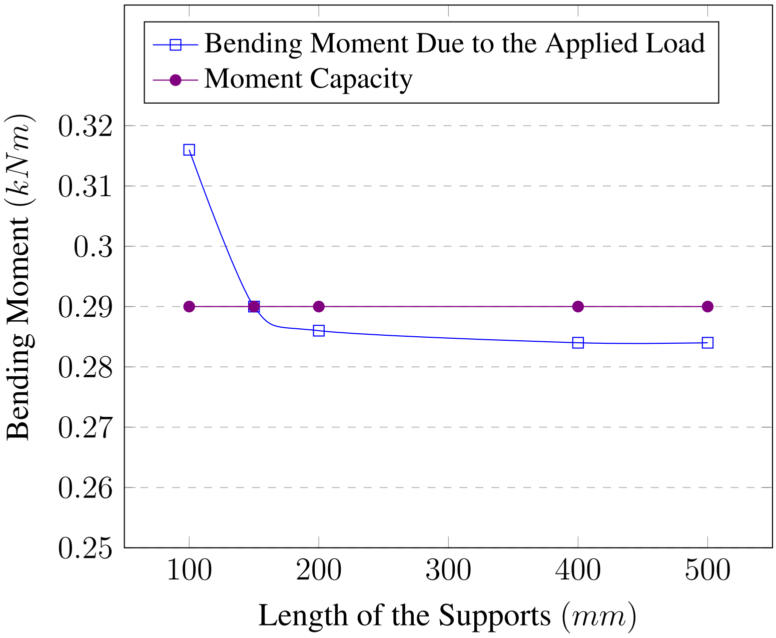


Figure 4.11: Bending Moments and Moment Capacities of the Protective Concrete Layer for a Discontinued Strip Arrangement with a Strip Spacing of 500mm for Different Support Lengths when the Clear Spacing between them is $100mm$

recommended to use a strip length of $200mm$ considering the safety aspects.

The same procedure was adapted for strip spacings of $300mm$ and $400mm$. The optimum systems for each of those spacings are shown in Table 4.1.

4.3.3 Step 3: Flat Slab Arrangement

When the length of the supports is reduced, the top protective concrete layer acts as a flat slab. Since the analysis and design procedure, in this case, is different from a

Table 4.1: The Optimum Arrangements for Each Strip-Spacing Considered

Span in Transverse Direction (mm) (‘1’ in Figure 4.5)	**Clear Spacing Between Strips (mm)** (‘2’ in Figure 4.5)	**Length of the Strips (mm)** (‘3’ in Figure 4.5)
300	400	300
400	300	300
500	100	200

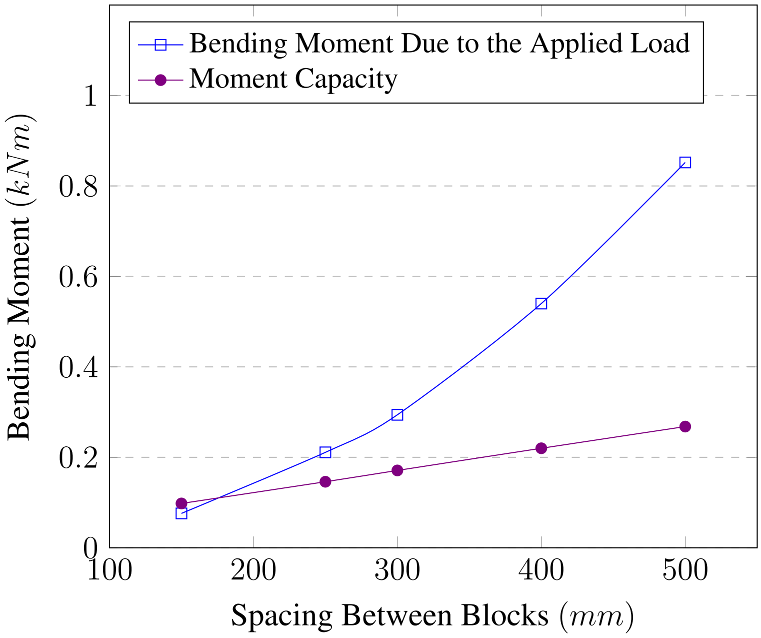


Figure 4.12: Bending Moments and Moment Capacities of the Protective Screed with a $50mm \times 50mm$ Gauge 12 Mesh for a Flat Slab Arrangement with Different Support Spacings

typical slab, this case was taken separately.

The actual bending moments due to applied load and the moment capacities for various arrangements are shown in Figure 4.12. (Even though the analysis was performed for different reinforcing arrangements, only the ’no top reinforcement’ case is presented here since it is the desired arrangement.) It shows that the system could withstand if the blocks are spaced $150mm$ in both directions.

4.4 Selecting a Suitable Width

The next step was to find an optimum width of the strips. The provided width should be able to carry the corresponding load applied on it, and in the meantime, should not be a larger value as it increases the concrete area in the insulation layer.

Since the height of the supporting strips is small on the length, the buckling failure was ruled out. Hence, the minimum width required was calculated by a simple compressive strength calculation. The results obtained are as shown in Table 4.2. In that, the effective area per strip according to each arrangement was found out. Then,

Table 4.2: Calculations for Finding Minimum Width of Strips

Calculation	**300 mm spacing between strips**	**400 mm spacing between strips**	**500 mm spacing between strips**	**Flat Slab Arrangement**
Effective Area (m^2)	0.21	0.24	0.15	0.04
Dead Load (kN)	0.21	0.24	0.15	0.04
Live Load (kN)	1.05	1.20	0.75	0.20
Design Load (kN)	1.97	2.26	1.41	0.38
Minimum Area of Support (mm^2)	131	150	94	25
Minimum Required Width (mm)	0.44	0.50	0.47	5.00

the dead load and live load applied on a strip was calculated. The design load was calculated using the partial factors of safety specified in BS 8110 Part 1 (British Standards Institution, 1997). The dead loads were multiplied by 1.4, and the live loads by 1.6.

Then the minimum area of the support required was calculated assuming that the strength of concrete to be $15N/mm^2$. Finally, the optimum width was calculated since the lengths of the supports were known by this stage.

According to the Table 4.2, a minute width is sufficient to carry the load applied on it. However, this concrete should be able to be compacted in this area. Hence, a width of $25mm$ was selected since chip-concrete is used.

4.5 Selecting the Optimum Arrangement

At this stage, there were four systems short-listed as described in Section 4.3. The initial objective was to develop a system which is structurally sound and durable. Those short-listed systems were developed by considering the structural aspects, and they all have been incorporated with a drainage path that takes care of the durability.

The next step was to single out a system among them. The insulation layer is

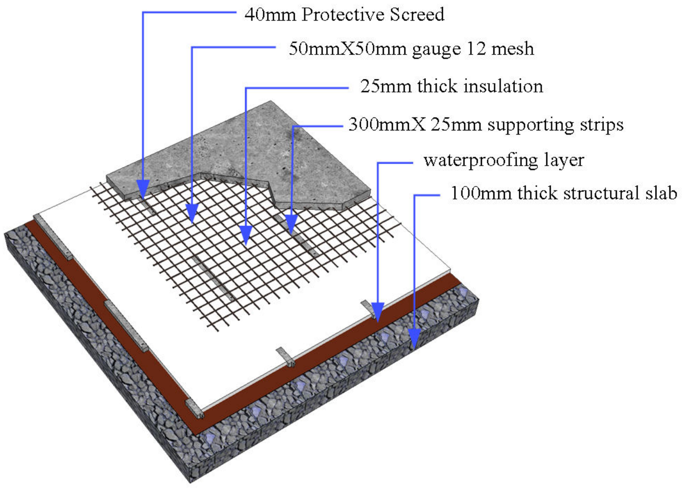


Figure 4.13: Isometric View of the Selected System
(Nandapala & Halwatura, 2016)

bridged by a set of concrete strips in these systems. These strips affect adversely to the thermal performance of the system since the heat conducted through concrete is far higher than that of the insulation material.

Hence, the concrete area has to be reduced as much as possible to obtain a better thermal performance. Table 4.3 shows the calculation of the concrete area of an approximate area of $100m^2$. The same calculation was performed for the existing system by Halwatura and Jayasinghe and presented in the table for comparison purpose (Halwatura & Jayasinghe, 2008).

Table 4.3 shows that all the short-listed systems in this study have far small concrete areas than the existing system. However, since the option with $400mm$ - strips has the lowest percentage, it was selected for further analysis.

An isometric view of the selected system is shown in Figure 4.13.

4.6 Selecting a Suitable Concrete Mix

The strength of the concrete was assumed to be $15N/mm^2$ thus far. Since that particular strength was proven to be adequate for this system, a suitable proportioning was to be found out.

A mix design calculation was performed according to the procedure explained in

Table 4.3: Calculations for Finding Minimum Width of Strips

Calculation	**300 mm Spacing**	**400 mm Spacing**	**500 mm Spacing**	**Flat Slab**	**Existing System (Halwatura & Jayasinghe, 2008)**
Concrete Area (m^2)	3.71	3.51	3.57	5.61	16.16
Total Area (m^2)	97.5	105.5	101.5	99.0	100.8
Concrete Ratio	3.8%	3.3%	3.5%	5.7%	16.0%

BRE concrete mix design method. Several options were considered by fixing water-cement ratio in different values. The results are presented in Table 4.4. (Please see Appendix B for the detailed calculations.)

Compressive strength testing was performed to check whether those mixes achieve the target strength. Further, considering the durability, the minimum average strength requirement was fixed to $25N/mm^2$. According to the results presented in Table 4.5, all the tested mixes have achieved the required strength.

The next step was to find out a suitable volume proportion to be used in practical constructions. Volume proportioning was calculated by assuming the bulk density of cement to be $1440kg/m^3$ and that of sand and metal to be $1600kg/m^3$. The results are shown in Table 4.6.

In that, the mix with 0.7 water-cement ratio closely associates with 1:2:3 cement:sand:metal ratio and that of the mix with 0.6 water-cement ratio is approximately 2:3:5. However, since this concrete has to be compacted well in a small area, the mix with higher workability (the mix with 0.7 water-cement ratio) was selected as the mix to be used. (It had a strength of more than $25N/mm^2$ too.)

Table 4.4: Weights of Each Material as per the Mix Design Calculations Performed for Different Water-Cement Ratios for $1m^3$ of Concrete

W/C Ratio	**Cement** (kg)	**Sand** (kg)	**Metal** (kg)	**Water** (kg)
0.78	299	790	1048	233
0.75	311	767	1059	233
0.70	333	722	1082	233
0.65	358	694	1085	233
0.60	388	647	1102	233

Table 4.5: Mix Design Options Tested by Varying Water-Cement Ratio

W/C Ratio	**Cube No.**	**Crushing Load (kN)**	**Size of the Block**	**Strength (N/mm^2)**	**Average Strength (N/mm^2)**
0.78	1	517.8	150 x 153	22.56	22.48
	2	530.4	148 x 151	23.73	
	3	478.3	155 x 146	21.14	
0.75	1	506.3	150 x 151	22.35	23.78
	2	526.7	151 x 149	23.41	
	3	594.7	155 x 150	25.58	
0.70	1	478.8	150 x 153	25.86	25.63
	2	562.5	148 x 147	25.85	
	3	551.5	150 x 146	25.18	
0.65	1	536.4	150 x 150	25.84	25.40
	2	567.2	148 x 146	26.25	
	3	599.5	153 x 150	26.12	
0.60	1	683.4	150 x 153	29.78	27.63
	2	589.1	149 x 151	26.18	
	3	609.3	155 x 146	26.92	

Table 4.6: Volume Proportions of the Different Mixes Tested in Table 4.4

W/C Ratio	Cement	Sand	Metal
0.78	1	2.382	3.157
0.75	1	2.222	3.069
0.70	1	1.951	2.927
0.65	1	1.742	2.724
0.60	1	1.500	2.553

4.7 Physical Model Testing

Results of the values obtained by computer simulations were needed to be verified. In other words, it had to be proven that this selected system is robust enough to carry the applied load, by a physical model testing.

The system was loaded with a calibrated proving ring to measure the applied load, and the deflection was measured with a dial gauge. The experimental setup used is shown in Figure 4.14. Both the readings were continuously taken down till the system failed. The obtained load-deflection curve is shown in Figure 4.15.

The graph in Figure 4.15 shows that the system can be loaded up to about 30 kN without cracking, and the system can be loaded up to 37 kN without failing structurally. This value is higher than any practical load specified in BS 6399-1: 1996 (British Standards Institution, 1996). Therefore, it is proven that this system is structurally sound.

Even though the deflection showed higher values, it was observed that the top screed sags independently without affecting the structural slab. Hence, it was not considered as a serviceability failure of the system.

Figure 4.14: Experimental Setup of the Actual Scale Testing

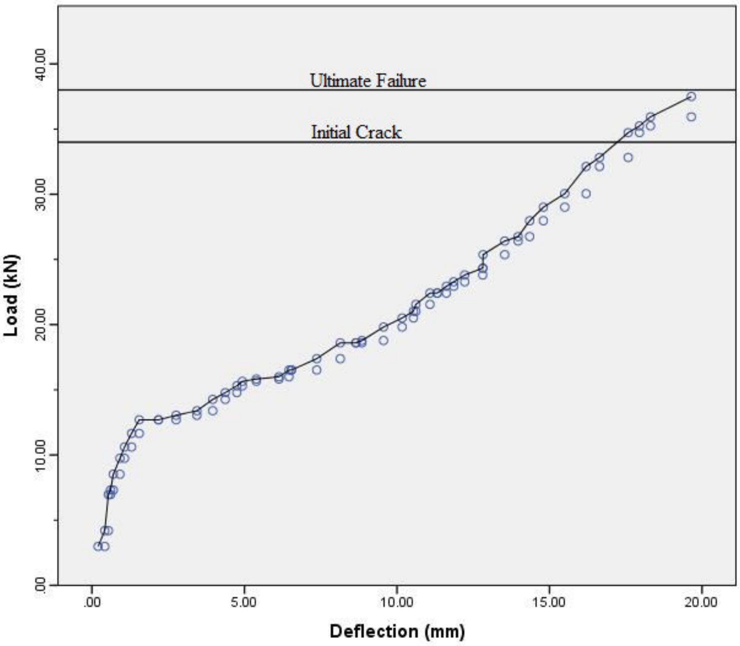


Figure 4.15: The Graph of Load Vs. Deflection Obtained by Actual Scale Testing

4.8 Summary of Structural Arrangement and Performance

Using flat slabs as roofs has many advantages like resistance to natural disasters of which the intensity and the severity increase day-by-day as a result of the climate change in the world. However, it increases the thermal discomfort in the uppermost floor as the slab acts as a heated body and emits long-wave radiation to the immediate space underneath. Mechanical cooling is the most common remedy used in the industry, but it increases the energy consumption which is not favourable for a sustainable world.

In this context, insulation of slabs has gained the popularity among the researchers in the modern world. There are many such techniques developed in the world, of those the most efficient method for tropics was selected. A field study was carried out to identify the performance of the system. It was noted that this system has an issue of durability.

The system was further investigated to find out the reason, and an improved system was developed with a minimum concrete area and a proper drainage path. It has been discovered that 300 mm x 25 mm strips with 300 mm clear span, and a transverse spacing of 400 mm is structurally sound to carry any possible load on a roof.

A mix design was performed to obtain the required strength out of chip concrete and 1:2:3 volume proportion of cement, sand and metal with a water/cement ratio of 0.7 was found to be suitable to be used in the system.

Chapter 5

Thermal Performance of the System

5.1 General

Roof slab insulation has been identified as one of the better passive ways of addressing the issue of thermal discomfort associated with roof slabs, as mentioned in Section 2.5. Several roof slab insulation systems have been developed in the world and observed to be fruitful in thermal performance. A quantitative analysis on this is depicted in Table 2.1.

In this study, the most recent system developed in tropical climatic conditions was selected and its drawbacks have been identified. Then, those drawbacks have been addressed while trying to improve the thermal performance.

The existing system with continuous supporting strips by Halwatura and Jayasinghe is shown in Figure 5.1. It had been proven that this system provides a heat gain reduction of 75% (Halwatura & Jayasinghe, 2008). However, since this system had a durability issue, a new system was developed by providing a drainage path and optimising it as described in Chapter 4. The finalised system is shown in Figure 5.2.

This chapter contains an analysis and a comparison of the thermal performance of the newly developed system.

Four types of systems were selected for comparison purposes.

- A control system

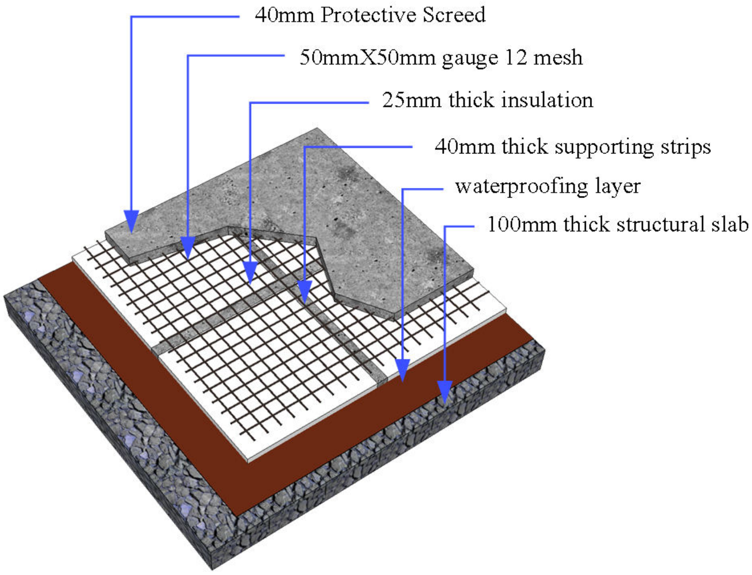


Figure 5.1: The System with Continuous Concrete Strips (Halwatura & Jayasinghe, 2008)

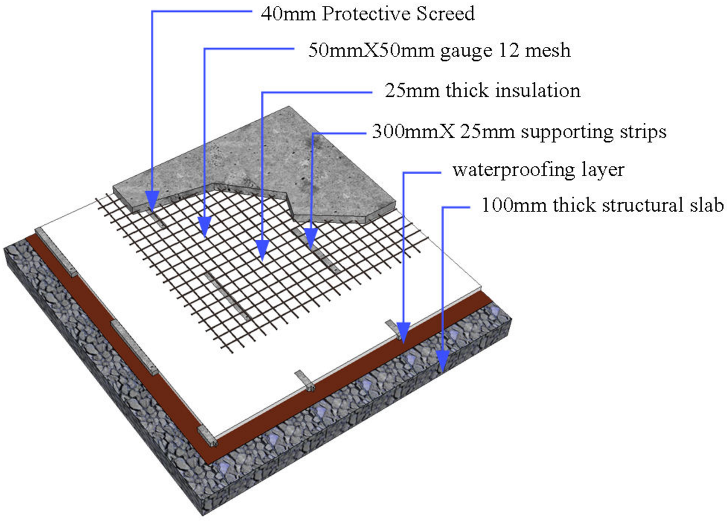


Figure 5.2: Isometric View of the Newly Developed System

- The existing system with continuous strips developed by Halwatura and Jayasinghe (shown in Figure 5.1)
- A system with continuous insulation (without any supporting arrangement)
- The newly designed system (shown in Figure 5.2)

The control system was used to obtain an idea on the total heat gain reduction that can be achieved by insulation.

The system without any supporting arrangement is commonly practised in the industry. However, this has an issue of structural capacity (described in Section 4.1). This system was considered to obtain an idea of the effect of concrete strips within insulation, to the thermal performance of the system.

The analysis was performed in three different perspectives.

- Theoretical analysis
- Physical model testing
- Numerical modelling

5.2 Theoretical Analysis of Thermal Performance

The theoretical analysis on thermal performance was carried out based on the values obtained in literature (Halwatura & Jayasinghe, 2009), and the calculations performed for the arrangements above. In this section, it is intended to find the composite thermal conductivities of each of the systems mentioned in Section 5.1, and to see the theoretical values the heat gain reductions.

In these cases, heat is flown across the slab as shown in Figure 5.3. Hence, these systems (other than the control system) can be considered to have three layers in series.

However, the insulation layer is not made out of a homogeneous material, since it is bridged by a set of concrete supports. Therefore, a composite conductivity for the insulation was to be found out. This calculation was performed using equation 5.1 (Progelhof, Throne, & Ruetsch, 1976).

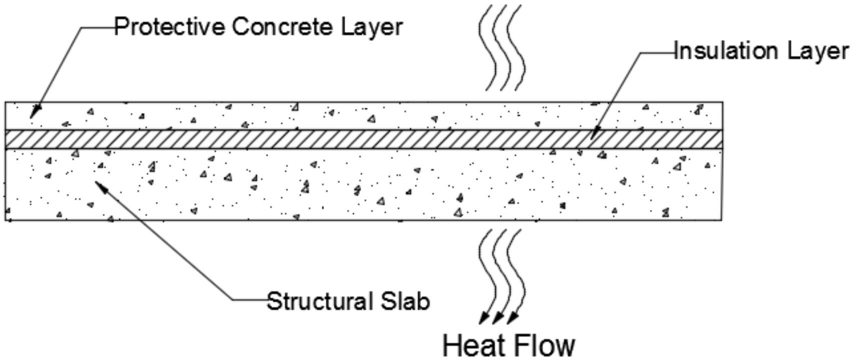


Figure 5.3: The Cross-Section of a Typical Insulation System

In this equation, ϕ is the volume fraction of the bridging material, which is concrete in this case. Because the thickness is uniform for both the insulation layer and the supporting concrete strips, area fractions were used. Those values were obtained from Table 4.3.

$$\frac{1}{K_I} = \frac{1-\phi}{K_p} + \frac{\phi}{K_c} \tag{5.1}$$

Where,

K_I = Thermal conductivity of the composite insulation layer ($Wm^{-1}K^{-1}$)

K_p = Thermal conductivity of the insulation material - polystyrene ($Wm^{-1}K^{-1}$)

K_c = Thermal conductivity of concrete ($Wm^{-1}K^{-1}$)

ϕ = Volume fraction of concrete

Table 5.1 shows the calculations performed to find out the composite conductivities for each system. As it has been mentioned, ϕ values were obtained by Table 4.3. Then, $\frac{1}{K_I}$ values, and hence the K_I values were calculated by Equation 5.1.

The next step was calculating the composite resistance values based on the thickness of the layers. Since the layers are placed in series in the perpendicular direction of heat flow, the summation of the $\frac{Thickness}{Conductivity}$ values was used (Halwatura & Jayasinghe, 2008). The thermal conductivities of concrete and polystyrene were taken to be $1.7Wm^{-1}K^{-1}$ and $0.033Wm^{-1}K^{-1}$ respectively (Al-Homoud, 2005).

Table 5.1: Theoretical Analysis on the Thermal Performance of the Systems Mentioned in Section 5.1

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Parameter	**Control System**	**Continuous Strips**	**Continuous Insulation**	**Newly Designed**
ϕ	-	16%	0%	3.3%
$\frac{1}{K_I}$ (mkW^{-1})	-	25.5	30.3	29.3
K_I $(Wm^{-1}K^{-1})$	1.7	0.039	0.033	0.034
Composite Resistance (m^2KW^{-1})	0.059	0.721	0.840	0.815
Air-to-Air Resistance (m^2KW^{-1})	0.24	0.90	1.02	1.00
'U' - Value $(Wm^{-1}K^{-1})$	4.19	1.11	0.98	1.00
Percentage Reduction of U-value	-	73.5%	76.6%	76.0%

Then it was necessary to calculate the air-to-air resistance values of each system. The surface resistance of the out concrete area and the air was taken to be 0.04 and that of the inner surface to be 0.14. The effective composite conductivity of the system ('U' - value) is the inverse of this air-to-air resistance.

According to the values obtained, an approximate U-value reduction of 75% was observed. This value is on par with the values specified in literature (Halwatura & Jayasinghe, 2008).

The detailed calculation of this section is presented in Appendix C.

5.3 Results of Physical Model Testing

5.3.1 General

Then it was necessary to construct a set of physical models to check the performance under actual conditions. This analysis was performed in two stages.

1. **Small-Scale Model Testing**

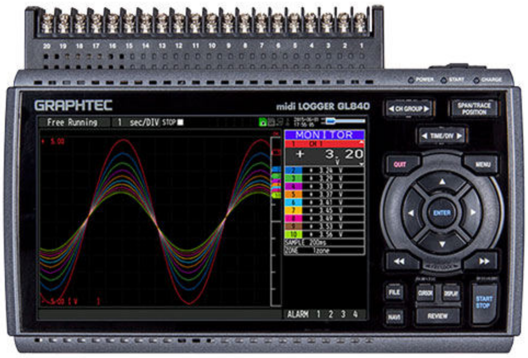


Figure 5.4: GL820 Midi Data Logger

   Four physical models of $1600mm \times 1300mm \times 600mm$ in dimensions were constructed to simulate four insulation cases mentioned in Section 5.1. Top and bottom temperatures were recorded in one-hour intervals to analyse the performance.

2. **Actual Scale Model Testing**

   After analysing the data of small-scale models, an actual-scale physical model was used to compare the thermal performance of the newly developed system with an uninsulated slab and a calicut-tiled roof.

A calibrated GL820 Midi Data Logger (shown in Figure 5.4) with K-type thermocouples was used to obtain the temperature readings. The readings were taken in late March and early April to simulate the extreme conditions, as it is known that it is the warmest period of the year for Sri Lanka.

Time lags and decrement factors for each of these cases were calculated and compared. Time lag was taken as the time gap between peak temperatures of two surfaces of a particular system. Decrement factor was calculated as the fraction of the inner surface temperature to the outer surface temperature (Shaik & Talanki, 2015).

5.3.2 Small Scale Physical Model Testing

The four systems mentioned in Section 5.1: a control system, a system with continuous supporting strips, a system with continuous insulation (with no supports) and the newly designed system were constructed. These were placed closer to each other to keep

Figure 5.5: Experimental Setup of the Small Scale Physical Models to Compare Thermal Performances

other variables, such as cloud cover and wind velocity, constant. The arrangement of the models is shown in Figure 5.5. The insulation layers of the system with continuous concrete strips and the newly developed system just before concreting are shown in Figure 5.6 and Figure 5.7 respectively.

Figure 5.8 shows the slab top and slab soffit temperatures of the control system over a period of 24-hours. It is observed that the slab top temperature rises to 53.5^0C around 1300h, marking the peak. The soffit peak temperature of 45.7^0C was observed with a two-hour lag, around 1500h.

Figure 5.9, Figure 5.10 and Figure 5.11 show the slab top and soffit temperatures of the systems with continuous supporting strips, continuous insulation (without supporting strips) and the newly designed system respectively.

Table 5.2 shows the peak temperatures of slab top and slab soffit and their times of occurrences. Then, the analysis on the corresponding time lags and decrement factors are given in Table 5.3.

Results reveal that there is a one-hour increment in the time lags in the systems

Figure 5.6: Experimental Setup of the System with Continuous Supporting Strips to Compare Thermal Performance

Figure 5.7: Experimental Setup of the Small Scale Physical Model of the Newly Designed System to Compare Thermal Performance

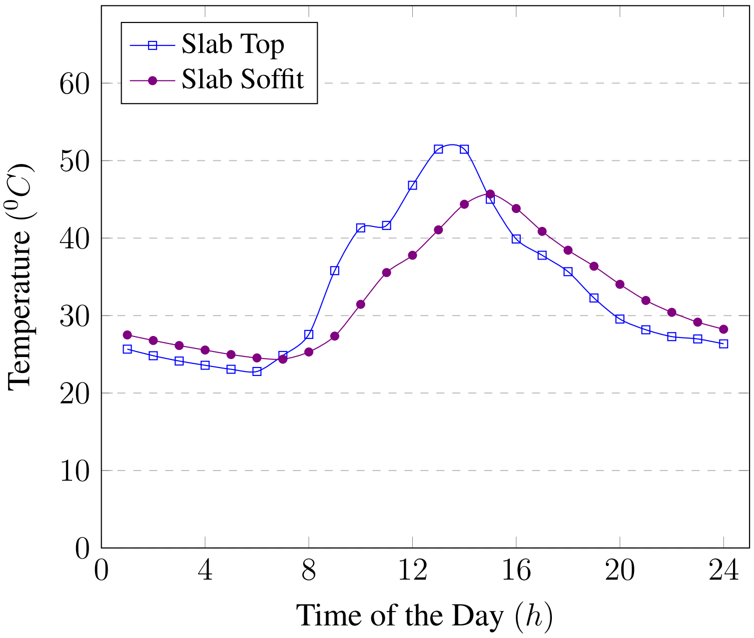


Figure 5.8: Slab Top and Slab Soffit Temperatures of the Control Experiment over a Period of 24 Hours

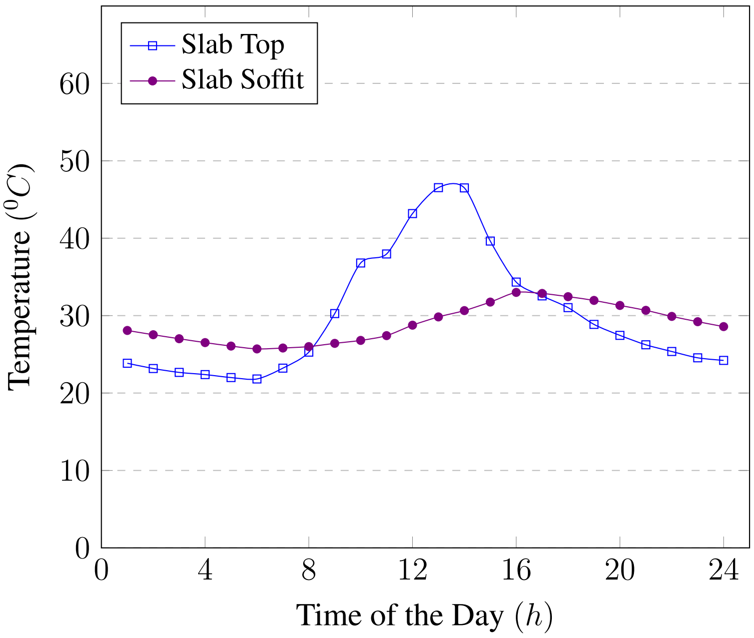


Figure 5.9: Slab Top and Slab Soffit Temperatures of the System with continuous-strip supports over a Period of 24 Hours

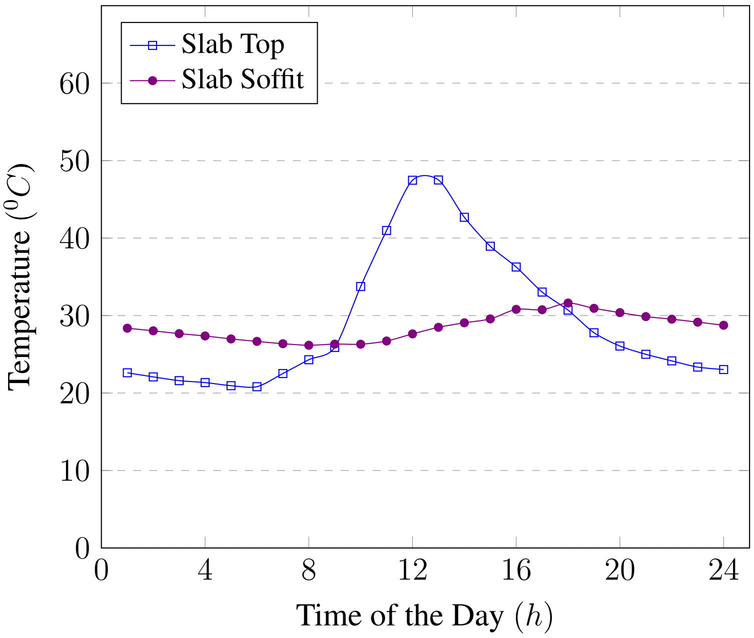


Figure 5.10: Slab Top and Slab Soffit Temperatures of the System without supporting strips over a Period of 24 Hours

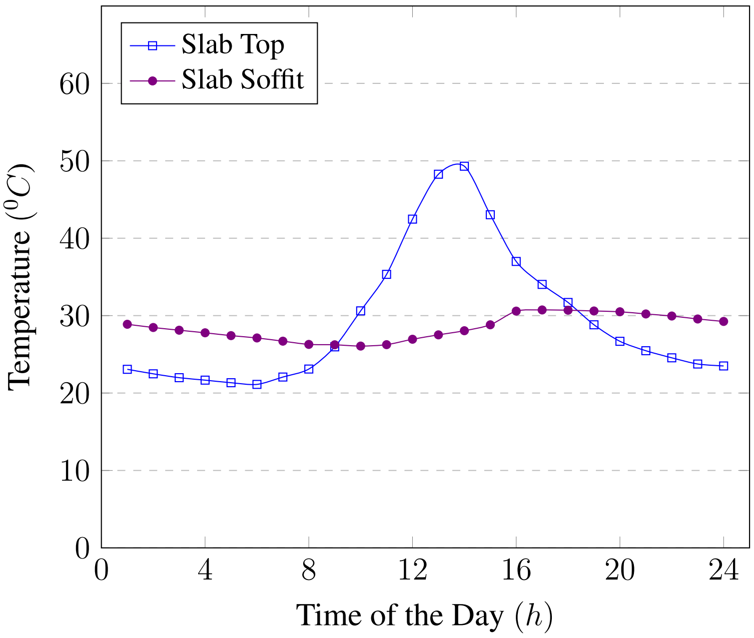


Figure 5.11: Slab Top and Slab Soffit Temperatures of the Newly Developed System over a Period of 24 Hours

Table 5.2: Peak Temperatures and Their Times of Occurrences for Each System

The System	**Peak Top Temperature** (^0C)	**Time of Occurrence**	**Peak Soffit Temperature** (^0C)	**Time of Occurrence**
Control System (without Insulation)	51.5	$1300h$	45.7	$1500h$
System with Continuous supporting Strips	46.5	$1300h$	33.0	$1600h$
System without Supporting Strips	47.5	$1300h$	30.8	$1600h$
Newly Designed System	49.3	$1400h$	30.7	$1700h$

Table 5.3: Time Lags and Decrement Factors of Four Types of Insulation Systems

The System	**Time Lag (hours)**	**Decrement Factor**
Control System (without Insulation)	2	0.89
System with Continuous supporting Strips	3	0.71
System without Supporting Strips	3	0.61
Newly Designed System	3	0.62

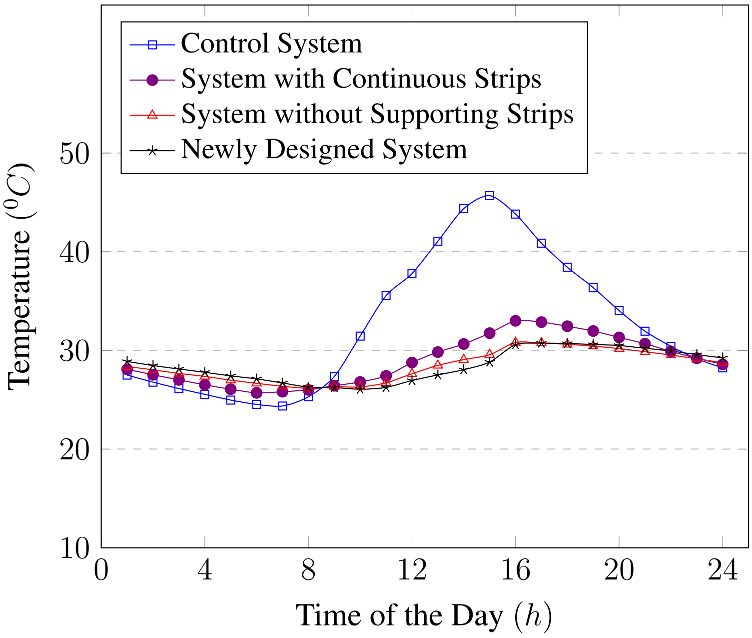


Figure 5.12: Slab Soffit Temperatures of Different Arrangements Considered

where there is some form of insulation. The system with continuous concrete strips has fed a 20% reduction in decrement factor. The newly designed system has reached a reduction of 27% which is almost similar to that of the system without any supports.

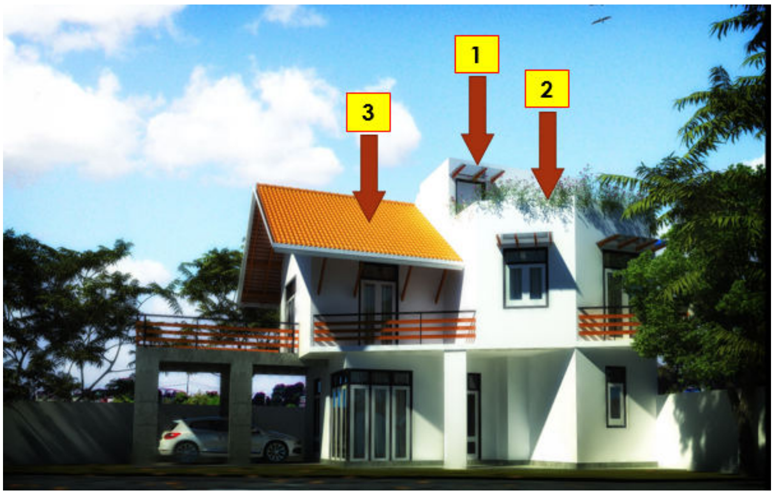
These results suggest that the newly designed system is optimised to such an extent that the effect of concrete bridging (supporting by concrete strips) is negligible in terms of the thermal performance.

Since all those measurements are taken in the same span of time, a comparison of the soffit temperatures can be presented in the same graph. Figure 5.12 shows the variation of that over the 24-hour period considered. It can be clearly observed that the curves of the newly designed system and the system without any support (concrete bridging) almost go on top of each other, emphasising the fact that the concrete strips of the newly developed system do not have a significant effect on the thermal performance of the systems.

5.3.3 Actual Scale Physical Model Testing

Section 5.3 has shown that the newly designed system perform well in thermal aspects. However, it is a small-scale model under controlled conditions. Further, it compared

(a) The Building Used to Obtain Thermal Measurements



(b) The 3D Model Developed of the Building

Figure 5.13: The Actual Scale Physical Model Used to Compare Thermal Performances

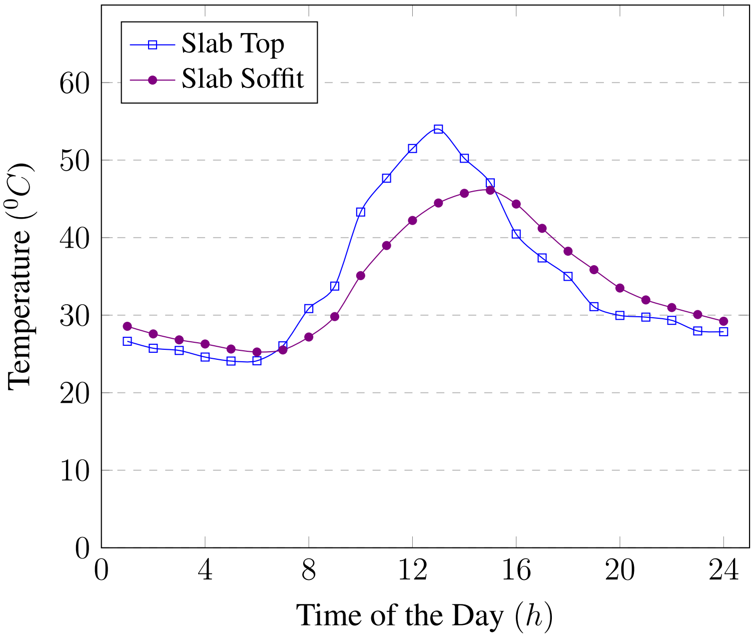


Figure 5.14: Slab Top and Slab Soffit Temperatures of the Uninsulated Slab of Actual Model Testing over a Period of 24 Hours

the performance of different types of roof slabs, but not with existing roofing materials.

Chapter 3 confirmed that the general public prefers calicut tiles over other roofing materials. Hence, it is worthwhile to compare the performance of the system with calicut tiles as well.

Figure 5.13 shows a graphical view of the model used to asses the thermal performance of the system under real conditions. This contained a slab without insulation, a slab insulated by the newly designed system and a calicut tiled roof with a 3mm-foil insulation and a timber ceiling (number 1,2 and 3 in Figure 5.13b respectively). The roofs under consideration were placed in East-West directions, and the readings were taken in early April to take an extreme exposure into account.

The readings obtained for the uninsulated slab is shown in Figure 5.14. It indicates that the peak top temperature reaches 54^0C at $1300h$, and the peak soffit is 46^0C around$1500h$, with a two-hour time lag and a decrement factor of 0.87. These are almost identical values obtained for small scale models.

Figure 5.15 shows those values obtained for the insulated case. In this, the peak top surface temperature has reached a 56^0C at $1300h$, transferring a 33^0C peak to the soffit temperature in the time range of $1400h - 1700h$. This scenario has shown a time lag

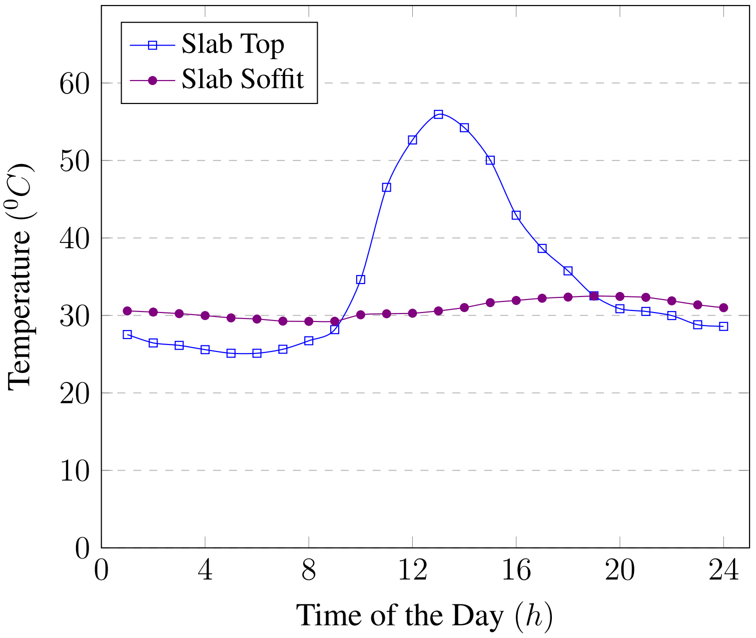


Figure 5.15: Slab Top and Slab Soffit Temperatures of the Insulated Slab of Actual Model Testing over a Period of 24 Hours

of 3-4 hours with a decrement factor of 0.6, showing similar values as in small scale models.

The top surface of the calicut tiled roof has reached around 60^0C at its peak. This value is slightly higher than the peaks of other two cases due to the higher albedo value of clay tiles. The consequent temperature under the ceiling was observed to be around 37^0C, but with hardly any time lag (See Figure 5.16). Even though the decrement value is similar to that of the insulated slab, the bottom surface temperature has reached a higher value due to the higher top surface temperature of tiles.

These are further emphasised by Figure 5.17 and Figure 5.18, of those the top surface temperatures and bottom surface temperatures are plotted separately.

Conclusively, the insulated slab performs even better than a calicut tiled roof with a timber ceiling. Hence, the initial objective of the study is satisfied.

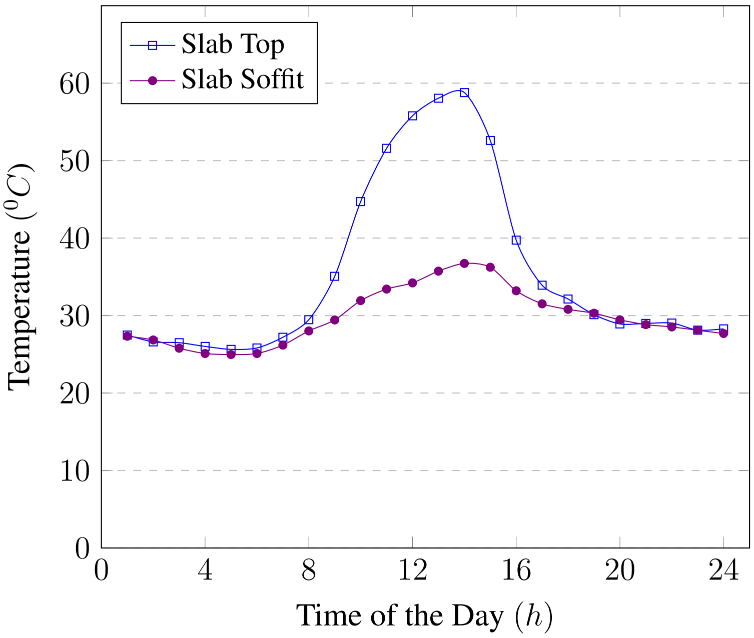


Figure 5.16: Top and Bottom Surface Temperatures of the calicut Tiled Roof of Actual Model Testing over a Period of 24 Hours

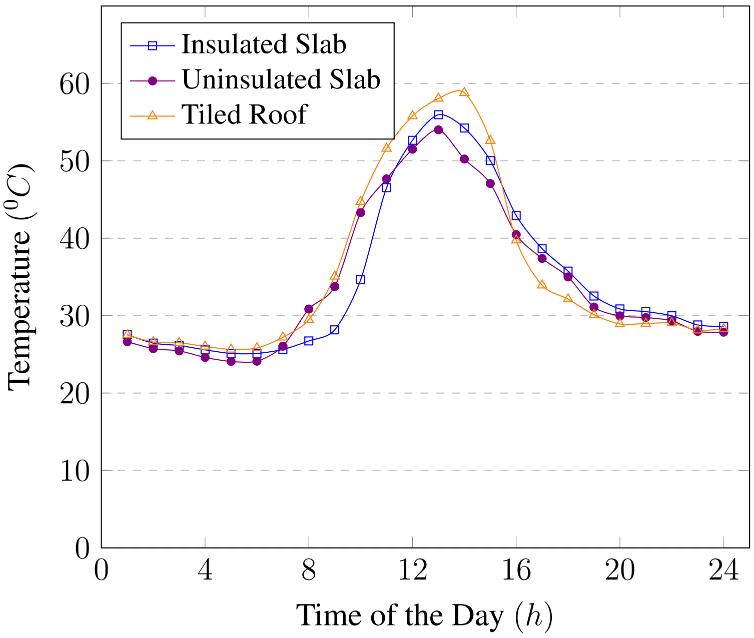


Figure 5.17: Top Surface Temperatures of the Insulated Slab, Uninsulated Slab and calicut Tiled Roof over a Period of 24 Hours

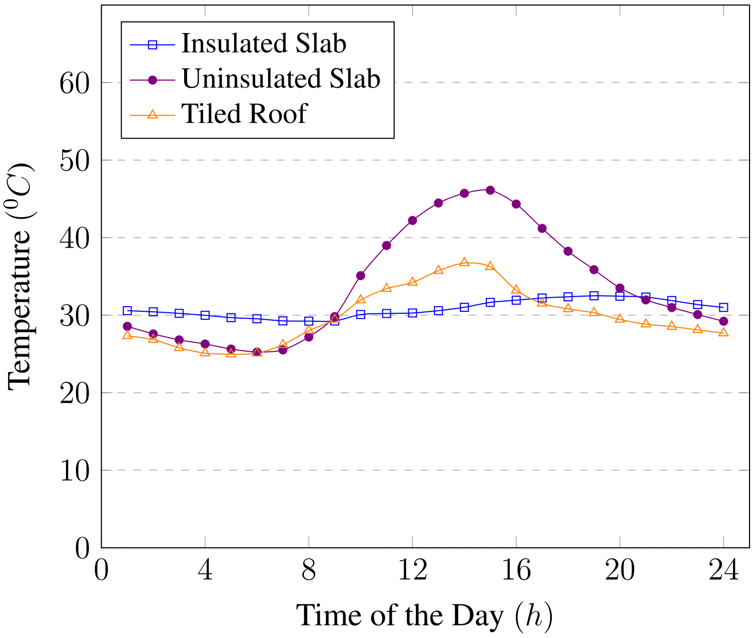


Figure 5.18: Bottom Surface Temperatures of the Insulated Slab, Uninsulated Slab and calicut Tiled Roof over a Period of 24 Hours

5.4 Computer Simulation

5.4.1 Model Calibration

Since it was intended to find out the cooling load reduction by this insulation, a computer simulation was performed by using 'DESIGN BUILDER V4' for the small scale model of the newly developed system mentioned in Section 5.3.2. It was decided to use that model due to the possibility of comparing the thermal performance of all the systems considered in that section.

The first step was to calibrate the models so that the actual cooling loads can be predicted. The physical model mentioned in Section 5.3.2 was simulated by the software package. The calibrated top and bottom temperatures are shown in Figure 5.19 and Figure 5.20 respectively.

Results demonstrate that the model is sufficiently calibrated so that the results can be expanded to predicted the performance of an actual scale model.

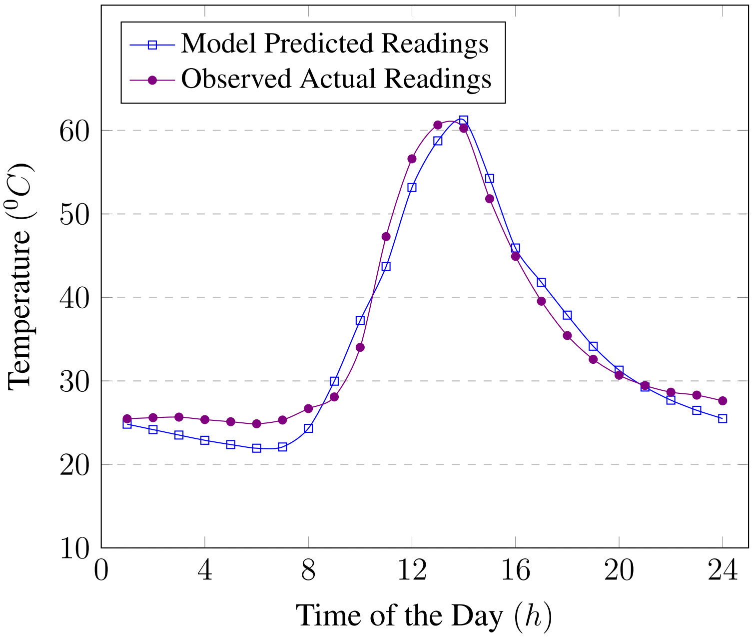


Figure 5.19: Results After Calibration for Slab Top Temperatures of the Small Scale Model

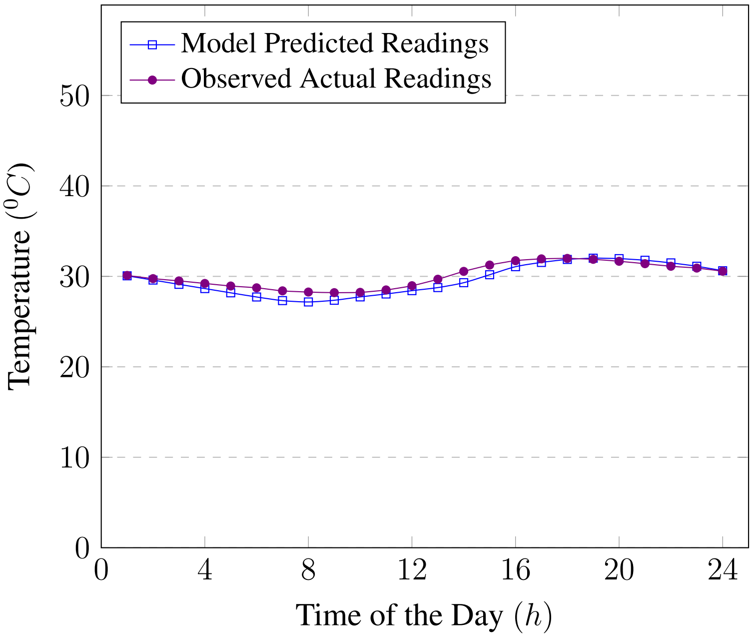


Figure 5.20: Results After Calibration for Slab Soffit Temperatures for the Small Scale Model

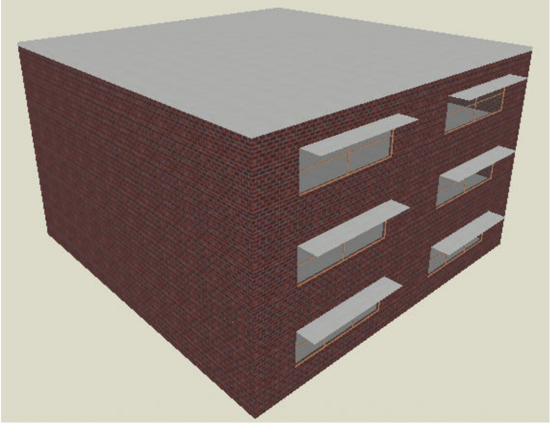


Figure 5.21: The Computer Model Used for Computer Simulations

5.4.2 Calculation of Cooling Loads

A computer simulation was performed using the Software Package, 'Design Builder' to find out the reduction in cooling load of an actual scale building. A typical office building $15m \times 15m$ was selected. Since the objective was to compare the results on heat gain from the roof, other housing elements were included with as many passive features as possible. The external walls were taken to be $225mm$ thick brick walls. No windows were incorporated in East and West walls, and the provided windows in North-South directions were provided with $1m$ overhang to prevent direct solar radiation being penetrated to the building. The model used for simulations is shown in Figure 5.21. Further details of the model are given in Appendix D.

This model was developed in 'Design Builder' software package to find out the cooling energy required to obtain neutral operating conditions on a typical summer day. The neutrality temperature was taken to be 26^0C which is a reasonable value for tropical conditions (Halwatura & Jayasinghe, 2008).

The cooling energy requirements obtained for this particular building under the mentioned conditions are shown in Figure 5.22. The displayed results are for the designed system. Even though the simulations were carried out for all the four options specified in methodology, all of them are not presented here since the energy requirements for the insulated systems differ by less than 1% of each other.

By Figure 5.22, it is clearly evident that the peak energy requirement can be reduced by about 20% by insulating. This clearly reduces the requirement of A/C

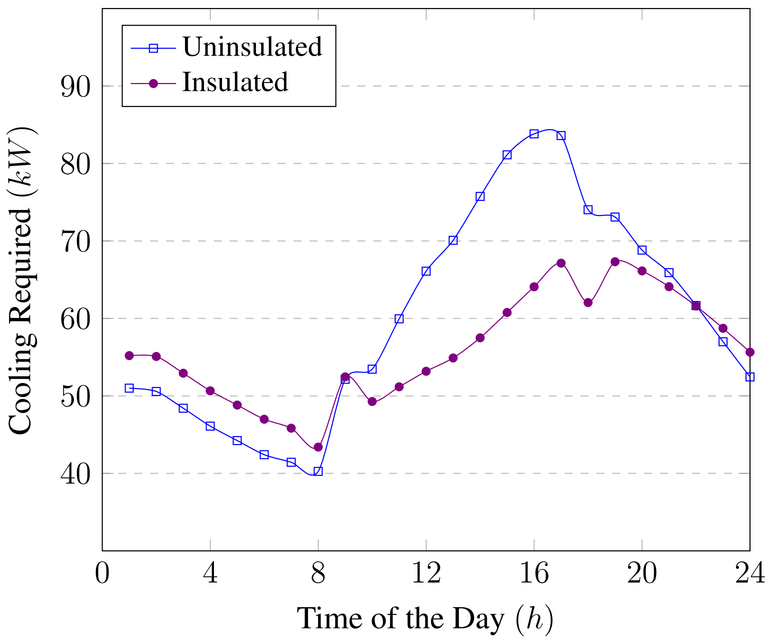


Figure 5.22: Predicted Cooling Energy Required for Insulated and Uninsulated Slabs over a Period of 24 Hours

equipment required, thus the initial cost as well.

5.5 Summary of the Thermal Performance

Structural performance and the durability are not considered in most of the thermal insulation systems in the world. In this newly designed intermittent-stripped system, the structural performance is taken care of by providing concrete supports within the insulation system, and durability is enhanced by providing a protective screed and discontinuing the strips.

However, the thermal performance in comparison with existing insulation systems had not been studied yet. In this study, the thermal performance of an intermittent-stripped roof slab insulation system is evaluated as comparison with traditional insulation techniques available in tropical countries.

Small-scale physical models were cast, and thermal readings were taken to assess the performance. It has been proven that the supporting strips within the insulation layer do not have any significant impact on the thermal performance of the system. The time lag and the decrement factor of the system with intermittent strips and the system without any support were six hours and 0.60 respectively.

An actual scale model was tested to find out the performance of the system under realistic conditions, and proven to be performing well regarding thermal aspects. It further resulted in finding that the system is performing even better than a calicut-tiled roof with a timber ceiling.

Finally, a computer simulation was carried out to analyse the cooling energy saving potential of the system for a typical office building of $15m \times 15m$ in the plan area. For a general summer day, the energy requirement for cooling was reduced by about 20%. This contributes severely to recover the additional initial investment for insulating.

Chapter 6

Developing a Natural Insulation Material

6.1 General

By this stage, the core structure of the insulation system had been finalised, and it had been proven that the system performs well in structural and thermal aspects in tropical climatic conditions. The mentioned structure had been designed in such a way that the load is transferred through a path of rigid concrete structure, without being transferred to the insulation material.

The general rationale of choosing a typical insulation material was that: it should have a high porosity so that the heat conduction is disturbed. In this context, expanded polystyrene and expanded polyethylene have become the most common insulation materials. Even though they perform well in thermal aspects, it has to be noted that these materials are produced by the crude oil extraction process. It emits a large amount of Greenhouse gasses (Wang et al., 2003; Gavenas, Rosendahl, & Skjerpen, 2015; Nimana, Canter, & Kumar, 2015; Mjean & Hope, 2013). This phenomenon is highly undesirable in the context of Global Warming.

Consequently, different replacements have been tried out throughout the world, and some are proven to be successful. Some of the published data in this regards were shown in Table 2.5.

Figure 6.1: The Physical Model Used to Test Air Gap as an Insulator

In this section, it is intended to replace the polystyrene layer with an environmentally friendly, natural and locally available material, without sacrificing the thermal performance.

6.2 Air Gap as an Insulation material

6.2.1 Effectiveness of the Thickness of Air Gap

As it has been mentioned, the logic of choosing an efficient insulation material is to select a material with a high porosity, as it disturbs the heat conduction. The pores in the material absorb heat and disturb the conduction flow and reduce the composite conductivity of the system. According to this process, increasing the void ratio in the insulation layer should theoretically increase the effectiveness of the insulation system. Therefore, the extreme condition, a system with a 100%-void ratio, a layer of air, was selected for a trial analysis. Such a system has been successfully tested in Greece (Dimoudi et al., 2006), but not in tropical conditions.

The physical model used to evaluate the performance of air gap is shown in Figure 6.1, and the temperatures on the top surface and the soffit with a 25mm-air gap insulation is provided in Figure 6.2.

Results indicate that the peak top surface temperature of the system with a

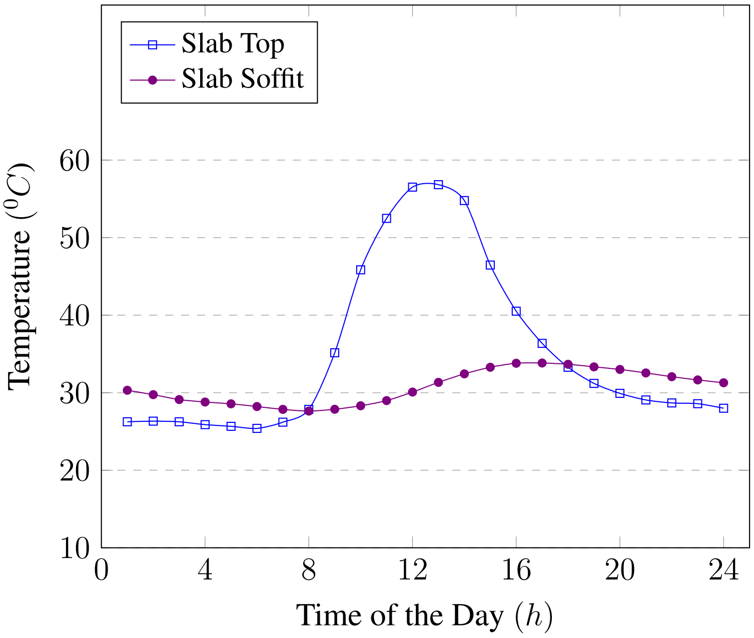


Figure 6.2: Observed Slab Top and Slab Soffit Temperatures of the System with 25mm Air Gap

25mm-air gap was 56.8^0C around $1300h$. The peak is transferred to the soffit with a time lag of 3 hours at $1600h$ with a decrement factor of 0.59 (as the peak soffit temperature was 33.8^0C). These themselves are significant figures for an insulation system as this has reduced the heat flow considerably.

Then it was tried to find out the effect of the thickness of the air gap to the thermal performance of the system. The results are elaborated in Figure 6.3.

The results obtained for a 75mm-air gap shows that the time lag was 3 hours with a decrement factor of 0.6, almost identical to the values obtained for an air gap of 25mm. The variation is not significant to be considered significantly for an increase of 50mm in thickness.

Meanwhile, it was observed that the top surface temperatures observed with 75mm insulation were slightly lower than that with 25mm insulation. This can be explained as a result of the higher ventilation provided by the additional thickness. However, the magnitude of the effect is not reflected by the order of the change in thickness. This is further emphasised by the variation of soffit temperature over the day. Hence, it can be concluded that the effect of the thickness of the air gap to the thermal performance is negligible.

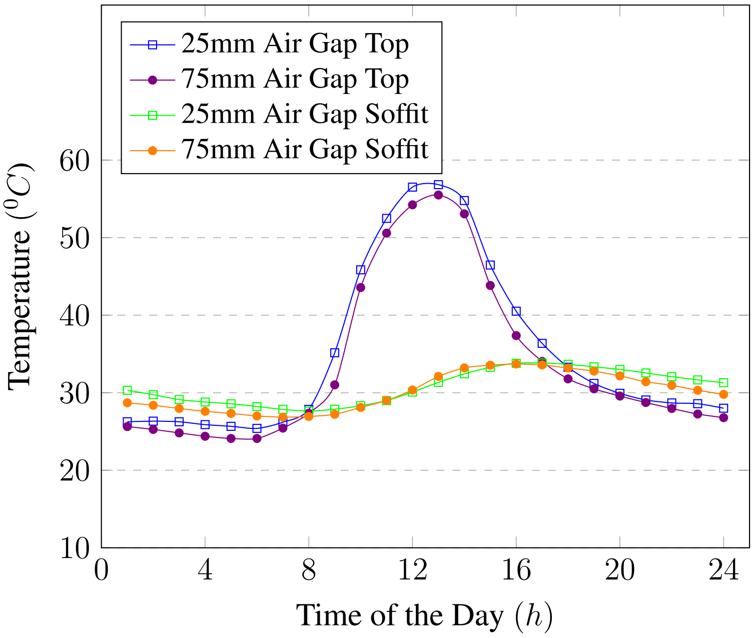


Figure 6.3: Observed Slab Top and Slab Soffit Temperatures of the Systems with 25mm and 75mm Air Gaps

Table 6.1: Time Lags and Decrement Factors of Four Types of Insulation Systems

Insulation Material	**Time Lag (hours)**	**Decrement Factor**
25mm Polystyrene Layer	4	0.54
Air Gap	3	0.60

6.2.2 A Comparison with Polystyrene as an Insulator

The next step was to compare the effectiveness of an air gap with a 25mm-polystyrene insulation layer, which is the baseline that was considered in the study so far. Hence, a physical model was cast, and the temperature readings of top and soffit were obtained on the same day.

Table 6.1 shows the summary of the comparison of time lags and decrement factors of a 25mm-polystyrene layer and an air gap (different values of the thickness of the air gap was not considered here as it was proven that there's no effect in that). It suggests that an air gap is marginally less efficient as an insulator in comparison with a 25mm-polystyrene layer.

Figure 6.4 shows the top surface temperature variation of a 25mm polystyrene and

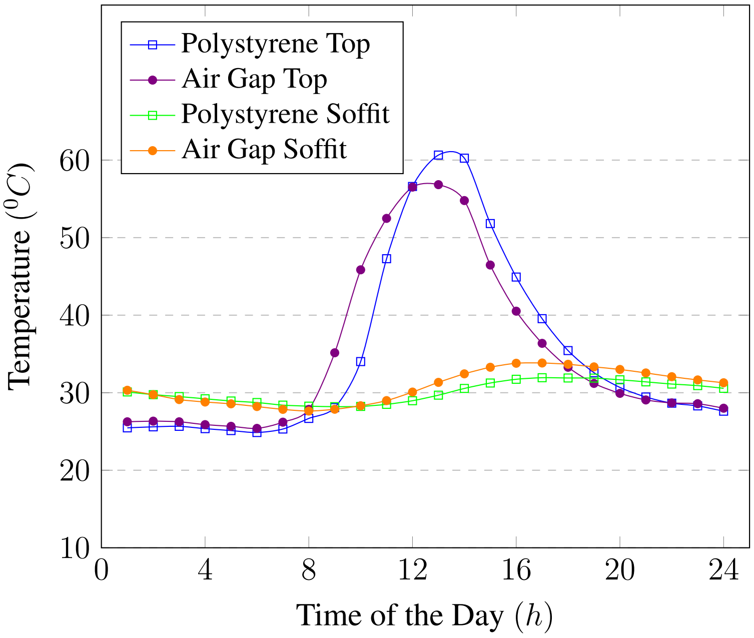


Figure 6.4: Observed Slab Top and Slab Soffit Temperatures of the Systems with 25mm Polystyrene Layer and an Air Gap

a 25mm air gap insulation. The peak temperature of the system with air gap is less than that of polystyrene and the peak is reached earlier than polystyrene. This means that the heat is transferred by convection quickly in the case of the air gap. However, the heat barrier created by polystyrene is stronger than that of the air gap and hence is the better insulator. The soffit temperatures shown in the same figure emphasised this fact. Even though the system with polystyrene showed a higher top temperature, it has become the lower at soffit level.

These results imply that the earlier hypothesis that the porosity directly affects the insulation properties is rejected.

However, the results obtained by the software, Design Builder v4, suggested that if an air gap layer can be placed as an insulator, it has to be better than polystyrene. But it was observed that the model had assumed the air gap to be confined with no infiltration.

Therefore, it is concluded by this section that a ventilated air gap is a good insulator, but is not as useful as a 25mm-polystyrene layer. However, it would be more efficient if it is possible to confine the air gap.

6.3 Bamboo Cut in Transverse Direction as an Insulation Material

6.3.1 The Designed Experimental Setup

From the previous section, it was found out that a ventilated air gap alone is not sufficient to obtain the effectiveness that a 25mm-polystyrene insulation layer provides, and the computer simulations suggested that a confined air gap could be a better insulator. Summing those up, it was decided to confine the air gap in such a way that the additional cost for confinement is minimised, and the system is conveniently constructive.

Despite, polystyrene is a product of the crude oil extraction process which emits an extensive amount of greenhouse gases (Gavenas et al., 2015; Nimana et al., 2015; Mjean & Hope, 2013). Since the focus of this study is to address the issue of global warming, it is favourable if such materials can be avoided in the design.

Hence, a detailed literature survey was carried out to find out a suitable insulation material that can be used in local conditions in Sri Lanka. A summary of the literature made was presented in Table 2.5.

Bamboo is a fast-growing plant which is freely available and is used for many construction purposes. In fact, bamboo holds the Guinness record for the fastest growing plant in the world (Tracy Li, 2013). Therefore, the adverse effects imposed by using bamboo for construction is negated in a shorter span of time. On the other hand, It has been proven that it has significant insulation properties as well (Mounika, Ramaniah, Prasad, Rao, & Reddy, 2012).

In summary, the intention was to create a confined air gap with a stiff material that is thermally resistive and locally available. Also, the impact to the environment due to the utilisation of that had to be minimised since the study focuses on sustainability. Bamboo cut in transverse direction does possess to be an ideal material, satisfying all those requirements. The planned structural arrangement with bamboo is shown in Figure 6.5.

As the process moved forward, it was necessary to develop a modular unit so that the required structural arrangement mentioned in Chapter 4 is obtained. Panel units as shown in Figure 6.6 were pre-cast and placed in the insulation layer in such a way that the contiguous stacking provides the structural arrangement that is intended.

Figure 6.7 shows the construction of the system with bamboo insulation with the designed modular units. It is the small scale physical model used to calibrate the model developed by Design Builder v4.

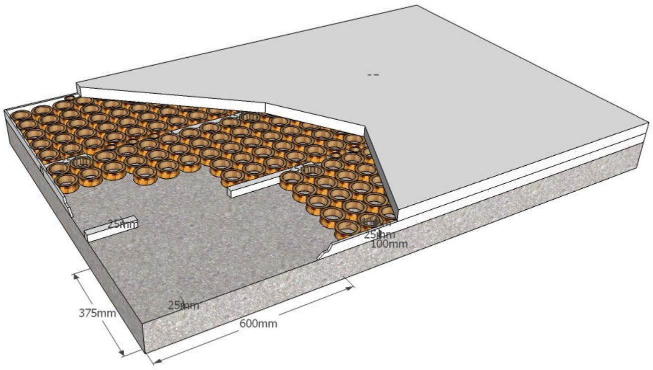


Figure 6.5: Planned arrangement in the Construction of Bamboo Insulation Layer

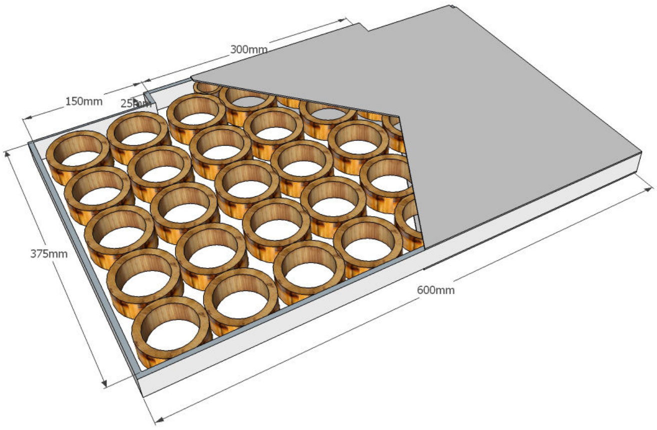


Figure 6.6: Panel Units Used in the Construction of Bamboo Insulation Layer

Figure 6.7: Construction of the System with 25mm Bamboo Insulation

6.3.2 Effectiveness of Bamboo as an Insulation Material

After the obtained results of the previous sections, it was necessary to find out the thermal characteristics of the system with bamboo insulation. Hence, a physical model was cast to evaluate the thermal performance and the insulation properties.

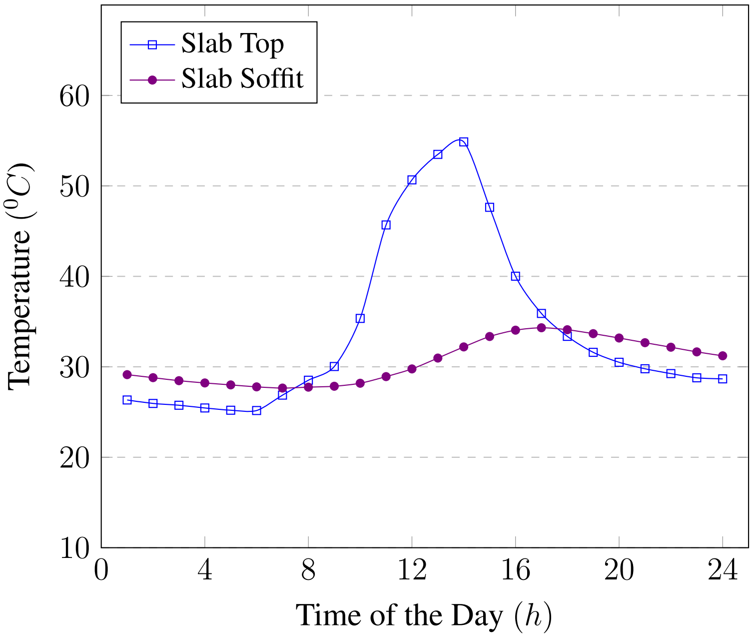


Figure 6.8: Observed Slab Top and Slab Soffit Temperatures of the System with a 25mm bamboo strip Layer as an Insulator

Figure 6.8 shows the slab top and soffit temperature variations observed in the model constructed with a 25mm-bamboo insulation. The peak top temperature was

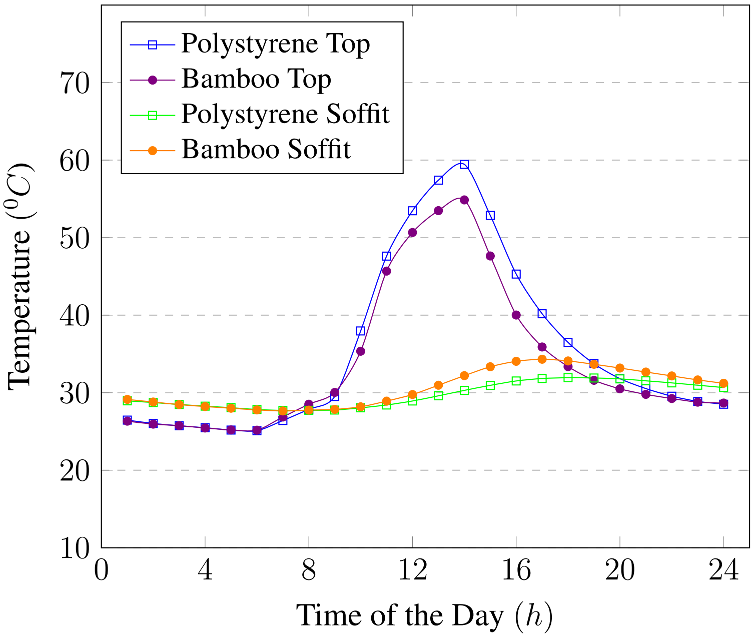


Figure 6.9: Observed Slab Top and Slab Soffit Temperatures of the System with a 25mm Polystyrene Layer and a 25mm Bamboo Layer

observed to be 54.9^0C, and the peak soffit was 34.3^0C with a four-hour time lag. Hence, the decrement factor was calculated to be 0.61, showing almost the same value as in the case of bamboo, laid in the specified arrangement.

Nevertheless, it was necessary to analyse the thermal performance of bamboo (cut and laid in transverse direction) quantitatively in comparison with a 25mm-polystyrene layer, which has been the baseline that is considered in this study so far.

The comparison of the slab top temperatures of the two systems is presented in Figure 6.9. The top surface of the system with bamboo is lower than that of the system with polystyrene, similarly to the case of ventilated air gap. However, the soffit temperatures behave conversely.

Considering these, it is evident that polystyrene has marginally better insulation properties than bamboo as well. However, with the construction convenience, availability and the economics that bamboo provides, this thermal performance of bamboo is a significant achievement.

A detailed analysis on the life cycle cost is presented in Chapter 7.

The next immediate step was to check the performance of these systems when vegetation is laid on top of the protective concrete layer.

6.4 Effectiveness of a Vegetation Layer on Top for the Insulation Properties

6.4.1 The System with Air Gap and Vegetation

Rooftop vegetation is very common these days since it adds a pleasant aesthetics to the buildings and creates a favourable micro-climate. Most of those who have roof slabs tend to incorporate a greenery layer on top to avoid the thermal discomfort, in addition to those advantages.

In the previous section, it was found out that a ventilated air gap did not match the thermal effectiveness that an equivalent thickness of polystyrene layer possesses. Further, it was found out that heat is transferred by convection quickly in the system with an air gap. Therefore, a 50mm-vegetation layer on top of both the systems were tried, and their performances were compared. Construction of the systems with vegetation is shown in Figure 6.10.

Figure 6.10: Construction of the System with 25mm Bamboo Insulation

According to Figure 6.11, the system with polystyrene reached a peak top temperature of 36.2^0C, which is about 23^0C reduction in comparing with the system without a vegetation layer. This is highly favourable to mitigate the heat island effect. However, this drastic reduction in top surface temperature was not reflected in the

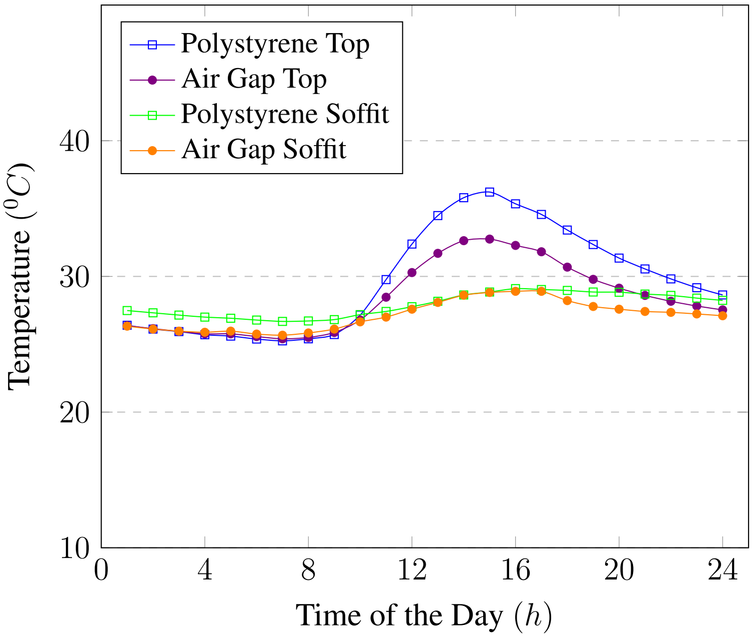


Figure 6.11: Observed Slab Top and Slab Soffit Temperatures of the System with a 25mm Polystyrene layer and a 25mm-Air Gap with a 50mm Vegetation Layer on Top

soffit. The peak soffit, in this case, was observed to be 29.1^0C, which is only about 3^0C less than the system without vegetation. Nevertheless, this reduction itself could yield a significant energy saving, but incorporates an additional initial investment and maintenance. Practically, a solid comment on the overall performance of the systems demands a life cycle cost analysis.

However, if these systems are considered as insulation systems themselves, they show poor performances mathematically, but not in terms of real performance. In the cases with vegetation, the decrement factors observed were in the order of 0.8-0.9, whereas in the systems without vegetation it is in the range of 0.5-0.6. This is due to the drastic reduction in top surface temperature due to the presence of vegetation.

Further, the system with polystyrene seems to have a higher top surface temperature with no time lag between the systems. However, the soffit temperatures were observed to be more-or-less the same, with the curve of the system with an air gap moves slightly below the other. This proves the fact that polystyrene layer is a better insulator, but only marginally.

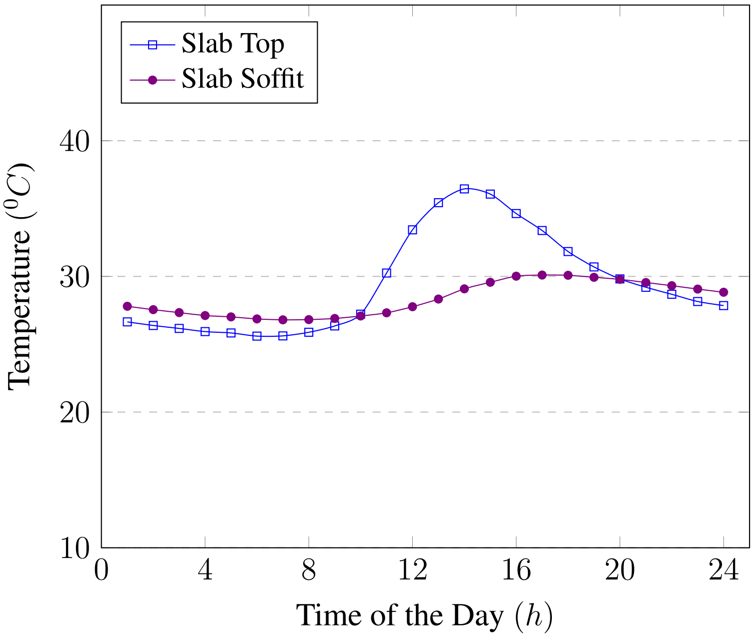


Figure 6.12: Observed Slab Top and Slab Soffit Temperatures of the System with a Bamboo Strip Layer as an Insulator and a 50mm-Vegetation Layer on Top

6.4.2 The System with Bamboo and Vegetation

The previous section proved that bamboo cut in transverse direction shows similar thermal characteristics to an air gap, and is marginally less efficient than a 25mm-polystyrene layer as a thermal insulator. Further, it proved that the effectiveness of a ventilated air gap is higher in comparison with a vegetation layer on top. Hence, a vegetation layer on top of bamboo insulation was also checked as an option.

Figure 6.12 shows the temperature variation of the either surfaces of the system. Here, the top temperature was peaked at 36.5^0C, while the soffit reaches 30.1^0C at its peak with a two-hour time lag. Here, the decrement factor was observed to be 0.83, which is in the same order as in the previous cases with vegetation.

Then, the performance of this system was compared with that of a system with 25mm-polystyrene insulation layer with a vegetation layer on top of the protective concrete layer. The variation of the top and soffit surface temperatures in this case for the two systems are shown in Figure 6.13.

Those figures reveal that the two systems with vegetation behave more-or-less in

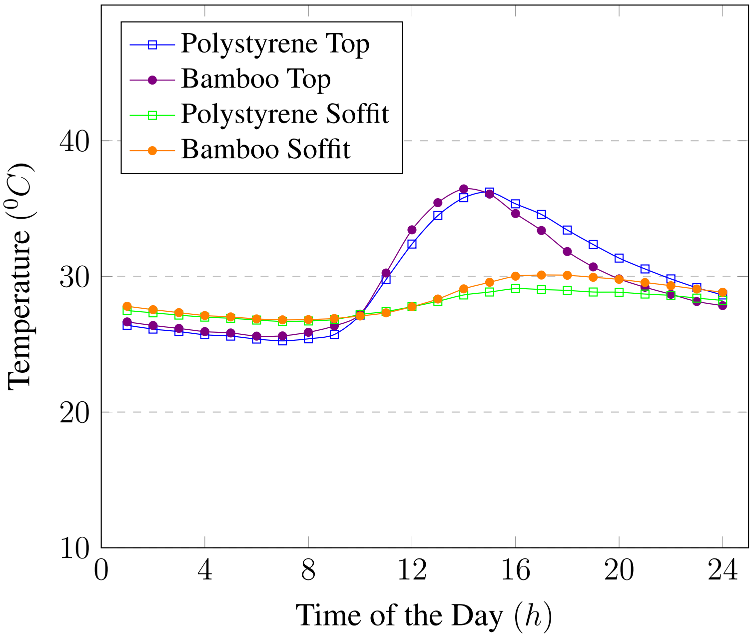


Figure 6.13: Observed Slab Top and Slab Soffit Temperatures of the System with a 25mm Polystyrene Layer and a 25mm Bamboo Layer with a 50mm-Vegetation Layer on Top

a similar manner, with a slight edge to polystyrene, when vegetation is laid on top. The soffit temperatures of the system with polystyrene show marginally small values in the evening. However, considering the cost and the environmental impacts, this performance of the system with bamboo is an excellent achievement.

6.5 Summary of the Effort on Developing a Natural Insulation Material

Table 6.2 shows the quantitative summary of the final figures in this chapter. The peak top temperatures rise to about 55^0C-60^0C, without vegetation, but is only around 35^0C when a vegetation layer is placed on top. This is a drastic reduction and highly favourable in order to mitigate heat island effect. However, this is not reflected in such magnitudes in soffit temperatures, showing only about $3-5^0C$ reduction.

Even though the systems with vegetation perform well in general in thermal aspects, the parameters to be considered in commenting on insulation, time lag and

Table 6.2: Summary of the Results Obtained of the Systems Tested to Replace Insulation Material

Parameter	**Without Vegetation**			**With Vegetation**		
	Polystyrene	Airgap	Bamboo	Polystyrene	Airgap	Bamboo
Peak Top (^0C)	59.5	56.8	54.9	36.2	32.8	36.5
Peak Soffit (^0C)	31.9	33.8	34.3	29.1	28.9	30.1
Time Lag ($hours$)	4	3	4	1	1	2
Decrement Factor	0.54	0.60	0.61	0.80	0.88	0.83

decrement factor, do not reflect that. It is mainly due to the drastic reduction in top surface temperatures.

A ventilated air gap was tested as an insulation layer as it was intended to replace the traditional polystyrene insulation layer. A physical model testing suggested that polystyrene has a better thermal performance than it marginally.

However, computer simulations suggested that confining air gap could improve the thermal performance. Since the confined construction emerged to be an issue, circular trunk arrangement of bamboo was checked as an option. Its strength and the insulation characteristics had been verified by literature. The thermal performance was found to be similar to the ventilated air gap, resulting a conveniently constructable and thermally efficient system.

Nevertheless, a further analysis on life cycle costing was necessary to quantify the net economic gains. It is presented in the next chapter (Chapter 7) in this report.

Chapter 7

Life Cycle Cost Analysis

7.1 General

With the excess usage of energy, the price of energy has reached a level such that the operational cost of energy is paid a significant attention as well as the initial cost. However, since the initial cost is a one-time expenditure and the operational energy is a recurrent cost, a balance needed to be struck to assess the net effect of those two parameters quantitatively.

life cycle assessing has been invented as a technique to strike this balance. It has been defined as follows (Fuller & Peterson, 1996);

"The total discounted dollar cost of owning, operating maintaining and disposing of a building or a building system over a period. life cycle Cost Analysis (LCCA) is an economic evaluation technique that determines the total cost of owning and operating a facility over a period."

There are several life cycle assessment technologies in the world;

- Payback Period
- Net Present Value
- Annual Worth
- Internal Rate of Return

- Benefit-Cost Ratio

Net present value is the best method to compare alternatives if the project life is known and assumed to be a constant value over all the alternatives. It takes all the cost and revenue items over the lifespan, and its present value is calculated for an appropriate discounting factor. It is an additional advantage that this method takes the depreciation of money into account as well (Ross, 1995).

Two basic formulae were used in this analysis to calculate the present worth. Equation 7.1 was used when discrete values need to be considered whereas when annual values such as annual energy saving are considered Equation 7.2 was used.

$$P = F(1+i)^{-n} \tag{7.1}$$

$$P = A\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \tag{7.2}$$

Where,

P = Present Value of Money

F = Future Value of Money

i = Discounting Factor/ Interest Rate

n = Project Life

A = Annual Worth

7.2 A Comparison with Traditional Roofing Materials

As it has been discussed in Chapter 3, a majority of the occupants still use traditional roofing materials, particularly calicut tiles, and still they prefer to use that due to the favourable thermal environment created by it. The results of the questionnaire survey went in par with the statistics in literature in the fact that calicut tiles are overwhelmingly popular than other roofing materials.

However, as it has been reiterated, the use of roof slabs is in the process of gaining its popularity due to many advantages. It can recover the land since rooftops can be utilised as working spaces. Further, it provides an additional robustness to the structures which leads to a higher degree of disaster resistance in comparison with traditional roofs. Despite these advantages, roof slabs are not as popular, for which the major reason identified in Chapter 3 was the thermal discomfort associated.

As a remedy, an insulation system has been developed by Halwatura and Jayasinghe and has been proven to be effectively behaving regarding the thermal performance (Halwatura & Jayasinghe, 2007). Further, a life cycle cost assessment has shown that it is more economically viable than a traditional calicut tiled roof (Halwatura & Jayasinghe, 2009).

In this study, the thermal performance of the system developed by Halwatura and Jayasinghe was compared with the newly developed system as described in Chapter 5. There, it was proven that the newly developed system is performing favourably regarding thermal aspects.

Further, the different options tested in Chapter 6 showed more-or-less similar results.

Cross-referencing the above facts, it can be deduced without an in-depth analysis that the newly developed system is economically feasible than the traditional roofing materials.

7.3 Method of Comparing Different Insulation Options

7.3.1 The Approach

Even though it has been proven that the insulation system is more economically feasible than traditional roofing materials, the different options of insulation materials mentioned in Chapter 6 needed an analysis and is performed here.

There were five types of insulation systems considered;

1. Uninsulated Slab

2. 25mm polystyrene insulation
3. 25mm polystyrene insulation with a 50mm vegetation layer on top
4. 25mm of bamboo cut and laid in transverse direction
5. 25mm bamboo with a 50mm vegetation layer on top

Options of different insulation thickness or different vegetation thickness were not considered as it has already been researched and found out that it is not economically feasible to incorporate a higher thickness than the considered values above (Halwatura & Jayasinghe, 2008).

There are two major parameters to be finalised in the Equations 7.1 and 7.2: the service life and the discounting factor.

Service life itself is a debatable topic in this area of study. Several studies have estimated different lives for different components, but this study requires a constant value for the entire structure. According to the literature, this value varies from 10 years (Vijaykumar et al., 2007; Halwatura & Jayasinghe, 2009) to 40 - 50 years (Emmanuel, 2004; Kofoworola & Gheewala, 2009; Keoleian, Blanchard, & Reppe, 2000). Hence, three cases in the forms of 10 years, 20 years and 50 years were considered in the analysis

A discounting factor was the other variable to be incorporated. Three cases were considered in this analysis: 8%, 10% and 12%. Those are typical values in Sri Lankan context (Halwatura & Jayasinghe, 2008). The analysis was carried out in Sri Lankan Rupees, since this study was performed in Sri Lanka, and converted to United States Dollars (USD) due to the convenience of interpreting globally.

Figure 7.1 shows the building used to compare the life cycle costs of the different alternatives considered. It is a three-storey building with a plan area of $15m \times 15m$. It is incorporated with all the possible passive features so that the effect of the other elements is minimised, and it is feasible to compare the real effect of the roof. Moreover, the other relevant parameters were selected as typical default values (mentioned in Appendix D).

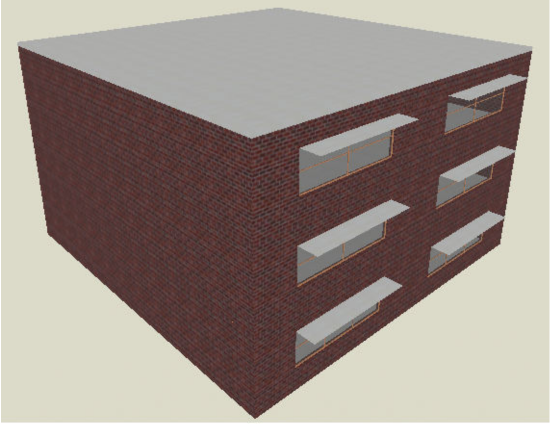


Figure 7.1: The Model Used to Compare life cycle Costs

There are several cost elements needed to be considered in the analysis and are presented herein. All those elements were computed per unit area to generalise the results obtained.

7.3.2 Factors Considered in the Analysis

Initial Cost

Construction cost of Rs. 45000/= per m^2 was assumed in the analysis as per the expert comments related to the field. This is a reasonable value based on the market rates by mid-2016. The insulation layer was considered separately. The market rate of polystyrene was taken to be Rs. 900/= per m^2 and the acquisition and the labour rates of bamboo was taken as Rs. 150/= per m^2. The rate of the protective concrete was derived from the building schedule of rates published in 2015 (*Building Schedule of Rates*, 2015).

Land Recovery

One of the major benefits of flat roof slabs is that it is usable as a working space. Since the expedition of land prices due to the scarcity created by urbanisation, the recovery of land is one of the paramount reasons for the roof slabs to be made popular. It obviously provides a significant economics to the buildings. Nevertheless, in this analysis, all the options considered are roof slabs and are designed in such a way that there's no restriction for loading. Hence, the values do cancel out in the analysis and thus are not included in the analysis.

Maintenance Cost

Maintenance cost was considered as an annual expenditure only for systems with vegetation since all the other maintenance works cancel out over all the options.

There are two basic processes of maintaining green roofs. Monthly maintenance includes cutting and trimming, watering and other maintenance works, which would cost about Rs. 2000/= per month with transportation, according to the field experts. Fertilizing is performed quarterly, which costs around Rs. 400/= per application. These sum up to Rs. 256/= per year per m^2.

Cooling Load

Cooling loads were calculated for the model shown in Figure 7.1, using the software package, 'Design Builder v4'.

As it has been mentioned, the simulated building is a three-storey office building with a plan area of $15m \times 15m$, located at Moratuwa, Sri Lanka. No openings were provided in East-West directions to avoid the effect of short-wave radiation into the building. A 30% of glazed windows were provided in North-South directions and were provided with 1m-overhangs. The walls were taken to be 225mm thick brick walls. Other related details to the model are presented in Appendix D. The rationale of choosing these parameters was to minimise the heat gain into the building from the elements other than roof so that the real effect of the roof is evaluated properly.

The details of model calibration were presented in Chapter 6.

Two basic options were considered in the analysis;

1. When the operational period is from 0800h - 1700h
2. When the building is always operational

The first of the options was deemed to obtain the actual energy saving achieved for a typical office building by insulating the roof, and the latter was to get the peak energy saving potential.

For each option, there were nine cases considered as described above;

- Case 1A: Lifespan of 10 years and discounting factor of 8%
- Case 1B: Lifespan of 10 years and discounting factor of 10%
- Case 1C: Lifespan of 10 years and discounting factor of 12%
- Case 2A: Lifespan of 20 years and discounting factor of 8%
- Case 2B: Lifespan of 20 years and discounting factor of 10%
- Case 2C: Lifespan of 20 years and discounting factor of 12%
- Case 3A: Lifespan of 50 years and discounting factor of 8%
- Case 3B: Lifespan of 50 years and discounting factor of 10%
- Case 3C: Lifespan of 50 years and discounting factor of 12%

7.4 Results of the Life Cycle Cost Analysis

7.4.1 Option 1: When the Operational Period is from 0800h -1700h

As it has been mentioned, this option was considered to find out the overall energy saving potential for a typical day in summer under tropical conditions in Sri Lanka. Figure 7.2 shows the cumulative normalised (calculated per unit area) heat gain values obtained for the model considered. From that, it is evident that heat gains by exterior windows, occupants, office equipment and lighting sums up to about $37W/m^2$ at its peak. This is the load that sucks up the cooling load latently. Further, the peaks are observed in early morning and late evening due to a higher amount of energy used up for lighting, proving that the graph reflects the actual condition of a typical office building.

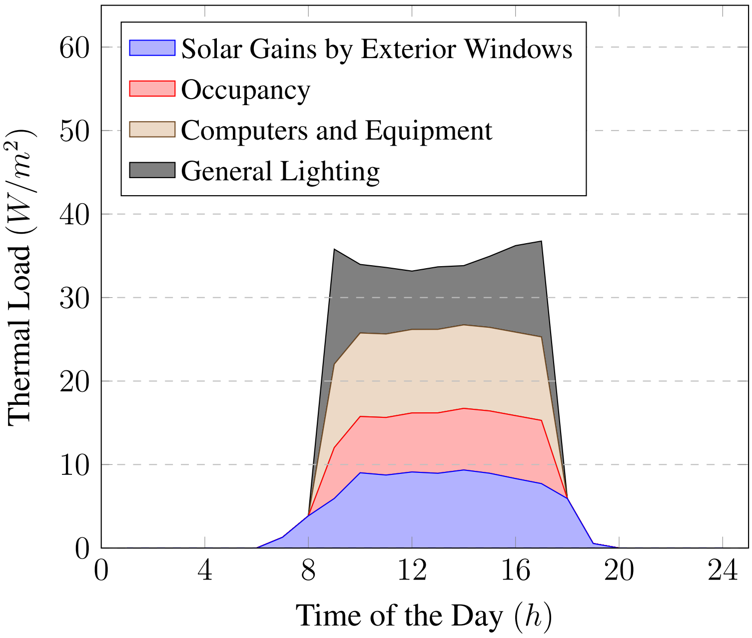


Figure 7.2: Cumulative Heat Gains other than Roof Solar Gains in the Building when the Building is Operational from 0800h-1700h

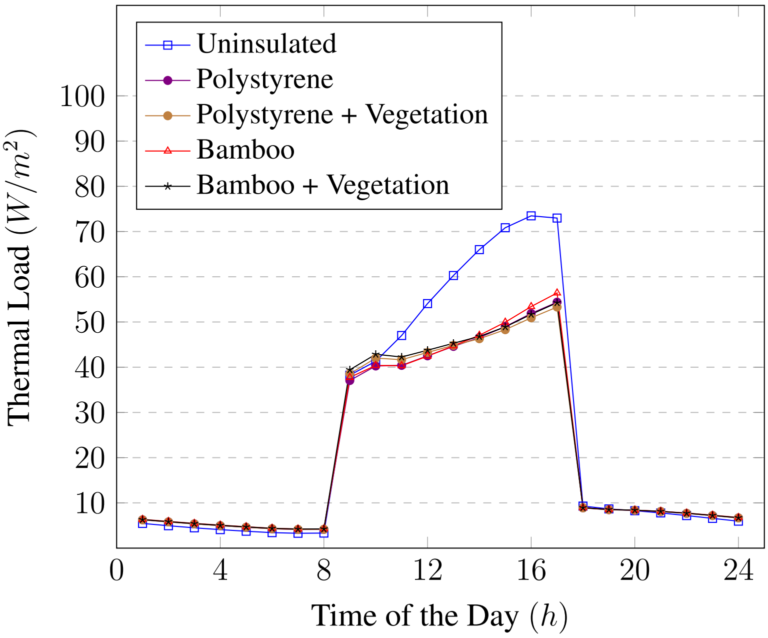


Figure 7.3: Sensible Cooling Loads for each of the Options Considered for Insulation

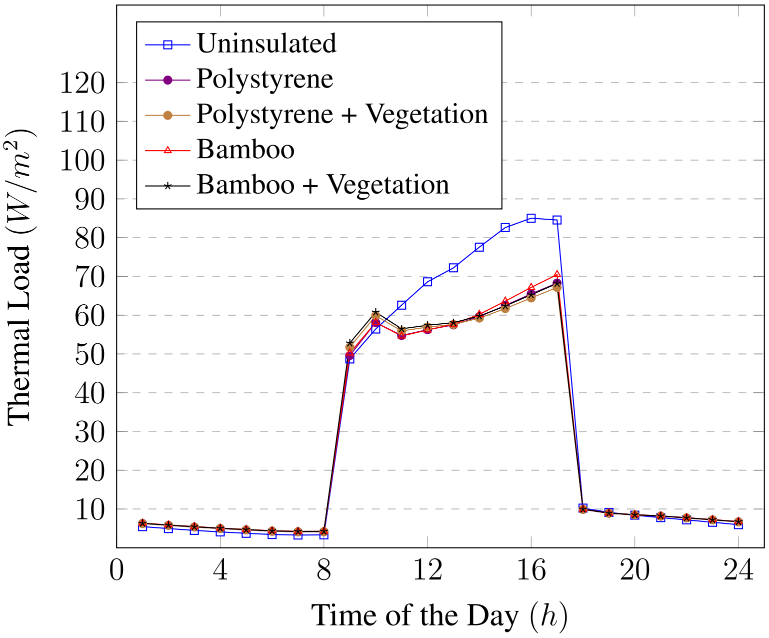


Figure 7.4: Total Cooling Loads for each of the Options Considered for Insulation

The sensible cooling load and the total cooling loads required to keep the building below the neutrality temperature, 26^0C for Colombo (Jayasinghe et al., 2002), are presented in Figure 7.3 and Figure 7.4 respectively.

Here, it is apparent that a significant cooling load reduction can be obtained by insulation of roof slabs in comparison with an uninsulated roof slab. However, the alternative options considered does not seem to have a significant effect on cooling load.

The life cycle cost values for the three different lifespans (case 1, case 2 and case3) considered are presented in Figures 7.5, 7.6 and 7.7 respectively.

Observing these figures, it is evident that insulation, in whatever the form, produces a significant economic benefit in comparison with an uninsulated case. The four insulation options considered have life cycle cost values in the same order, with minute differences. This proves that insulation is economically feasible in any case.

In the comparison two insulation materials, polystyrene and bamboo, when lifespan (N) is 10, bamboo has a clear edge regarding LCC, but when it reaches 50 years, the gap is narrowed. In any case, bamboo stays economically preferable for all the options considered and for all the lifespans analysed.

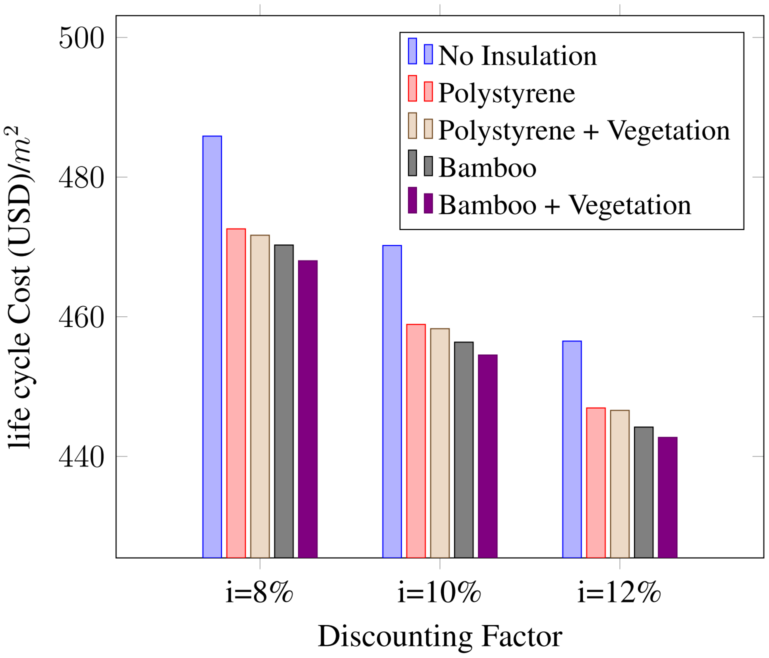


Figure 7.5: Case 1- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 10 years when the Office is Operational from 0800h-1700h

Despite the maintenance cost, laying vegetation on top has further increased the economics of both the insulation materials for all the lifespans. Yet, the difference in costing values do not provide a persuasive justification to lay vegetation on top.

Conclusively, the performance of bamboo, with or without vegetation, is economically beneficial.

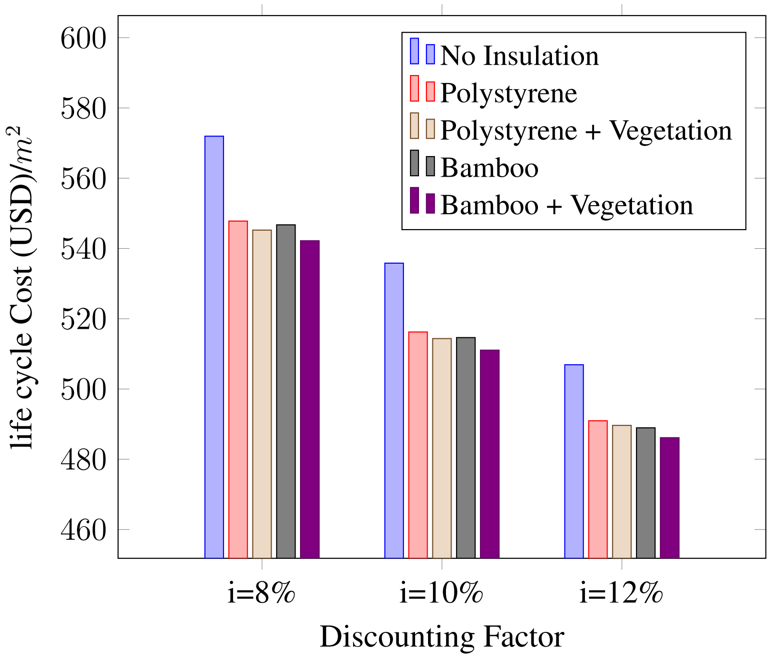


Figure 7.6: Case 2- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 20 years when the Office is Operational from 0800h-1700h

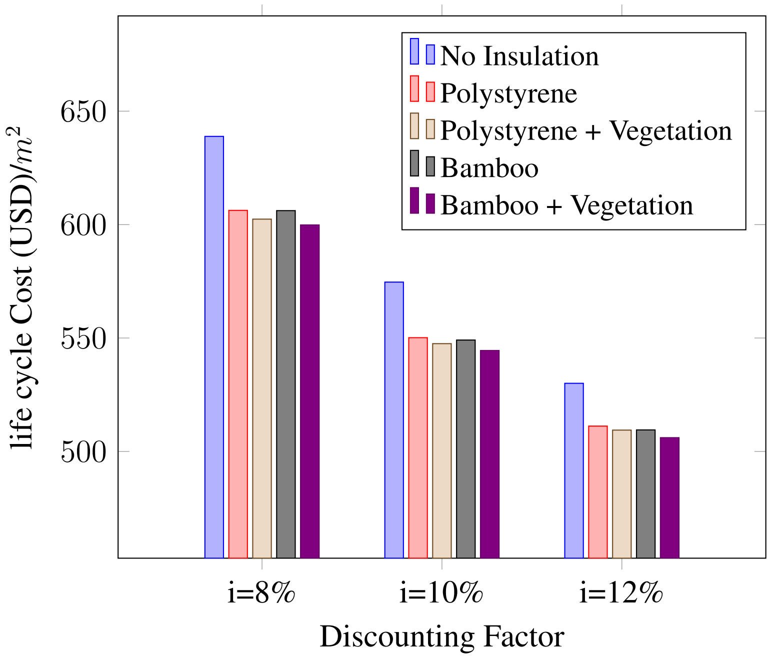


Figure 7.7: Case 3- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 50 years when the Office is Operational from 0800h-1700h

7.4.2 Option 2: When the Building is always Operational

The other option considered in the analysis was: when the building is continuously operational. This gives the peak value of the energy saving potential of the insulation system.

Figure 7.8 shows the heat gains within the building for this option. It depicts that lighting is the dominant contributor at night time, whereas in the daytime it is solar gains. The total heat gains are less in the daytime due to the less usage of the lighting equipment. The peak load of heat gains has added up to $42W/m^2$.

The total cooling loads required to keep the building under 26^0C are presented in Figure 7.9. The peak of it in the uninsulated case has been observed to be $85W/m^2$. It has been significantly reduced to around $65-70W/m^2$ with insulation, providing a 20%-peak cooling load reduction.

Figure 7.10, Figure 7.11 and Figure 7.12 show the results of the life cycle cost analysis performed for this option for the three lifespans considered (case 1, case 2 and case 3) respectively. Predictably, their life cycle costing values are in a higher order than the previous option.

Nonetheless, in this case, both the insulation materials considered in the study show a similar life cycle cost with a minute lead towards polystyrene. The difference increases with the increased lifespan but is not convincing enough up to 50 years. Thence, it can be concluded that the economic performance is similar in the two insulation materials considered for this option.

Laying vegetation on top has affected in a favourable manner in economic terms and has yielded fairly justifiable results in all the cases considered in this study.

Even though polystyrene shows slightly better performance in economic aspects, sustainability concerns force bamboo to be the dominant contender.

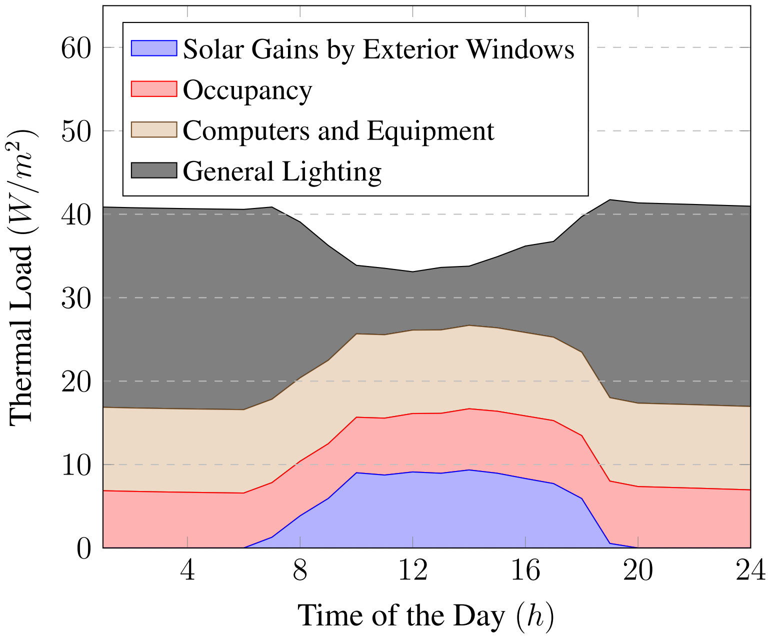


Figure 7.8: Cumulative Heat Gains other than Roof Solar Gains in the Building when the Building is always Operational

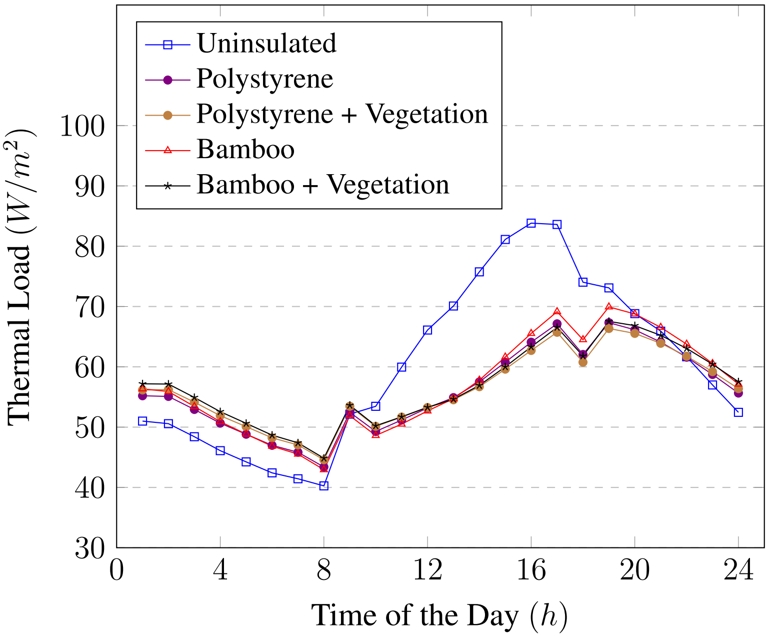


Figure 7.9: Total Cooling Loads for each of the Options Considered for Insulation when the Building is always Operational

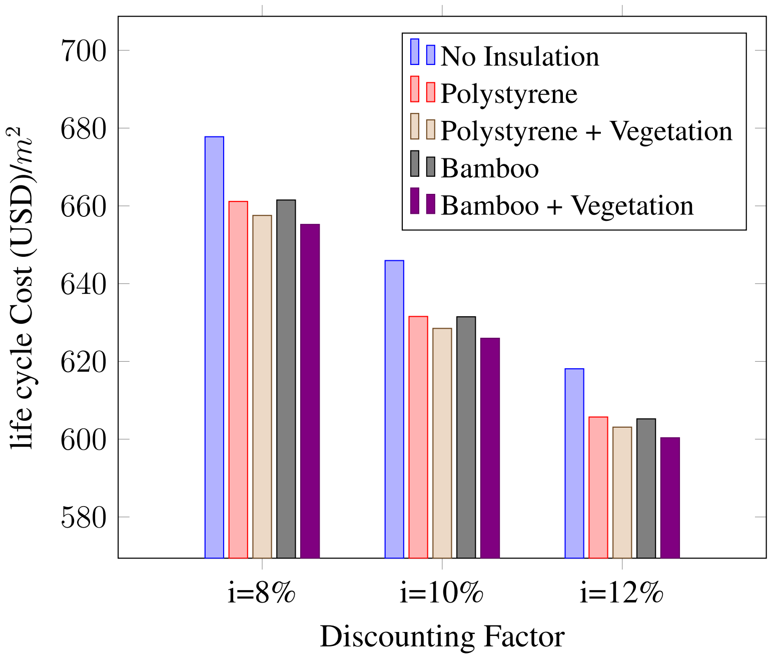


Figure 7.10: Case 1- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 10 years when the Office is always Operational

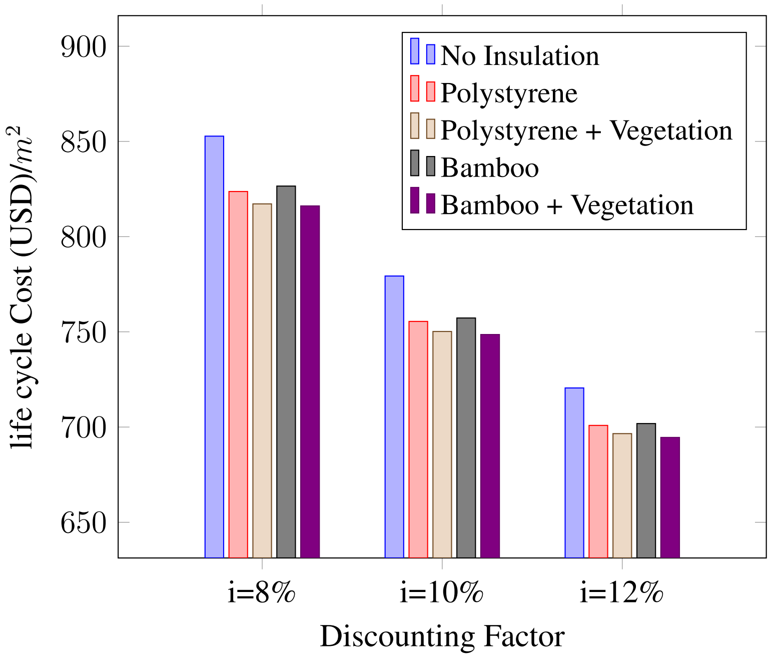


Figure 7.11: Case 2- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 20 years when the Office is always Operational

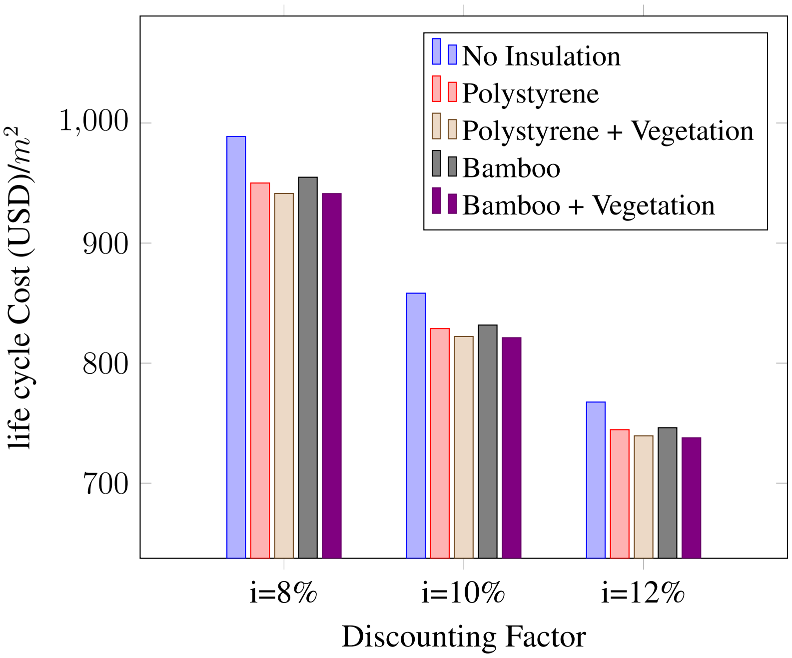


Figure 7.12: Case 3- Life Cycle Costing Analysis for Different Insulation Systems Considered for a Lifespan of 50 years when the Office is always Operational

7.5 Summary of the Life Cycle Costing Analysis

Due to the energy cost, the efficiency in the operational stage of the buildings has become a paramount concern of the end-users nowadays. This efficiency can be significantly enhanced by incorporating passive features, which demands an additional cost in some cases. life cycle Costing has been invented to strike a balance between those two cost categories.

Chapter 6 considered four different options: Polystyrene and bamboo cut in the transverse direction, with and without vegetation on top. In this case, those four options were compared for their economic feasibility with a control experiment of an uninsulated roof slab. A three-storey office building with as many passive features as possible was used for comparing the alternatives. The additional initial cost incurred and the energy saving obtained by that were compared after calculating the present values of all the cost items.

Results suggested that bamboo cut in transverse directions is performing well in economic aspects, behaving in par with polystyrene. Further, a better thermal performance and a positive economic gain can be obtained by placing a vegetation layer on top of the insulation system.

Chapter 8

Conclusions, Recommendations and Future Works

8.1 Main Conclusions

This study mainly focused on developing a new roof slab insulation system that is thermally effective, structurally sound and durable.

Flat roof slabs are incorporated with many advantages in comparison with traditional roofs. They can be used as a working or living space, or as a rooftop garden. Further, the robustness that it adds to the structure has a long-term advantage in the form of disaster resistance, particularly against cyclones.

Despite these advantages, the use of roof slabs is not that popular among the general public. It has been found out that it is because of the thermal discomfort in the immediate underneath floor. Hence, most of the buildings that have a concrete roof as a slab are either air-conditioned or use fans almost throughout when they are occupied. This increases the energy usage in the buildings, which is highly undesirable in the context of sustainability.

Roof insulation has been found out as a better remedy in addressing this issue. There are several roof insulation systems developed in the world and are proven to be effective in thermal performance. However, even the most developed systems were observed to have an issue with either their strength or durability. In this study, a new insulation system has been developed to address the observed issues.

A questionnaire survey was performed to find out the actual reasons for roof slabs be not-so-popular. According to the results, it has been emphasised that the thermal discomfort is the leading causes of the unpopularity.

Since it was intended to develop a system that is structurally sound and durable, an optimised structural arrangement with a drainage path was developed by computer simulations and was tested physically. It was proven that a discontinuous strip arrangement of $300mm \times 25mm$, with a $300mm$-longitudinal spacing and $400mm$ transverse spacing, is capable of carrying any practical load applied on that.

The thermal performance of this system was tested and compared with existing systems by small-scale physical model testing. It was observed that this newly designed system is performing even better than the existing system which is already proven to be thermally effective. Then, an actual scale model was used to check the thermal performance under real conditions, and shown that this insulation system performs even better than a calicut tiled roof with a timber ceiling. The last step of analysing the thermal performance was performing computer simulation to quantify the actual cooling load reduction. The results gave that this gives a peak cooling load reduction of around 20%.

The next step was to replace the polystyrene layer (insulation layer) with a locally available material. A 25mm-air gap was tested, and proven to be less effective than polystyrene. Further, it was observed that the thickness of the air gap does not have a significant effect on the thermal performance of the system. Then, a confined air gap was tried out with 25mm-bamboo strips laid in the transverse direction, and proven to be almost as effective as the previous case. Due to the construction convenience and the available of bamboo. This is a highly favourable option.

Consequently, the three systems above, 25mm polystyrene layer, 25mm bamboo strips and 25mm air gap, were tested with vegetation layers on top of a 50mm soil strata. Even though it was observed that there is a drastic reduction in slab top temperature, it was not reflected in such magnitudes in the soffit. Yet, a significant cooling load reduction was observed.

Finally, a life cycle cost analysis was performed and proven that the system with bamboo performs well in economic aspects, on par with a similar thickness of polystyrene. Further, a detailed study suggested that rooftop vegetation can further enhance the thermal and economic performance of the system.

8.2 Recommendations

Global Warming is the major issue that the current world is facing, and it is a burning necessity to take measures to mitigate and adapt to it. Roof slabs have been identified as a better strategy of adapting since it improves the robustness and the disaster resistance of the structures. Further, it has some additional advantages like the regaining of land by making the roof a functional space and possibility of converting to a rooftop garden

However, a concrete roof slab itself incorporates an issue of thermal discomfort. It is essential to attain the comfort levels with passive strategies in the process of mitigating global warming. Insulation is proven to be a better strategy, making those ends meet.

In this study, a new insulation system has been developed that is structurally sound, thermally efficient and durable. An insulation material is laid on top of the slab, and a protective concrete layer on top of that. There is a discontinuous strip arrangement within the insulation layer to carry the load to the slab. This system does not sacrifice any benefit that a roof slab has.

Bamboo cut in transverse direction has been tested as an insulation material, and proven to be effective in thermal aspects, and beneficial in economic aspects. A greenery layer on top was proven to be enhancing the performance both thermally and economically

8.3 Future Works

This study can be further extended in following aspects;

- This system was intended to be used in tropical climatic conditions. However, the experiments were performed in Sri Lanka. It will be worthwhile if this can be implemented in different climatic conditions and check the performance of the system.

- Only cooling effect of the insulation system was considered as this study focused on tropical climates. A complete analysis of the insulation performance can be done in different conditions.
- Several options of insulation materials can be experimentally tested to replace the traditional insulation material by a low cost locally available material.
- Durability aspects of the system under actual conditions can be performed over an extended period.
- Concrete slabs contribute to the heat island effect to a greater extent due to the light nature in colour. The actual effect of this with different colours and with rooftop vegetation can be analysed.

Appendix A

The Questionnaire Form Used

Basic Details

- **Name**

- **Age**

- **Gender**

  ☐ Male

  ☐ Female

- **Number of occupants in home**

  ☐ 1

  ☐ 2

  ☐ 3

  ☐ 4

  ☐ 5

  ☐ Other

- **Date of participation of the questionnaire survey**

- **District that your home is located**

- **Number of stories in your home**

  ☐ 1

  ☐ 2

  ☐ 3

  ☐ Other

- **Flooring material**

☐ Cement rendered

☐ Tiled

☐ Mud

☐ Cow dung

☐ Rough concrete (to be tiled)

☐ Other

- **Walling material**

☐ Brick

☐ Cement block

☐ Rammed earth

☐ Mud

☐ CSE blocks

☐ Other

Roofing Material

- **Roof covering material**

  ☐ Concrete slab

  ☐ calicut tiles

  ☐ Asbestos sheets

  ☐ Hay

  ☐ Other

Concrete Slab Users

- **Are you generally satisfied with the concrete roof slabs?**

  ☐ Yes

  ☐ No

- **Why did you go for a concrete roof slab?**

  ☐ Possibility of future extension

  ☐ Possibility of having a rooftop garden

  ☐ Cyclonic resistance

  ☐ Other

- **What are the problems you observe with concrete roof slabs**

  ☐ Too costly

  ☐ Too warm

  ☐ Cracking

  ☐ Other

- **What is the roofing material that you like?**

  ☐ Concrete slab

  ☐ calicut tiles

  ☐ Asbestos sheets

  ☐ Hay

  ☐ Other

- **The reason for that**

  ☐ Cost effective

  ☐ Beautiful

  ☐ Comfortable

  ☐ Other

Those Who Use Roofing Materials Other than Concrete Slabs

- **Are you satisfied with your roofing material?**

  ☐ Yes

  ☐ No

- **The reason that you didn't go for a concrete roof slab**

  ☐ It's too costly

  ☐ It's too warm inside

  ☐ It's not durable

  ☐ Other

- **What is the roofing material that you like?**

  ☐ Concrete slab

  ☐ calicut tiles

  ☐ Asbestos sheets

  ☐ Hay

  ☐ Other

- **The reason for that**

  ☐ Cost effective

  ☐ Beautiful

  ☐ Comfortable

  ☐ Other

Actions against Thermal Discomfort

- **What do you normally do when you feel too warm?**

  ☐ Opening the windows

  ☐ Switching on fans

  ☐ Switching on air-conditioner

  ☐ Other

- **How many fans do you have in your home**

  ☐ 0

  ☐ 1

  ☐ 2

  ☐ 3

  ☐ 4

  ☐ Other

- **How many hours do you use fans per day?**
  (Please state in total number of machine hours. For example, if you use 2 fans for 4 hours, the answer should be 8 hours)

  ☐ 1-3

  ☐ 3-4

  ☐ 4-5

  ☐ 5-7

  ☐ 7-9

  ☐ 9-12

  ☐ I don’t use fans

  ☐ Other

- **How many air-conditioned rooms do you have in your home?**

  ☐ 0

  ☐ 1

  ☐ 2

  ☐ 3

  ☐ 4

  ☐ Other

Appendix B

Mix Design Calculations Performed

The mix design calculations performed to obtain a chip-concrete mix is shown in following tables (Teychenn, Franklin, & Erntroy, 1997).

Table B.1: The Mix Design Calculation Performed to Obtain a Strength of $15 N/mm^2$ with Chip-Concrete with Water-Cement Ratio of 0.78

Stage	**Item**	**Reference or Calculation**	**Values**
1	1.1 Characteristic strength	Specified	15 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3	08 N/mm^2 (No data)
	1.3 Margin	C1 or Specified	$1.64 \times 8 = 13.12$ N/mm^2
	1.4 Target mean strength	C2	15 + 13.12 = $28.12 N/mm^2$
	1.5 Cement strength class	Specified	42.5
	1.6.1 Coarse aggregate type		Crushed
	1.6.2 Fine aggregate type		Uncrushed
	1.7 Free-water/cement ratio	Table 2,Fig 4	0.78
	1.7 Maximum free-water/cement ratio	Specified	-
	Water-Cement Ratio		**0.78**
2	2.1 Slump	Specified	125 mm
	2.2 Maximum aggregate size	Specified	10mm
	Free water content	Table 3	**233**kg/m^3
3	3.1 Cement Content	C3	233 / 0.78 = 299 kg/m^3
	3.2 Maximum cement content	Specified	-
	3.3 Minimum cement content	Specified	-
	Cement content		**299**kg/m^3
4	4.1 Relative density of aggregate (SSD)		2.7 (assumed)
	4.2 Concrete density	Fig 5	2370kg/m^3
	Total aggregate content	C4	**1838** kg/m^3
5	5.1 Grading of fine aggregate		75%
	5.2 Proportion of fine aggregate	Fig 6	43%
	Fine aggregate content	C5	**790**kg/m^3
	Coarse aggregate content	C5	**1048** kg/m^3

Table B.2: The Mix Design Calculation Performed to Obtain a Strength of $15N/mm^2$ with Chip-Concrete with Water-Cement Ratio of 0.75

Stage	Item	Reference or Calculation	Values
1	1.1 Characteristic strength	Specified	15 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3	08 N/mm^2 (No data)
	1.3 Margin	C1 or Specified	1.64×8 = 13.12 N/mm^2
	1.4 Target mean strength	C2	15 + 13.12 = $28.12N/mm^2$
	1.5 Cement strength class	Specified	42.5
	1.6.1 Coarse aggregate type		Crushed
	1.6.2 Fine aggregate type		Uncrushed
	1.7 Free-water/cement ratio	Table 2,Fig 4	0.78
	1.7 Maximum free-water/cement ratio	Specified	0.75
	Water-Cement Ratio		**0.75**
2	2.1 Slump	Specified	125 mm
	2.2 Maximum aggregate size	Specified	10mm
	Free water content	Table 3	**233**kg/m^3
3	3.1 Cement Content	C3	233 / 0.75 = 311 kg/m^3
	3.2 Maximum cement content	Specified	-
	3.3 Minimum cement content	Specified	-
	Cement content		**299**kg/m^3
4	4.1 Relative density of aggregate (SSD)		2.7 (assumed)
	4.2 Concrete density	Fig 5	2370kg/m^3
	Total aggregate content	C4	**1826** kg/m^3
5	5.1 Grading of fine aggregate		75%
	5.2 Proportion of fine aggregate	Fig 6	40%
	Fine aggregate content	C5	**767**kg/m^3
	Coarse aggregate content	C5	**1059** kg/m^3

Table B.3: The Mix Design Calculation Performed to Obtain a Strength of $15 N/mm^2$ with Chip-Concrete with Water-Cement Ratio of 0.70

Stage	Item	Reference or Calculation	Values
1	1.1 Characteristic strength	Specified	15 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3	08 N/mm^2 (No data)
	1.3 Margin	C1 or Specified	$1.64 \times 8 = 13.12$ N/mm^2
	1.4 Target mean strength	C2	$15 + 13.12 = 28.12 N/mm^2$
	1.5 Cement strength class	Specified	42.5
	1.6.1 Coarse aggregate type		Crushed
	1.6.2 Fine aggregate type		Uncrushed
	1.7 Free-water/cement ratio	Table 2,Fig 4	0.78
	1.7 Maximum free-water/cement ratio	Specified	0.70
	Water-Cement Ratio		**0.70**
2	2.1 Slump	Specified	125 mm
	2.2 Maximum aggregate size	Specified	10mm
	Free water content	Table 3	**233**kg/m^3
3	3.1 Cement Content	C3	233 / 0.70 = 333 kg/m^3
	3.2 Maximum cement content	Specified	-
	3.3 Minimum cement content	Specified	-
	Cement content		**333**kg/m^3
4	4.1 Relative density of aggregate (SSD)		2.7 (assumed)
	4.2 Concrete density	Fig 5	2370kg/m^3
	Total aggregate content	C4	**1804** kg/m^3
5	5.1 Grading of fine aggregate		75%
	5.2 Proportion of fine aggregate	Fig 6	40%
	Fine aggregate content	C5	**722**kg/m^3
	Coarse aggregate content	C5	**1082** kg/m^3

Table B.4: The Mix Design Calculation Performed to Obtain a Strength of $15N/mm^2$ with Chip-Concrete with Water-Cement Ratio of 0.65

Stage	Item	Reference or Calculation	Values
1	1.1 Characteristic strength	Specified	15 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3	08 N/mm^2 (No data)
	1.3 Margin	C1 or Specified	$1.64 \times 8 = 13.12$ N/mm^2
	1.4 Target mean strength	C2	15 + 13.12 = $28.12N/mm^2$
	1.5 Cement strength class	Specified	42.5
	1.6.1 Coarse aggregate type		Crushed
	1.6.2 Fine aggregate type		Uncrushed
	1.7 Free-water/cement ratio	Table 2,Fig 4	0.78
	1.7 Maximum free-water/cement ratio	Sepcified	0.65
	Water-Cement Ratio		**0.65**
2	2.1 Slump	Specified	125 mm
	2.2 Maximum aggregate size	Specified	10mm
	Free water content	Table 3	**233**kg/m^3
3	3.1 Cement Content	C3	233 / 0.65 = 299 kg/m^3
	3.2 Maximum cement content	Specified	-
	3.3 Minimum cement content	Specified	-
	Cement content		**358**kg/m^3
4	4.1 Relative density of aggregate (SSD)		2.7 (assumed)
	4.2 Concrete density	Fig 5	2370kg/m^3
	Total aggregate content	C4	**1779** kg/m^3
5	5.1 Grading of fine aggregate		75%
	5.2 Proportion of fine aggregate	Fig 6	39%
	Fine aggregate content	C5	**694**kg/m^3
	Coarse aggregate content	C5	**1085** kg/m^3

Table B.5: The Mix Design Calculation Performed to Obtain a Strength of $15N/mm^2$ with Chip-Concrete with Water-Cement Ratio of 0.60

Stage	Item	Reference or Calculation	Values
1	1.1 Characteristic strength	Specified	15 N/mm^2 at 28 days
	1.2 Standard deviation	Fig 3	08 N/mm^2 (No data)
	1.3 Margin	C1 or Specified	1.64×8 = 13.12 N/mm^2
	1.4 Target mean strength	C2	15 + 13.12 = $28.12N/mm^2$
	1.5 Cement strength class	Specified	42.5
	1.6.1 Coarse aggregate type		Crushed
	1.6.2 Fine aggregate type		Uncrushed
	1.7 Free-water/cement ratio	Table 2,Fig 4	0.78
	1.7 Maximum free-water/cement ratio	Specified	0.60
	Water-Cement Ratio		**0.60**
2	2.1 Slump	Specified	125 mm
	2.2 Maximum aggregate size	Specified	$10mm$
	Free water content	Table 3	**233**kg/m^3
3	3.1 Cement Content	C3	233 / 0.60 = 388 kg/m^3
	3.2 Maximum cement content	Specified	-
	3.3 Minimum cement content	Specified	-
	Cement content		**388**kg/m^3
4	4.1 Relative density of aggregate (SSD)		2.7 (assumed)
	4.2 Concrete density	Fig 5	$2370kg/m^3$
	Total aggregate content	C4	**1102** kg/m^3
5	5.1 Grading of fine aggregate		75%
	5.2 Proportion of fine aggregate	Fig 6	37%
	Fine aggregate content	C5	**647**kg/m^3
	Coarse aggregate content	C5	**1102** kg/m^3

Appendix C

Theoretical Calculations of Thermal Conductivities of the Systems

Calculating Thermal Conductivity of the Insulation Layer

For the Newly Designed System,

(The assumed thermal conductivities are shown in Table C.1)

Table C.1: Thermal Conductivities of the Materials used

Material	**Thermal Conductivity (Halwatura & Jayasinghe, 2007)**
Concrete	1.7 $Wm^{-1}K^{-1}$
Polystyrene	0.033 $Wm^{-1}K^{-1}$

$$\frac{1}{K_I} = \frac{1-\phi}{K_p} + \frac{\phi}{K_c}$$

$$= \frac{1-3.3\%}{0.033} + \frac{3.3\%}{1.7}; (\phi = 3.3\% \text{ by Table 4.3})$$

$$K_I = 0.034 Wm^{-1}K^{-1}$$

For the Existing System,

$$\frac{1}{K_I} = \frac{1-\phi}{K_p} + \frac{\phi}{K_c}$$

$$= \frac{1 - 16\%}{0.033} + \frac{16\%}{1.7}; (\phi = 16\% \text{ by Table 4.3})$$

$$K_I = 0.039 W m^{-1} K^{-1}$$

For the System with Continuous Insulation,

$$\frac{1}{K_I} = \frac{1-\phi}{K_p} + \frac{\phi}{K_c}$$

$$= \frac{1 - 0\%}{0.033} + \frac{0\%}{1.7}; (\phi = 0\% \text{ by Table 4.3})$$

$$K_I = 0.033 W m^{-1} K^{-1}$$

Calculating Thermal Conductivities of the Systems Themselves

Table C.2: Surface Resistances of Roof Slab

Location	**Symbol**	**Surface Resistance**
Top Surface	R_T	0.04
Soffit	R_S	0.14
Insulation System	R_I	(calculated above)

$$\text{Thermal Resistance of the New System} = \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3}; (T_i - \text{Thickness of the layer})$$

$$= \frac{0.04}{1.7} + \frac{0.025}{0.034} + \frac{0.125}{1.7}$$

$$= 0.85m^2KW^{-1}$$

$$\text{Air-to-Air Resistance of the New System} = R_T + R_I + R_S$$

$$= 0.04 + 0.85 + 0.14$$

$$= 1.03m^2KW^{-1}$$

$$\textbf{Hence, the Composite Conductivity of the newly designed system} = \frac{1}{1.03}$$

$$= 0.97Wm^{-2}K{-1}$$

$$\text{Thermal Resistance of the Existing System} = \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3}$$

$$= \frac{0.04}{1.7} + \frac{0.025}{0.039} + \frac{0.1}{1.7}$$

$$= 0.75m^2KW^{-1}$$

$$\text{Air-to-Air Resistance of the Existing System} = R_T + R_I + R_S$$

$$= 0.04 + 0.75 + 0.14$$

$$= 0.93m^2KW^{-1}$$

$$\textbf{Hence, the Composite Conductivity of the existing system} = \frac{1}{0.93}$$

$$= 1.07Wm^{-2}K{-1}$$

$$\text{Thermal Resistance of the System with Continuous Insulation} = \frac{T_1}{K_1} + \frac{T_2}{K_2} + \frac{T_3}{K_3}$$

$$= \frac{0.04}{1.7} + \frac{0.025}{0.033} + \frac{0.1}{1.7}$$

$$= 0.87m^2KW^{-1}$$

$$\text{Air-to-Air Resistance of this System} = R_T + R_I + R_S$$

$$= 0.04 + 0.87 + 0.14$$

$$= 1.05m^2KW^{-1}$$

$$\textbf{Hence, the Composite Conductivity of this system} = \frac{1}{1.05}$$

$$= 0.95Wm^{-2}K{-}1$$

Appendix D

Details of the Simulation Model Used to Calculated Cooling Loads

Basic Details

Plan Area	$15m \times 15m$
Number of stories	03
Location	Moratuwa, Sri Lanka
Latitude	$6.79^0 N$
Longitude	$79.9^0 E$
Altitude	30m
Exposure to wind	Normal
Average monthly mean temperature	$28^0 C$
Nearest weather station	Ratmalana, Sri Lanka

Activity Details

Type of the building	Office
Occupancy rate	$0.1/m^2$
Metabolic rate	Corresponds to light office work
Degree of clothing	Summer clothing
Target luminance	600 lux
Energy generation by equipment	$10W/m^2$

Construction Details

Thickness of the roof slab	100mm
Thickness of the intermediate slabs	100mm
Walling material	Brick
Thickness of walls	225mm
Percentage of openings in E-W direction	0%
Percentage of openings in N-S direction	30%
Type of openings	Glazed windows with 1m-overhang

HVAC Details

Neutrality temperature (operative)	26^0C
Air infiltration	0.5 ach
Coefficient of performance	2.0
Supply air temperature	12^0C
Supply air humidity ratio	0.008

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