COOLING POTENTIAL OF PASSIVE ROOF TREATMENTS ON THE CONCRETE FLAT ROOF IN PENANG, MALAYSIA

by

ASMAT BINTI ISMAIL

Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

July 2013

ACKNOWLEDGEMENTS

Alhamdulillah, in completing this research project, I wish to express my heartfelt gratitude to a number of people without whom; this research project would not have been manifested.

First and foremost, I am greatly indebted to my main supervisor, Assoc Prof. Ar Dr Abdul Malek Abdul Rahman who has unrelentingly guided and supported me from the beginning of my PhD journey right up to the end. He has dealt with my ideas and failings with patience, always giving new insights so that I do not falter. His highly regarded knowledge of the subject matter is an inspiration to me.

My co-supervisor, Assoc Prof. Dr Muna Hanim Abdul Samad have also been instrumental in moulding me into the PhD candidate that I am today with her invaluable comments and ideas. She had inadvertently made me feel like a friend by listening, especially on those dark days when I was at my deepest lows.

I am also extremely grateful to Dr Foong Swee Yeok from the School of Biological Sciences for her kind assistance and for teaching me details of CO_2 uptake of green roof plants. My deepest gratitude goes to the lecturers and support staff of the School of Housing, Building and Planning, USM especially to Puan Normah Ismail for helping in all matters regarding PhD candidature; and to Encik Md Noh Suhaimi and En Zulyadain Hassan for their logistical support during the setting up of the experiments at the case study building.

I also wish to thank the Jabatan Pembangunan USM for allowing the planting of plants in the USM nursery for the purpose of carrying out the experiments in this research.

I am deeply indebted to the Ministry of Higher Education (Malaysia), Universiti Teknologi MARA, Malaysia and Universiti Sains Malaysia for sponsoring this research. This research project would not have been possible without the necessary logistics provided by Dr Khairun Yahya; the Director of the Centre for Marine and Coastal Studies (CEMACS), USM, who have allowed me to use their portable photosynthesis meter and for deploying her staff to assist me during conducting CO_2 uptake measurements. Many thanks go to Mr Kumaradevan a/l Saminathan; Science Officer and Abdullah Nanyan; Senior Lab Assistant from CEMACS for their timely assistance in operating the portable photosynthesis machine and conducting the measurements. In this aspect, special thanks go to the owner of the experimental building (during the experimental period), Prof. Dr Mohamed Izham Mohd Ibrahim and Dr Norlela Maarup for opening the doors of their house for use as a case study building.

All my love and gratitude go to my beloved husband Azamuddin Husin, and children Ahmad Naufal Haziq, Amelia Ilyana and Alya Najwa for all their sacrifices, moral support and patience in seeing me through all the ups and downs of my PhD struggle. Thank you for being there.

Not forgetting my love and gratitude to both my beloved parents, Hj Ismail bin Awang Seman and Pn Maznah bte Semail for their support and unending prayers for my success and wellbeing. Many thanks are also due to my beloved mother-in-law, Pn Hjh Rayahan Abdullah for her full support and encouragement for me to complete this PhD. Special thanks too to all my family and friends who have endlessly given me their moral support and a shoulder to cry on, may Allah bless you all! My last acknowledgement goes to my beloved youngest sister, Azleen Ismail, who had spent her precious time in helping me on the thesis formatting.

TABLE OF CONTENTS

PAGE

CHAPTER 2: LITERATURE REVIEW ON THE COOLING POTENTIAL OF GREEN ROOFS, WHITE ROOFS AND DOUBLE ROOFS

CHAPTER 3: METHODOLOGY AND RESEARCH DESIGN

CHAPTER 5: RESULTS AND DISCUSSION: CARBON DIOXIDE (CO_2) UPTAKE BY GREEN ROOF PLANTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

ACH	- Air Change per Hour
CDM	- Clean Development Mechanism
CFC	- Chlorofluorocarbon
CH_4	- Methane
CO_2	- Carbon Dioxide
CR	- Coverage Ratio of Leaf
EE	- Energy Efficiency
EQ	- Environmental Quality
GBI	- Green Building Index
GHG	- Greenhouse Gas
IPCC	- Intergovernmental Panel of Climate Change
JMO	- Japan Meteorology Office
NASA	- National Aeronautics and Space Administration
N_2O	- Nitrogen Oxide
NOAA	- National Oceanic and Atmospheric Administration
NRE	- Natural Resources Environmental
PAR	- Photosynthetically Active Radiation
RH	- Relative Humidity
SM	- Sustainable Site Planning and Management
SRI	- Solar Reflectance Index
TLT	- Total Leaf Thickness
TRR	- Thermal Reduction Rate
UHI	- Urban Heat Island
UNFCC	- United National Frame Convention on Climate Change

LIST OF SYMBOLS

A	- Net Photosynthesis Rate
d	- thickness of the material (m)
k	- thermal conductivity of the material (W/m K)
Pn	- Daytime Photosynthesis Rate
r	- Correlation Coefficient
R	- Dark Respiration Rate
R^2	- Coefficient of Determination
R	- *thermal* resistance of the component (m^2 K/W)
Rsi	- Standard inside surface resistance
R_1, R_2	- Resistance of that particular material
R_a	- Standard resistance of any air space
R_{so}	- Standard outside surface resistance
U	- *U*-value (W/m^2 K)
ΣR	- Sum of all component thermal resistances (*R-value*)

POTENSI PENYEJUKAN RAWATAN BUMBUNG SECARA PASIF KE ATAS BUMBUNG KONKRIT RATA DI PULAU PINANG, MALAYSIA

ABSTRAK

Peningkatan suhu global akibat pemanasan global telah memberikan impak besar ke atas persekitaran dan penghuni bangunan. Kepekatan gas rumah hijau yang lebih tinggi di atmosfera, terutamanya karbon dioksida (CO_2), diandaikan sebagai penyebab kepada fenomena berkenaan. Suhu luaran dan dalaman yang lebih tinggi mengakibatkan penggunaan tenaga yang tinggi di dalam bangunan akibat daripada penggunaan alat penyaman udara serta lain-lain sistem pengudaraan mekanikal secara berlebihan. Salah satu kaedah berkesan untuk mengatasi masalah ini ialah dengan melaksanakan sistem penyejukan pasif ke atas elemen-elemen bangunan. Kajian lalu menunjukkan bahawa teknik-teknik penyejukan pasif menggunakan teknologi bumbung hijau, bumbung dua lapis, dan bumbung reflektif (bumbung putih) boleh memberi impak positif ke atas persekitaran bangunan. Sungguhpun begitu, potensi penyejukan teknologi berkenaan berbeza bergantung kepada reka bentuknya dan iklim. Oleh yang demikian, satu kajian perbandingan ke atas teknologi penyejukan pasif berkenaan telah dijalankan di dalam penyelidikan ini bagi menyiasat keberkesanan teknologi-teknologi tersebut dalam iklim di Malaysia. Satu siri kajian ujikaji lapangan telah dijalankan ke atas bumbung rata sebuah bangunan kediaman setingkat, dalam keadaan cuaca sebenar. Persekitaran luaran dan dalaman telah dipantau di dalam penyelidikan ini bertujuan menilai rawatan penyejukan bumbung secara pasif yang paling berkesan di antara bumbung hijau tumbuhan berpasu (bumbung dengan tumbuhan berpasu), bumbung dua lapis (bumbung dengan ruang pengudaraan selebar 6 inci) dan bumbung putih. Hasil kajian menunjukkan kesan penyejukan yang signifikan bagi semua strategi. Perbezaan suhu udara

dalaman-luaran yang paling tinggi, yang merupakan kriteria utama dalam penentuan kesan penyejukan, telah diambil kira dalam penyelidikan ini. Bumbung dua lapis mempamerkan perbezaan purata suhu dalaman-luaran yang paling tinggi, iaitu 4.97^{o}C, diikuti oleh bumbung hijau tumbuhan berpasu (4.22^{o}C) dan bumbung putih (3.30^{o}C). Bumbung asal yang kosong menunjukkan perbezaan purata suhu udara dalaman-luaran yang paling rendah iaitu 3.00^{o}C. Tesis ini juga membentangkan hasil penyerapan CO_2 oleh pokok-pokok bumbung hijau yang diletakkan di atas bumbung rata. Hasil kajian menunjukkan bahawa jumlah penyerapan CO_2 oleh 102 buah pasu pokok *Ipomoea pes-caprae* yang diletakkan di atas bumbung rata berkeluasan 11.90 m^2 adalah dijangkakan sebanyak 0.057 tan setahun.

COOLING POTENTIAL OF PASSIVE ROOF TREATMENTS ON THE CONCRETE FLAT ROOF IN PENANG, MALAYSIA

ABSTRACT

The rise in global temperature due to global warming has a major impact on the environment and building occupants. The higher concentration of greenhouse gases, in the atmosphere, especially carbon dioxide (CO_2), is thought to be the reason for this phenomenon. Higher outdoor and indoor air temperatures lead to higher energy consumption in buildings due to the excessive use of air conditioning and other mechanical ventilation systems. Implementing passive cooling systems into the building elements can be a promising way to overcome this problem. From the literature, passive cooling techniques using green roof, double roof, and reflective roof (white roof) technologies could have a positive impact on the building environment. However, the cooling potential of these technologies varies depending on their design and the type of climate. Therefore, in order to investigate the effectiveness of these technologies in the Malaysian climate, a comparative study of these passive cooling technologies is carried out in this research. A series of field experimental studies has been carried out on a real building, i.e., on the flat roof of a single-storey residential building, in the actual weather conditions. The indoor and outdoor environments were monitored in this research to evaluate the most effective passive cooling roof treatment between the potted plant green roof (roof with potted plants), double roof (roof with 6 inches ventilated air gap) and white roof. The results show a significant cooling effect for all strategies. The highest indoor-outdoor air temperature difference, which is the main criteria in determining the cooling effect, is taken into account in this research. The double roof exhibited the highest average indoor-outdoor temperature difference, which was 4.97^{o}C, followed by the potted

plant green roof (4.22^{o}C) and the white roof (3.30^{o}C). The existing bare roof demonstrated the lowest indoor-outdoor air temperature difference, which was at 3.00^{o}C. This thesis also presents the results of CO_2 uptake by the green plants installed on the flat roof. The result shows that the amount of CO_2 uptake by 102 pots of *Ipomoea pes-caprae* installed on 11.90m^2 flat roof was predicted 0.057 tonnes per year.

CHAPTER 1

INTRODUCTION

1.1 Background

The global warming phenomenon is becoming a worldwide alarming concern nowadays. By definition, climate change or global warming refers to an increase in the mean annual surface temperature of the earth's atmosphere, due to an increase in the atmospheric concentrations of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), CFCs and nitrous oxide (N_2O) (Houghton et al., 2002). The Intergovernmental Panel on Climate Change (IPCC) defined climate change as a change in a state of the climate that can be identified by changes in the mean and/or the variability of its properties that persists for an extended period, typically decades or longer (e.g., using statistical tests) (Core Writing Team, et al., 2007). The IPCC has predicted that the global average surface temperature will increase from 1.4^{o}C to 5.8^{o}C by 2100 (relative to the 1961 – 1990 average) by taking into account the intensive use of fossil fuel scenarios. According to the United Nations Framework Convention on Climate Change (UNFCCC), global warming is caused by an excess of heat-trapping gases, particularly carbon dioxide, methane and nitrous oxides produced by the burning of fossil fuels, from agriculture and waste dumps. These gases prevent the sun's energy from radiating back into the atmosphere after reaching the earth's surface and act like the glass of a greenhouse (UNFCCC, 2011). Amongst the effects of global warming are the melting of the ice shelf in Antarctica, the rise of sea level and retreating glacier, more frequent occurrences of drought and flooding, rise in malaria and increased incidents of hurricanes and forest fires

(Bulkeley & Betsil, 2005 ; UNFCCC, 2011). For the past 30 years, the global surface temperature has increased approximately 2^{o}C per decade with the western Equatorial Pacific being warmer than the Eastern Equatorial Pacific throughout the past century (Hansen et al., 2006). The IPCC, in their fourth assessment report, presented that the last twelve years (1995 to 2006) were among the warmest years record for global surface temperature since 1850 (Core Writing Team, et al., 2007). These reports also stated that the linear warming trend over the last 50 years from 1956 to 2005, which was 0.13 [0.10 to 0.16] °C per decade, is nearly double compared to the last 100 years, from 1906 to 2005.

According to analysis from NASA's Goddard Institute for Space Studied, 2010 tied 2005 as the warmest year on record, and January 2000 to December 2009 came out as the warmest decade on record ("Global Climate Change"; Cole & McCarthy, 2011). A previous analysis shows that 2009 was granted as the warmest year on records in the Southern Hemisphere (Cole & McCarthy, 2010). Separate analyses done in Britain and Japan lists 2010 as the second warmest (JMA, 2010; NOAA, 2010; "Global Warming Continues," 2011).

In 1992, more than 180 countries signed the Framework Convention on Climate Change in Rio de Janeiro, which declared that serious action should be taken to reduce man-made GHG gas emissions. In 1997, 38 countries comprising mainly industrialized countries, including the US, all countries of the European Union and some other European countries such as Norway and Switzerland, as well as Australia, New Zealand, Canada and Japan, and a few countries in transition to a market economy, such as Russia and Ukraine, signed the Kyoto Protocol. They agreed to reduce their GHG emissions by an average of 5.2 percent compared to the 1990 emission levels by the target period 2008 – 2012. However, after four years of the signing the Kyoto Protocol, the parties have still not agreed on the final details. None of the countries that committed themselves to binding abatement targets has ratified the Protocol. The situation is even worse in as much as the emissions of most countries have increased over the last few years. After taking office, President Bush declared that the US would withdraw from the Protocol (Bohringer et al., 2002).

“Malaysia is already committed under the UNFCCC to formulate, implement, publish and regularly update national and, where appropriate, regional programmes containing measures to mitigate climate change by addressing anthropogenic emissions by sources and removals by sinks of all greenhouse gases” (Selamat and Abidin, 2012). In September 2002, Malaysia ratified the Kyoto Protocol and categorised as Non-Annex 1 member or non-industrialised countries member. Annex 1 countries are the industrialised countries that are required to reduce the carbon emissions (“Signing of Memorandum,” 2006). Under the Kyoto Protocol, three mechanisms have been stipulated in assisting Annex 1 countries to reduce their carbon emissions. Clean Development Mechanism (CDM) is one of the stipulated mechanisms. In Malaysia, National Committee for CDM was formed in 2003. The Ministry of Natural Resources and Environment (NRE) headed this committee to screen and evaluate the applications of project from industry. This is to ensure that the projects meet the CDM criteria and national policies. In the Ninth Malaysia Plan, CDM was identified as a mechanism to promote renewable energy (RE) since the energy sector is the major contributor to the carbon emission in Malaysia (“Signing of Memorandum," 2006). In 2009, Malaysia Prime Minister, Najib Razak, has announced that Malaysian Government has targeted and committed to reduce its carbon emission up to 40% by the year 2020, at the United Nation Climate Change Conference 2009 in Copenhagen (Bernama, 2009).

1.2 Greenhouse Gas (GHG) Emissions

GHG is defined as the quantities of gas emissions into the atmosphere from the increase in human activities, such as in industry, agriculture and home or transport. This scenario is resulting in an increase in the amount of carbon already present in the atmosphere. Carbon dioxide acts like a blanket over the surface and keeps the earth even warmer because of its ability to absorb heat radiation from the earth's surface. When the air temperature is increased the amount of water vapour in the atmosphere will also increase, thus providing more blanketing and causing it to be even warmer (Houghton, 2004). With an increase in global temperature, the problem of global climate change is becoming a real nightmare.

1.3 Carbon Dioxide Concentration in the Atmosphere

Carbon compounds in the atmosphere play a major role in ensuring that the planet is warm enough to support its rich diversity of life (Smith, 2005). According to research into Antarctic ice cores published in *Science*, the CO_2 levels are 27% higher than at any point in the last 650,000 years (Brook, 2005). This finding was supported by Schmid (2007) who stated that carbon dioxide emissions in the atmosphere are increasing faster than expected. When comparing the emissions between 2006 and 1990, the emissions were 35% higher in 2006 than in 1990. Robinson (2007), stated that the atmospheric CO_2 has increased by 22% in the past 50 years and higher CO_2 concentration in the atmosphere enables the plants to grow larger, faster and sustain in drier climates. Carbon dioxide, which is the leading GHG causes potentially dangerous warming of the planet because of its capability to trap heat from the sun. Carbon dioxide contributed to 80% of global warming compared to other GHGs (Lashof & Ahuja, 1990). This excessive emission into the atmosphere will lead to higher temperatures, rising sea level and an increase in the urban heat island effect. The predicted average world growth of gas emissions between 2000 and 2020 is about 2.2% per year (Galeotti & Lanza, 1999). According to Schmid (2007), burning fossil fuels and making cement are the major sources of carbon emissions. Carbon released from both items rose from 7.0 billion metric tons per year in 2000 to 8.4 billion metric tons in 2006.

Buildings are also major contributor in releasing carbon dioxide into the atmosphere. Diane et al., (2007) reported that the energy used in building around the world is one of the significant sources of GHG emissions with the use of energy in the building sector responsible for 7.85 Gt carbon dioxide (CO_2) emissions in 2002. This statement was supported by Santamouris (2007) who concluded that the use of air conditioners in buildings is the key factor associated with this problem. Santamouris also stated that the corresponding energy consumption and carbon dioxide emissions in Europe have increased substantially due to the rapid expansion of air conditioning. The use of air conditioning in buildings not only results in a high electricity load but also creates environmental problems, such as ozone depletion and global warming. In addition, a problem with indoor air quality becomes common when windows and doors are kept closed due to the use of air conditioning systems.

In Malaysia, lighting and air conditioning are the major causes of energy consumption in buildings, especially in commercial buildings (Ahmed et al., 2005). The increase in energy consumption and demand inevitably lead to an increase of GHG emissions which contribute to the impact of global climate change (Ahmed et al., 2005). A hot and humid climate such as Malaysia will require greater air condition cooling power due to the relatively high solar radiation and ambient temperature. A higher sol-air temperature will increase the temperature difference between the outdoor and indoor state (Md Zain, 2007).

From the above facts, it is clearly understood that the excessive use of mechanical ventilation in buildings, especially air conditioning, has led to human and environmental disadvantages. Air conditioning not only contributes to high energy consumption and demand but can also cause indoor air quality problems and environmental problems associated with ozone depletion and global warming (Santamouris, 2007). Therefore, reducing CO_2 emissions becomes a major consideration, especially in the built environment in order to reduce energy consumption and to save the environment.

1.4 Problem Statement

As mentioned earlier, global warming or climate change is one of the most serious environmental threats to the current and future world generations. It has been widely accepted as being a reality. Climate scientists worldwide have agreed that this climate change is 90% certain to be due to human activities (Smith, 2005). Malaysia is not immune to this current environmental threat. The vast development of the construction industry in Malaysia nowadays has resulted in the cutting down of trees, which causes warmer conditions for the environment and building occupants. The situation is much more critical during daytime hours when the indoor temperature is high. This, in turn, will result in higher dependency on mechanical ventilation and increase the energy use in buildings. By 2025, Malaysians can expect higher temperatures, which will cause frequent, widespread and more intense heat waves, flooding, droughts, tropical storms and surges in sea levels. According to weather experts, global warming could even turn Malaysia into an arid state just like Africa's parched states. Professor Dr Fredolian Tanggang, Climatologist and Physical Oceanographer said that the weather was expected to increase by 1^{o} Celsius in the next 20 years (Kaur, 2007). Since human activities are one of the main causes of global warming, as agreed by many scientists, a commitment to bioclimatic architectural design and renewable energy is inevitable.

The phenomenon of global warming that the world is facing today has contributed to the increase in outdoor and indoor temperatures. Implementing passive cooling systems into the building elements can be a promising way to overcome these problems. As the roof is the hottest part of a building, passive roof treatments are a suitable technique to cool the building.

Many researchers around the world have studied different types of roof treatment while reducing energy consumption (Bansal, 1992; Barrio, 1998; Eumorfolous &

Aravantinos, 1998; Konopacki, 1998; Akbari et al., 2000; Takakura et al., 2000; Onmura, 2001; Jayasinge et al., 2003; Ciampi et al., 2005; Gaffin, et al., 2005; Dimoudi et al., 2006; Nyuk Hien et al., 2007; Shcherba et al., 2011; Shen et al., 2011, Xu, T. et al., 2012). Researches on the cooling potential of green roofs, reflective roofs and double roof's are among the passive cooling techniques studied for various climate conditions. However, based on the background research, limited research has been done to compare the thermal performance between these three kinds of passive cooling techniques, especially in Malaysian climatic conditions. Therefore, this study is carried out to compare the cooling potentials of these three types of passive cooling roof treatments, particularly in respect of their thermal performance, and to investigate which one will have the most positive impact, not only for the indoor building environment, but also the outdoor environment.

As for the green roof, most of the researchers have studied the thermal performance, plant selection, storm water run-off of either extensive or intensive types of green roof, which use several types of green roof vegetation planted on the roof. To date, research on the thermal performance and carbon dioxide uptake by a single type of selected green roof plant is scanty. Moreover, constructing either an intensive or extensive green roof requires higher costs and the involvement of an expert green roof contractor. Therefore, to retrofit the existing bare roof with a simple green roof system, the use of potted plants on the roof top might be advantageous due to its simple installation and portability. Therefore, this study will emphasize the use of potted plants on the roof top in order to investigate their thermal performance.

Carbon dioxide, which is the main GHG, and which is thought to be the cause of global warming, has increased faster than predicted. The higher concentration of CO_2 in the atmosphere can cause higher atmospheric temperature because of its ability to trap heat from the sun, and reduce the size of ice and snow fields, and also reduce the shortwave energy absorbed by the surface of snow and water (Manabe and Stouffer, 1979; Choudhury and Kukla, 1979).

With the ability to uptake CO_2 through the photosynthesis process and abundant sunlight in the Tropics, the potential of green plants potential as thermal shield and carbon sequester on the roof is studied in this research. Since Malaysia is still new to green roof technology and still lacks experts in this field, other flexible green roof systems such as potted plant green roof should be studied in order to ensure this technology can be implemented more effectively.

1.5 Research Questions

A few research questions have been developed in this research to identify the phenomenon to be studied. Below are four questions, which have been highlighted for this research.

a. What is the improvement on the cooling potential of the concrete roof and space underneath by implementing passive cooling roof treatment in the warm and humid climate condition of Malaysia?

b. Among the various passive roof treatments, which one could exhibit the best cooling potential in single-storey residential buildings, especially on a concrete flat roof in the Malaysian climate condition?

c. Which plant can uptake the highest CO_2 and can be selected as a plant for the potted plant green roof?

d. How much of the atmospheric CO_2 could the selected green roof plant absorb in order to mitigate the impact of climate change?

1.6 Research Aim and Objectives

The aim of this research is to investigate the cooling potential of selected passive roof treatments, namely, double roof, potted plant green roof and white roof in improving indoor thermal condition in Malaysia's climate. Several specific objectives have also been formulated in this research as follows:

1. To analyse and compare the thermal performance of selected passive roof treatment chosen in this study, namely, double roof, potted plant green roof and white roof, and its cooling potential, particularly in warm and humid climate conditions of Malaysia, for concrete flat roof.

2. To determine the most suitable green plant that can uptake the highest atmospheric carbon dioxide and be used for a potted plant green roof.

3. To calculate the total amount of CO_2 uptake by selected green plants installed on the flat roof in order to estimate the CO_2 reduction in the atmosphere.

1.7 Research Methodology and Approach

The research methodology employed in conducting this research, and answering the research question stated in Section 1.5 and in achieving the research objectives highlighted in Section 1.6 can be divided into two main parts. The major part of the research methodology is the research design. The most appropriate approach considered by the author for this subject matter is by conducting experiments to test several passive cooling roof treatments. “Experiments are basically about measuring phenomena and collecting accurate and reliable data which are used for analysis and evaluation in scientific research” (Khan, 2005, p.20). The experiments in this research are done in several stages, beginning with preliminary study and field experimentation on existing building which will be further discussed in Chapter 3.

The second part of the research methodology entails the method, in which primary and secondary data were collected for the research. The main primary data gathered for this research are from the experiments, based on observations and measurements obtained during the investigation process. It is vital to investigate the real cooling potential of the passive roof treatments selected for this research in a hot humid tropical country. Since the green roof is one of the passive cooling roof treatments studied in this research, the preliminary study was conducted to select the most suitable type of green plant that can be used as a plant for the green roof. After that, the experiment to investigate the cooling potential of each passive roof treatment was conducted on the case study building. The measurements of outdoor and indoor air temperature, solar radiation, indoor humidity, indoor wind speed, indoor surface temperature and outdoor surface temperature were conducted on the roof with three different types of passive roof treatment. The measurement on an existing bare roof was also conducted during this phase. The third phase was the measurement of the photosynthesis rate of selected green roof plants in order to estimate the average CO_2 uptake. The detailed explanation of the experiment is highlighted in Chapter 3.

In gathering secondary data for this research, the author had reviewed some of the earlier works by other researchers from international journals, books and websites. It is crucial in the early stage of research to determine the research problems, by collecting data from the past and previous research projects or experiments. The secondary data is also critical in giving an overview on the fundamental insight and the theoretical framework on the subject matter. The literature review was conducted to identify the current passive cooling techniques that have been conducted worldwide in respect of improving indoor thermal performance, especially in a tropical climate. The comparative cooling effects for various types of passive cooling roof treatment gathered from previous research conducted worldwide were also identified at this stage. This literature survey led to the conclusion that green roof technology can significantly contribute to many positive effects including, among others, improving the thermal performance of the building, improving the air quality and reducing the stormwater run-off.

After the experiment was conducted, all information and data were tabled appropriately before analysis to ensure the validity of the results. All the information and data gathered from the field experiment were analysed and reported in the thesis. Finally, the conclusion and recommendations regarding the results obtained from the experiment are made at the end of this research. The summary of the research methodology is shown in Figure 1.1

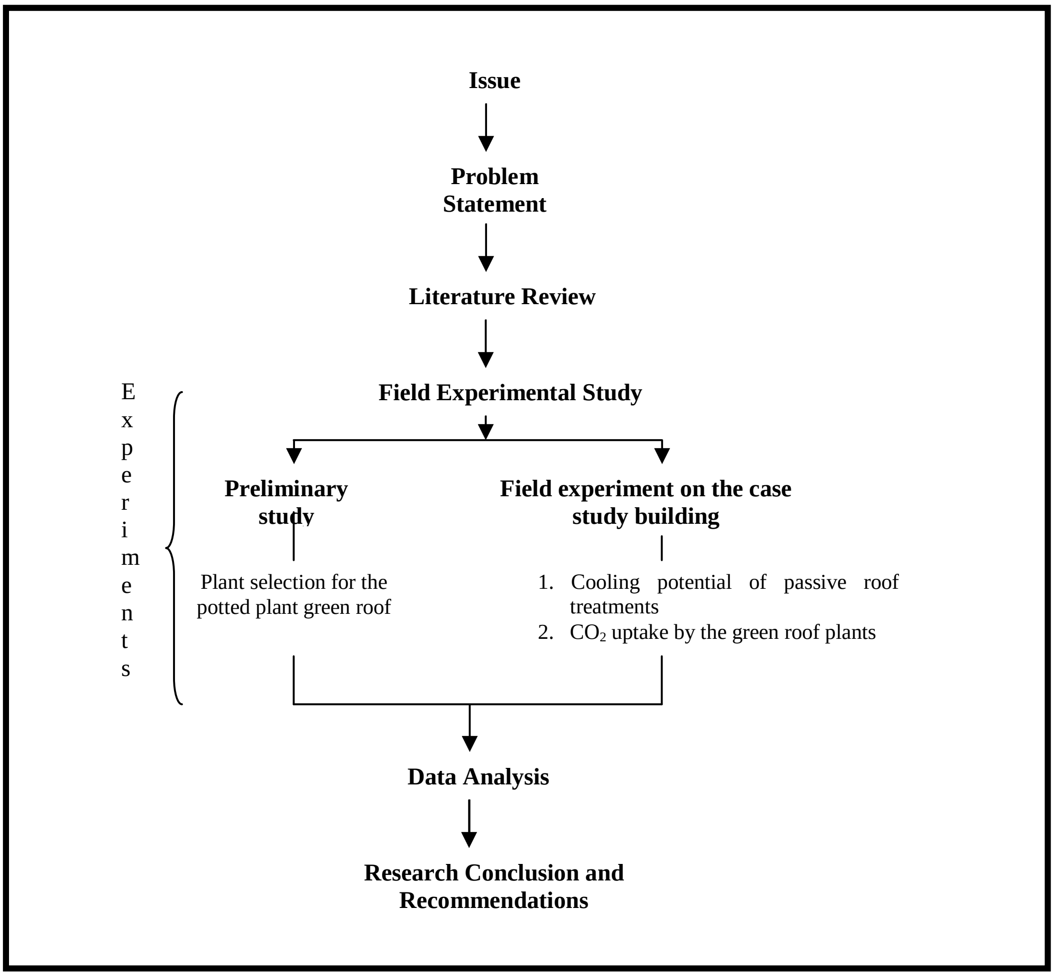

Figure 1.1: Summary of research methodology used in investigating the cooling potential of the passive roof treatments on a concrete flat roof in Malaysia.

1.8 Scope and Limitations of Research

This study emphasises on the effects of different types of passive roof treatment on indoor and outdoor cooling potential on a single-storey residential buildings with a concrete flat roof selected as the case study building in this research. This is because a single storey building experience a higher indoor temperature, particularly in the daytime hours as the distance of the roof is normally quite close to the level of occupancy in the room. Flat roofs, which are an infamous type of roofs in the Malaysian climate due to the intensive amount of rainfall, were chosen as the type of roof to study to enable the installation of potted plants on the roof surface. The indoor temperature reduction of the three different types of roof treatment was measured in order to identify the most significant methods in improving the indoor climate condition of a building. Three different types of roof treatment were investigated in this study, potted plant green roof (a roof covered with potted plants), double roof (roof with air gap), and white roof. Passive cooling strategies using a green roof and white roof were selected to be the type of roof treatment studied because these two roofs are among the most popular passive cooling techniques currently being studied. However, in this study, potted plant is used for the green roof because of its simple installation.

In addition, passive cooling using a roof with an air gap or double roof or shaded roof is chosen in this study for its simple construction. The application of double roof using plywood is limited to the fact of this experimental set-up only. However, this simple method can be used in the worst case conditions, in which the protection provided by the plywood could prevent the roof surface from an excessive solar radiation penetration, especially during daytime hours, This, in turn, could reduce or delay the heat transfer process from the roof surface into an interior surface.

The indoor and outdoor environments of the case study building will be measured for each roof treatment in order to evaluate their cooling potential. Measurement of the exposed roof will also be conducted in order to examine the temperature reduction after applying each individual treatment. In order to obtain reliable data on the temperature reduction and cooling potential of each roof treatment, the experiments were conducted on the same roof and in the same test room underneath the roof on different weeks. The outdoor and indoor environments were monitored during the experimental period in order to determine which roof treatment could give the most impressive result in terms of thermal performance and cooling potential. The outdoor air temperature, solar radiation, outdoor surface temperature, indoor air temperature, indoor surface temperature, indoor air humidity, and indoor wind speed are among the variables measured on the flat roof and in the room below.

This research also emphasizes how much the potted plants installed on the concrete flat roof can contribute to reducing the carbon dioxide concentration in the atmosphere in order to reduce the greenhouse gases emission. The measurement of the indoor environment was conducted in a room underneath the flat roof. A pitch roof was not considered in this research since a green roof using potted plants was used as one of the roof treatments to be measured.

1.9 Significance of Research / Contribution to the Body of Knowledge.

The results of this study could be used to improve the indoor cooling potential and reduce the problem of indoor discomfort due to high ambient temperature, especially in Malaysia’s climate. The research findings can be applied to improve existing passive cooling methods as well as provide added value to the existing body of knowledge in related fields. In addition, in light of the reduced environmental impact and energy consumption, the outcomes of this research might be taken as a guideline for green building design or bioclimatic building design for the future.

1.10 Conceptual Framework

The conceptual framework is developed in this study to show a relationship between the passive cooling roof treatments selected with the effect/improvement on the indoor and outdoor environment. Figure 1.2 shows the conceptual framework developed for this research. Based on the literature survey, the green roof, white roof and double roof are able to improve the indoor comfort conditions. In addition, the green roof could have a direct effect in reducing the concentration of CO_2 in the atmosphere and add extra value in improving the outdoor environment. However, to date, studies on the carbon uptake of green roof plants in the Malaysian climate are lacking. Therefore, one of the objectives of this study is to calculate and estimate the amount of CO_2 that can be taken up by selected green roof plants.

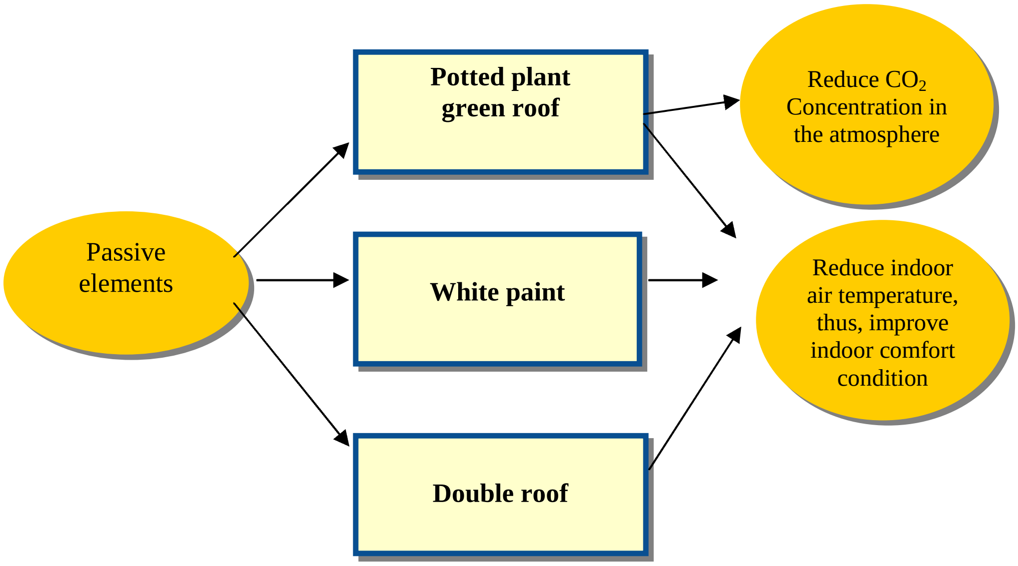

Figure 1.2: Conceptual framework designs for this research.

1.11 Research Hypothesis

From previous studies conducted in various climatic conditions, the green roof could reduce the indoor air temperature effectively compared to other passive elements. Therefore, it is assumed that potted plant green roof also will be able to reduce indoor temperature in Malaysian climate effectively compared to the double roof and white roof.

1.12 Organization of Thesis

This thesis comprises of 6 chapters. The first chapter gives an overview of the research conducted, including the problem statement, research question, research objectives, research methodology, scope and limitation of research, significant of research, hypothesis and expected output of this research. It also highlights the outline of the whole thesis. Chapter 2 covers the literature review of previous research conducted on thermal performance of selected passive cooling roof treatments. The methodology has been detailed in Chapter 3. Chapter 4 covers the data analysis for thermal performance of passive cooling roof treatments conducted from this research and the discussion. Data analysis and the discussion on the CO_2 uptake by selected green roof plants have been discussed in Chapter 5. The conclusion of the thesis and suggestion for future research are highlighted in Chapter 6.

CHAPTER 2

LITERATURE REVIEW ON THE COOLING POTENTIAL OF GREEN ROOFS, WHITE ROOFS AND DOUBLE ROOFS.

2.1 Introduction

This chapter presents the review of literature regarding three different types of passive elements to cool the roof. There are six sections highlighted in this chapter: an introduction to the chapter, an overview of passive cooling strategies, an overview of basic principles of roof thermal process, an explanation of the climate conditions in Malaysia, a review of previous research on the selected passive roof treatments, and a summary of the chapter with particular reference to the reviewed literature.

2.2 Introduction to Passive Cooling Strategies

Passive cooling strategy is the method used to cool buildings without the use of any mechanical equipment. In other words, passive cooling refers to technologies or design features used to cool buildings without the consumption of any power. Givoni (1994) defined passive cooling as cooling techniques that lower the indoor temperature of buildings by using natural energy sources. According to Givoni (1994, p.3-4), passive cooling systems can be classified into various types depending on the major, or obvious natural source from which the cooling energy is derived. The classifications of passive cooling systems are as follows:

- **Comfort ventilation** - refers to providing direct human comfort, particularly during the daytime hours. This strategy is the simplest technique in hot and humid regions. The indoor air temperature will closely follow the outdoor air temperature if there is effective cross ventilation through the building. This situation can be achieved if the cross ventilation is accompanied by a relatively high indoor air speed. Assuming an indoor air speed of 1.5 to 2.0 m/s, comfort ventilation is applicable in regions and seasons when the outdoor maximum air temperature does not exceed about 28^{o}C to 32^{o}C (Givoni, 1994, p. 17).
- **Nocturnal ventilative cooling** - refers to cooling the structural mass of the building interior by night-time ventilation and closing the building during the daytime hours. This cooling strategy could result in satisfactory performance if the building design details are appropriate. It would be preferable to comfort ventilation in regions where the daytime temperatures in summer are above the upper limit of the comfort zone, with an air speed of about 1.5 m/s. Arid regions, where the daytime temperatures are between 30^{o}C and 36^{o}C and the night temperatures are at or below 20^{o}C, are the most suitable to use this strategy (Givoni, 1994, p.17).
- **Radiant cooling** - refers to the transferring of cold energy generated during the night-time hours by radiant heat loss from the roof, or using a special radiator on the roof, with or without cold storage for the daytime hours. This cooling strategy utilizes metallic specialized radiators with fan-driven airflow, which can cool the night air below the ambient level.

- **Direct evaporative cooling** - refers to the humidified and cooled air introduced into the building after the air has been cooled by mechanical or non-mechanical evaporative cooling.
- **Indirect evaporative cooling -** refers to evaporative cooling of the roof, for example, using a roof pond. The indoor space is cooled without elevation of the humidity. Cooling the outdoor environment by evaporative mechanisms may help to lower the air temperature surrounding the building (Abdul Rahman, 2004, p. 44).
- **Soil cooling** - refers to cooling soil below its natural temperature in a given region and utilizing it as a cooling source for a building.
- **Cooling of outdoor spaces** - refers to cooling techniques that are applicable to outdoor spaces, such as patios that are adjacent to a building.

Other options for passive cooling systems are using planting next to the building skin to protect the building skin from excessive heat conduction into the interior, for example, climbing ivy or creeping plants. Roof and wall sprays are another type of passive cooling system that is simple and easy to handle. A roof spraying system can lower the roof surface temperature from 55-70^{o}C to 27-29^{o}C, while a wall spray can lower the indoor air temperature by up to 3^{o}C (Abdul Rahman, 2004, p.63). Providing an air gap and radiant barrier under the roof also has significant cooling potential. These strategies can block downward radiation from the sun by up to 97% (“Passive Cooling”, 2011). For advance passive cooling techniques, green roofs and cool roofs are the best options, which can significantly reduce or eliminate the peak outside and inside air temperatures of buildings and reduce the surface temperature by up to 21^{o}C in summer (“Passive Cooling”, 2011).

2.3 Malaysia Climate Condition

Malaysia is located in an equatorial region between 10^{o}N and 10^{o}S, and experiences hot and humid climatic conditions. The Tropics are located between 23.5^{o}N and 23.5^{o}S beginning from the Equator (Abdul Rahman, 2004). The main features of hot and humid tropical climates are relatively uniform temperatures, abundant rainfall, high relative humidity, high radiation intensities and light wind with long periods of still air due to its proximity to the Equator (Ariffin et al., 2002; Rao & Inangda, 2004). The Malaysian Meteorological Department describes the Malaysian climate as Maritime Equatorial Doldrums (Woods, 2004; Malaysian Meteorological Department, 2011). A full day, with completely clear sky (even if during a severe drought), or a few days with completely no sunshine except during the northeast monsoon seasons are rare for Malaysian skies (Syed Fadzil & Sheau Jiunn, 2002; Malaysian Meteorological Department, 2011).

Malaysia experiences a uniform temperature throughout the year (Ariffin et al., 2002; Zakaria et al., 2006; Malaysian Meteorological Department, 2011). The diurnal temperature ranges between 24.5^{o}C and 32^{o}C with +/- 0.75^{o}C, and for 60% of a 24-hour period, the ambient temperature is above the comfort level and rises to 100% for the normal working day (8.30 a.m. to 5.30 p.m.) (Woods, 2004). Solar radiation is approximately 12 hours per day from 7 a.m. until 7 p.m. (Syed Fadzil & Sheau Jiunn, 2002).

According to the Malaysian Meteorological Department, there are three types of seasonal rainfall variation in Peninsular Malaysia. November, December and January are the months with maximum rainfall over the east coast states, while June and July are the driest months in most districts. For the rest of Peninsular Malaysia, except for the southwest coastal area, the monthly rainfall patterns show two periods of maximum rainfall separated by two periods of minimum rainfall. The primary and secondary maximums occur in October-November and April-May, respectively. In the north-western region, the primary minimums occur in January-February the secondary minimum occurs in June-July, while elsewhere the primary minimum occurs in June-July with the secondary minimum in February. In the southwest coastal area, the rainfall pattern is much affected by early morning "Sumatras" from May to August. The maximum and minimum rainfalls occur in October-November and in February, respectively (Malaysian Meteorological Department, 2011).

2.4 Basic Principles of Roof Thermal Process

Roof is the building element that exposed to the climatic element such as solar radiation, rain and snow more than any other part of the building structure. According to Givoni (1976), the external surface of the roof is often subject to the largest temperature fluctuations, depending on its types and external colour. Due to this reason, roofs may be classified into two main categories, i.e. solid homogeneous or composite heavyweight roofs and lightweight roofs of a single layer or two layers (roof and ceiling) separated by an air space.

2.4.1 Solid Homogeneous or Composite Heavyweight Roofs

These types of roof are usually flat roof and built of concrete. Transference of heat from the external surface of the roof can only be affected by conduction through the mass of the roof to the ceiling surface (unless an air space is included in the structure of a composite heavyweight roof). The principal determining factors of the thermal characteristics of solid roofs are their external colour, thermal resistance and heat capacity (Givoni, 1976).

2.4.1.1 External Colour

External colour of the roofs determine the amount of solar radiation absorbed in the roof structure during the day and the amount of longwave radiative heat loss into space at night, and consequently the pattern of external surface temperature and internal heat exchange with the roof (Givoni, 1976, p.146, 154). The result of measurements carried out in Israel in summer time on lightweight horizontal panels of grey and whitewashed roofs showed that the surface temperature of a dark exterior was elevated up to $32^{o}C$ above the maximum air temperature, while the corresponding increase for whitewashed surfaces was only above $1^{o}C$. At night, the surface temperatures were invariably below the outdoor level due to the longwave radiant heat loss to the sky. The average surface temperature of the whitewashed roofs was lower than the ambient outdoor level (Givoni, 1976, p.147).

2.4.1.2 Thickness and Thermal Resistance

The thickness and thermal resistance of solid flat roofs give the major effects on the indoor climate. It is associated with the external colour and diurnal variations in outdoor air temperature (Givoni, 1976, p.149). When the external surface is dark, its temperature is elevated above the outdoor air, and resulting heat flow tends to raise the internal surface temperature. Under such condition, an increase in the thermal resistance reduces the heat flow across the wall or roof and generally lowers the internal temperatures (Givoni, 1976, p.128). The effect of thermal resistance, when the external colour is white, is quite different in regions where the outdoor temperature amplitude is small. The temperatures of the external surfaces are close to the level of the outdoor air, and heat flow across the building envelope is much smaller. Therefore, the thermal resistance of the walls or roof has only a slight effect on the daytime temperature, and may elevate the minimum temperatures more than reduce the maxima (Givoni, 1976, p. 129-130).

When the external colour is dark, the effect of thickness and insulation is very different. As the external temperature of a dark surface is higher than the outdoor and indoor temperatures, the thermal resistance of the roof determines the daytime ceiling temperature and heat flow from the roof into the house. In regions where the diurnal range is wide and the air temperatures rise above 33^{o}C, thermal insulation is useful even with whitewashed roofs to reduce heat flow due to the outdoor-indoor temperature gradient. The required amount of insulation is related to the external colour (Givoni, 1976, p.151-152).