EFFECTIVENESS AND OPTIMIZATION OF THERMAL INSULATION IN RESIDENTIAL ROOFING SYSTEM IN HOT-HUMID CLIMATE

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by

SYED AHMAD FARHAN BIN SYED AHMAD ISKANDAR

A Thesis
Submitted to the Postgraduate Studies Programme
as a Requirement for the Degree of

MASTER OF SCIENCE
CIVIL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR
PERAK

SEPTEMBER 2013

DECLARATION OF THESIS

Title of thesis	**Effectiveness and Optimization of Thermal Insulation in Residential Roofing System in Hot-Humid Climate**

I, SYED AHMAD FARHAN BIN SYED AHMAD ISKANDAR

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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DEDICATION

I would like to dedicate this research work to

my father,
Assoc. Prof. Ar. Dr. Syed Ahmad Iskandar

my mother,
Puan Jamaliah

my siblings,
Syed Hazmi Hussaini
Syed Ahmad Fahmi
Sharifah Iris Khaliesah
Syed Harraz Wildaan
Syed Afraaz Eirfan

and my wife,
Nadzhratul Husna

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Syed Ahmad Farhan bin Syed Ahmad Iskandar
September 2013

ABSTRACT (ENGLISH)

Solar radiation overheats the roof and causes thermal discomfort for occupants throughout the day. Room air-conditioners are used to improve level of thermal comfort. However, air-conditioners consume high amounts of electricity. Insulation can retard heat flow due to their high thermal resistance. Yet, developers and the public are not aware of the benefits of insulation and are unprepared to implement them. The purpose of this study is to optimize thermal insulation in residential roofing system in hot-humid climate for maximum reduction in cost and CO_2 emission. A questionnaire and interview were conducted to determine levels of awareness and preparedness and barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia. Results reveal that the level of awareness on building insulation is generally low. The level of preparedness is high among house owners but low among developers because of the lack of appreciation towards the long-term benefits of housing insulation. No legal requirement, low electricity tariff, trend of installing room air-conditioners and additional cost are identified as barriers of the implementation of housing insulation. Then, a house model experiment using two (2) small-scaled house models was carried out to validate the effectiveness of thermal insulation in roof in hot-humid climate. Findings show that insulation can significantly reduce indoor air temperature. The highest outdoor-indoor temperature difference of 8.40°C was obtained by 100-mm thick kapok fibre insulation. Next, a simulation was carried out to evaluate the indoor temperature profiles of thermal insulation of varying material, thickness and placement in energy-efficient residential roofing system. 50-mm thick reinforced silica aerogel insulation at roof pitch obtained the lowest indoor temperature of 27.20°C at peak outdoor temperature at 1600 hours. Lastly, calculations were done to project the cost and CO_2 emission of residential building for optimization of thermal insulation in roof. Maximum electricity consumption reduction of 2646.39 kWh was obtained for kapok fibre ceiling insulation. Maximum CO_2 emission reduction of 1720.15 kg CO_2, equivalent to removing 5.49 cars off the road or planting 10.81 new trees, was obtained, also for kapok fibre ceiling insulation. The lowest optimum insulation thickness of 0.0047 m was obtained for reinforced aerogel insulation at roof pitch, while the highest optimum insulation thickness of 0.0655 m was obtained for cellulose insulation above the ceiling. Optimization of thermal insulation in residential roofing system is achieved by determining the combination of material, thickness and placement of thermal insulation in residential roofing system that can lead to the highest cost savings and positive environmental impact. The optimum thermal insulation obtained in the research is 0.0641-m thick kapok fibre ceiling insulation.

ABSTRAK (BAHASA MALAYSIA)

Sinaran matahari memanaskan bumbung dan menyebabkan ketidakselesaan terma kepada penghuni sepanjang hari. Penghawa dingin digunakan untuk meningkatkan tahap keselesaan terma. Namun begitu, penghawa dingin menggunakan jumlah elektrik yang tinggi. Penebat boleh melambatkan aliran haba kerana rintangannya yang tinggi terhadap haba. Walaupun begitu, pemaju dan pemilik rumah tidak sedar tentang manfaat penebatan haba dalam bangunan kediaman dan tidak bersedia untuk melaksanakannya. Tujuan kajian ini adalah untuk mengoptimumkan penebatan haba dalam sistem bumbung kediaman bagi iklim panas lembap untuk mendapatkan penjimatan kos dan pengurangan pelepasan CO_2 yang maksimum. Satu soal selidik dan temu bual telah dijalankan untuk menentukan tahap kesedaran dan kesediaan dan halangan dalam kalangan pemilik rumah, pemaju dan para profesional terhadap pelaksanaan penebatan haba dalam bangunan kediaman di Malaysia. Keputusan menunjukkan bahawa tahap kesedaran terhadap penebatan bangunan kediaman adalah secara amnya rendah. Tahap kesediaan adalah tinggi dalam kalangan pemilik rumah tetapi rendah dalam kalangan pemaju kerana kurang penghargaan terhadap manfaat jangka panjang yang bakal diperolehi daripada penebatan haba. Ketiadaan keperluan dari segi undang-undang, kos elektrik yang rendah, tren pemasangan penghawa dingin dalam bangunan kediaman dan kos tambahan telah dikenalpasti sebagai halangan kepada pelaksanaan penebatan haba dalam bangunan kediaman. Kemudian, sebuah eksperimen menggunakan dua (2) buah model rumah berskala kecil dijalankan untuk mengesahkan keberkesanan penebat haba dalam bumbung bagi iklim panas lembap. Hasil kajian menunjukkan bahawa penebat boleh mengurangkan suhu udara dalaman. Perbezaan suhu luaran dengan dalaman yang tertinggi iaitu sebanyak 8.40°C telah diperolehi oleh penebat serat kekabu yang 100-mm tebal. Seterusnya, simulasi telah dijalankan untuk menilai profil suhu udara dalaman bangunan kediaman yang telah dipasang penebat haba yang mempunyai bahan, ketebalan dan perletakan yang berbeza-beza dalam sistem bumbung kediaman yang jimat tenaga. Model rumah yang mempunyai penebat silika aerogel diperkukuhkan bawah atap bumbung yang 50-mm

tebal telah memperolehi suhu udara dalaman yang paling rendah iaitu 27.20°C pada suhu puncak udara luaran iaitu pada jam 1600. Akhir sekali, pengiraan dijalankan untuk mengunjurkan kos dan pelepasan CO_2 bangunan kediaman bagi pengoptimuman penebatan haba dalam bumbung. Pengurangan elektrik maksimum sebanyak 2,646.39 kWh telah diperolehi bagi penebat serat kekabu atas siling. Pengurangan pelepasan CO_2 maksimum sebanyak 1,720.15 kg CO_2 iaitu bersamaan dengan mengeluarkan 5.49 kereta dari jalan raya atau menanam 10.81 pokok baru, telah diperolehi, juga untuk penebat serat kekabu atas siling. Ketebalan penebat optimum terendah sebanyak 0.0047 m telah diperolehi bagi penebat aerogel diperkukuhkan bawah atap bumbung, manakala ketebalan penebat optimum tertinggi 0.0655 m telah diperolehi bagi penebat selulosa atas siling. Pengoptimuman penebat haba dalam sistem bumbung kediaman dapat dicapai dengan menentukan kombinasi bahan, ketebalan dan perletakan penebat haba yang boleh membawa kepada penjimatan kos yang tertinggi dan kesan alam sekitar yang paling positif. Penebatan haba optimum yang diperolehi dalam kajian ini adalah penebat serat kekabu atas siling yang 0.0641-m tebal.

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LIST OF ABBREVIATIONS

TERM	ABBREVIATION
Air-Conditioners	AC
American Society of Heating, Refrigerating and Air-Conditioning Engineers	ASHRAE
Coefficient of Performance	COP
Cooling Degree Hours	CDH
Degree Day	DD
Direct Current	DC
Dynamic Insulation Material	DIM
Elastomeric Nitrile Rubber	ENR
Energy Efficiency Measure	EEM
Expanded Polystyrene	EPS
Extruded Polystyrene	XPS
Federation of Malaysian Manufacturers	FMM
Gas-Filled Panel	GFP
Green Building Index	GBI
Heating Degree Hours	HDH
Heating, Ventilating and Air-Conditioning	HVAC
Hydrofluorocarbon	HFC
Integrated Environmental Solutions <Virtual Environment>	IES <VE>
International Greentech & Eco Products Exhibition & Conference Malaysia 2010	IGEM 2010
Kuala Lumpur Convention Centre	KLCC

TERM	**ABBREVIATION**
Life Cycle Cost	LCC
Lightweight Aluminium Standing Seam Roofing System	LASRS
Liquefied Petroleum Gas	LPG
Low Emissivity	low-e
Malaysian Insulation Manufacturers Group	FMM-MIMG
Malaysian Standard 1525:2007	MS1525:2007
Nano Insulation Material	NIM
Pertubuhan Arkitek Malaysia	PAM
Phase-Change Material	PCM
Photovoltaic	PV
Polyurethane	PUR
Polyvinyl Chloride	PVC
Real Estate and Housing Developers' Association of Malaysia	REHDA
Reinforced Cement Concrete	RCC
Solar Reflectance Index	SRI
Tenaga Nasional Berhad	TNB
Thermal Conductivity	k-value
Thermal Resistance	R-value
Thermal Conductance	C-value
Uniform Building By-Laws	UBBL
Universiti Teknologi PETRONAS	UTP
Overall Heat Transfer Coefficient	U-value
Overall Thermal Transfer Value	OTTV
Vacuum Insulated Panel	VIP

LIST OF CHEMICAL FORMULAE

CHEMICAL FORMULA	TERM
$(C_6H_{10}O_5)_n$	Cellulose or Polysaccharide
Ar	Argon
C_6H_{12}	Pentane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H_3BO_3	Boric Acid
HFC	Hydrofluorocarbon
Kr	Krypton
$Na_2B_4O_7{\cdot}10H_2O$ or $Na_2[B_4O_5(OH)_4]{\cdot}8H_2O$	Borax or Sodium Borates
NO_x	Nitrus Oxide
SO_2	Sulphur Dioxide
Xe	Xenon

LIST OF NOTATIONS

SYMBOL	TERM
A	Cross-sectional area perpendicular to heat flow, surface area
A_1	Area of the first surface
$A_{insulation}$	Area covered by insulation
A_{roof}	Surface area of roof
C	Thermal conductance
C_{AC}	Cost of energy consumption for air-conditioner
$C_{electricity}$	Cost of electricity
$C_{install}$	Cost rate to install insulation
$C_{insulation}$	Cost of insulation
COP_{AC}	Coefficient of performance of air-conditioner
C_{supply}	Cost rate to supply insulation
d	Discount rate
D	Ratio of down payment to initial investment
dT/dx	Temperature gradient
ε_1	Emissivity of the first surface
E_{AC}	Energy consumption of air-conditioner
h_c	Surface heat transfer coefficient
h_r	Coefficient of heat transfer
i	Interest rate

SYMBOL	**TERM**
k	Thermal conductivity
k_1, k_2, k_n	Thermal conductivity of a layer of building component
$k_{insulation}$	Thermal conductivity of insulation
M	Ratio of first year miscellaneous costs
N	Lifetime of insulation
$N_{payback}$	Payback period
P_1	Ratio of life cycle energy
P_2	Ratio of life cycle expenditures incurred due to additional capital investment
Q	Heat transfer
$Q_{conduction}$	Heat transfer by conduction
$Q_{convection}$	Heat transfer by convection
$Q_{radiation}$	Heat transfer by radiation
Q_{roof}	Heat transfer through roof
R	Thermal resistance
$R_{insulation}$	Thermal resistance of insulation
R_{roof}	Thermal resistance of roof
R_v	Ratio of resale value at the end of economic period of initial investment
S	Cost savings from use of insulation
ΣR	Sum of thermal resistances of all layers composing a component

SYMBOL	TERM
T_1	Absolute temperature of the first surface
T_2	Absolute temperature of the second surface
$t_{equivalent}$	Equivalent hours of operation for indoor cooling
T_f	Fluid temperature
t_{full}	Full load hours
$T_{indoor-design}$	Design temperature of indoor air
$T_{outdoor-average}$	Annual average outside temperature
$T_{outdoor-design}$	Design temperature of outdoor air
T_s	Surface temperature
U	Overall heat transfer coefficient
U_{roof}	Overall heat transfer coefficient of roof
$U_{roof-insulated}$	Overall heat transfer coefficient of insulated roof
$U_{roof-uninsulated}$	Overall heat transfer coefficient of uninsulated roof
X	Thickness
X_1, X_2, X_n	Thickness of a layer of building component
$X_{insulation}$	Thickness of insulation
$X_{insulation-optimum}$	Optimum insulation thickness
ΔQ_{roof}	Difference between heat transfer of uninsulated and insulated roofs

SYMBOL	TERM
ΔT	Difference between design temperatures of outdoor and indoor air
ΔU_{roof}	Difference between overall heat transfer coefficients of uninsulated and insulated roofs
σ	Thermal resistivity, Stefan-Boltzmann constant

LIST OF UNITS

SYMBOL	TERM
°C	degree Celsius
cm	centimetre
J	Joule
J/kg-K	Joule per kilogram-Kelvin
K	Kelvin
K/m	Kelvin per metre
kg	kilogram
kg CO_2	kilogram of CO_2
kg CO_2/ year	kilogram of CO_2 per year
kg CO_2/car/year	kilogram of CO_2 per car per year
kg CO_2/J	kilogram of CO_2 per Joule
kg CO_2/km	kilogram of CO_2 per kilometre
kg CO_2/kWh	kilogram of CO_2 per kilowatt-hour
kg CO_2/tree	kilogram of CO_2 per tree
kg CO_2/tree/year	kilogram of CO_2 per tree per year
kg/m^3	kilogram per cubic metre
km	kilometre
km/litre	kilometre per litre
km/year	kilometre per year
kW	kilowatt
kWh	kilowatt-hour
M	Metre

SYMBOL	**TERM**
m	metre
m^2	square metre
m^2-K/W	square metre-Kelvin per Watts
m^3	cubic metre
mbar	milibar
m-K/W	metre-Kelvin per Watts
mm	milimetre
MPa	Mega Pascal
RM	Ringgit Malaysia
RM/m^2	Ringgit Malaysia per square metre
RM/m^3	Ringgit Malaysia per cubic metre
sen/kWh	sen per kilowatt-hour
W	Watts
W/m^2-K	Watts per square metre-Kelvin
W/m-K	Watts per metre-Kelvin

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In urban residential buildings, under hot-humid climate, occupants use room air-conditioners (AC) to reduce indoor temperature and humidity to improve level of thermal comfort. AC are also installed in commercial and industrial buildings to improve level of productivity as well as thermal comfort of workers. Besides from AC, fans are also used to reduce indoor temperature and humidity. Although fans can be operated with less electricity power, AC reduce temperature and humidity more effectively and ensure occupants achieve the desired level of thermal comfort. However, dependence on AC lead to negative impacts on both house owners and the country, which are the increase in electricity bills, energy consumption due to use of electricity and emission from power plants during generation of electricity.

Use of room AC in Malaysia has been increasing for the last two decades. The number of household units in Malaysia has been projected to have increased by 40.56% from 4,662,762 units in 2000 to 6,554,113 units in 2012 while the number of room AC units has been projected to have increased by 99.88% from 528,792 units in 2000 to 1,056,959 units in 2012 [1]. The ratio of the number of AC units to the number of household units increased from 0.1134 in 2000 to 0.1613 in 2012. Therefore, it has been demonstrated that there is an increasing trend of installing AC in houses. Other than the desire to achieve thermal comfort, population growth also contributes to this trend. The population in Malaysia has increased by 53.19% from

18,102,000 in 1990 to 27,730,000 in 2008 [2]. In addition, the residential sector in Malaysia contributes 19% of the energy consumption. Globally, the residential sector contributes 31% of the energy consumption [3-10].

Figure 1.1 compares the percentage of total energy consumption by AC with other household appliances in Malaysia in 2009.

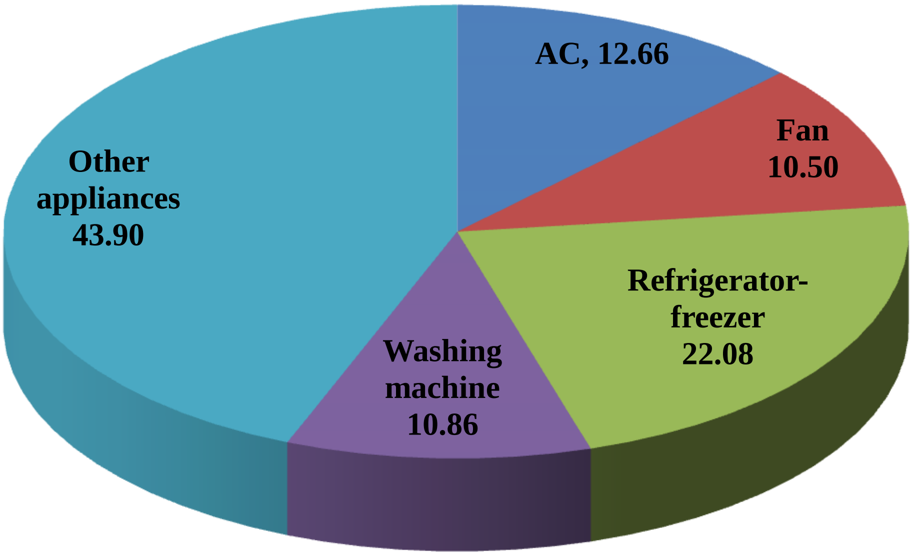


Figure 1.1: Percentage of total energy consumption by AC in comparison with other household appliances in Malaysia in 2009 [3, 11-16]

The total energy consumption by AC is the second highest among all household appliances, contributing 12.66% of the total energy consumption by household appliances. Interestingly, the total energy consumption by fans is the fourth highest, contributing 10.50%. Therefore, a total of 23.16% of the total energy consumption is from the use of fans and AC whereby both of these appliances serve the same purpose, which is to improve level of thermal comfort for occupants.

Most power plants in Malaysia use non-renewable sources of energy such as coal, natural gas, diesel and fuel oil. During generation of electricity, pollutants such as SO_2, NO_x, CO and CO_2 are emitted into the atmosphere and contribute towards global warming. Shekarchian *et al.* (2011) [2] calculated the electricity consumption per capita and total emission in power plants in Malaysia based on data obtained from the National Electricity Board of the States of Malaysia (1979, 1980, 1982, 1986, 1988 and 1989) [17-22] and Ministry of Energy (2000-2008) [23-31]. The electricity consumption per capita has increased from 1,175 kWh in 1990 to 3,798 in 2008, which is an increase of 223.23%. Furthermore, the total CO_2 emission from power plants has increased from 12,386,029 in 1990 to 199,450,710 in 2008, which is an increase of 1387.59%.

Occupants in residential buildings utilize room AC to reduce indoor temperature and humidity to achieve the desired level of thermal comfort. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined thermal comfort as “the condition of the mind in which satisfaction is expressed with the thermal environment” [32]. The process of metabolism in the human body causes it to produce heat, which dissipates through exchanges of heat with the surrounding environment and loss of heat by evaporation of body fluids. Thermal comfort is achieved when the rate of heat production is equivalent to the rate of heat dissipation. However, when the ambient temperature is higher than the body temperature, body heat cannot be dissipated to the surrounding environment. Hence, thermal discomfort is experienced. Consequently, room AC are turned on to reduce indoor temperature and humidity, enable the dissipation of body heat and improve the level of thermal comfort [33-36].

The climate in Malaysia is hot and humid with high ambient temperatures and relative humidity that range from 26°C to 40°C and 60% to 90% respectively. Effect of global warming has increased ambient temperatures even more. During the day, especially in the afternoon, solar radiation heats buildings and causes heat gain through the envelope and heat penetration through the windows. Hisham *et al.* (2006) [37] revealed that the roof is most exposed to solar radiation among other components of the building envelope. Consequently, most of the heat gain is through the roof. Vijaykumar *et al.* (2007) [38] reported that the heat transmission across the building roof is about 50%-70% of the total heat entry for the rooms below the exposed roof with the consideration that most residential buildings are low-rise. A typical residential building in Malaysia has a roof structure consisting of concrete roof tiles over an attic space and a cement board ceiling. Heat radiated onto the roof tiles is conducted into the roof structure and radiates into the attic. Then, heat is trapped in the attic and flows into the ceiling material. As a result, temperature of the ceiling rises. The hot ceiling radiates heat into the indoor space below and causes thermal discomfort to occupants. Occupants react to this thermal disturbance by reducing indoor temperature through use of room AC [36, 39].

1.2 Problem Statement

Malaysia is a hot and humid country with high ambient temperatures and relative humidity where the building roof receives solar radiation of high intensity throughout the day. Heat conducted through roof tiles is trapped in the attic space and flows into the ceiling material. During a hot day occupants in residential buildings experience high level of thermal discomfort due to the heat radiated from the ceiling. Room AC are utilized to reduce indoor temperature and humidity and improve level of thermal comfort. However, frequent and prolonged use of AC lead to increase of electricity bills, energy consumption and CO_2 emission. Alternatively, indoor temperatures can be reduced by retarding heat flow into the building through the installation of insulation. However, implementation of insulation in buildings in Malaysia is still uncommon due to lack of awareness on its positive cost and environmental impact and preparedness to make the initial investment for installation of insulation. Figure 1.2 illustrates the formulation of the research problem.

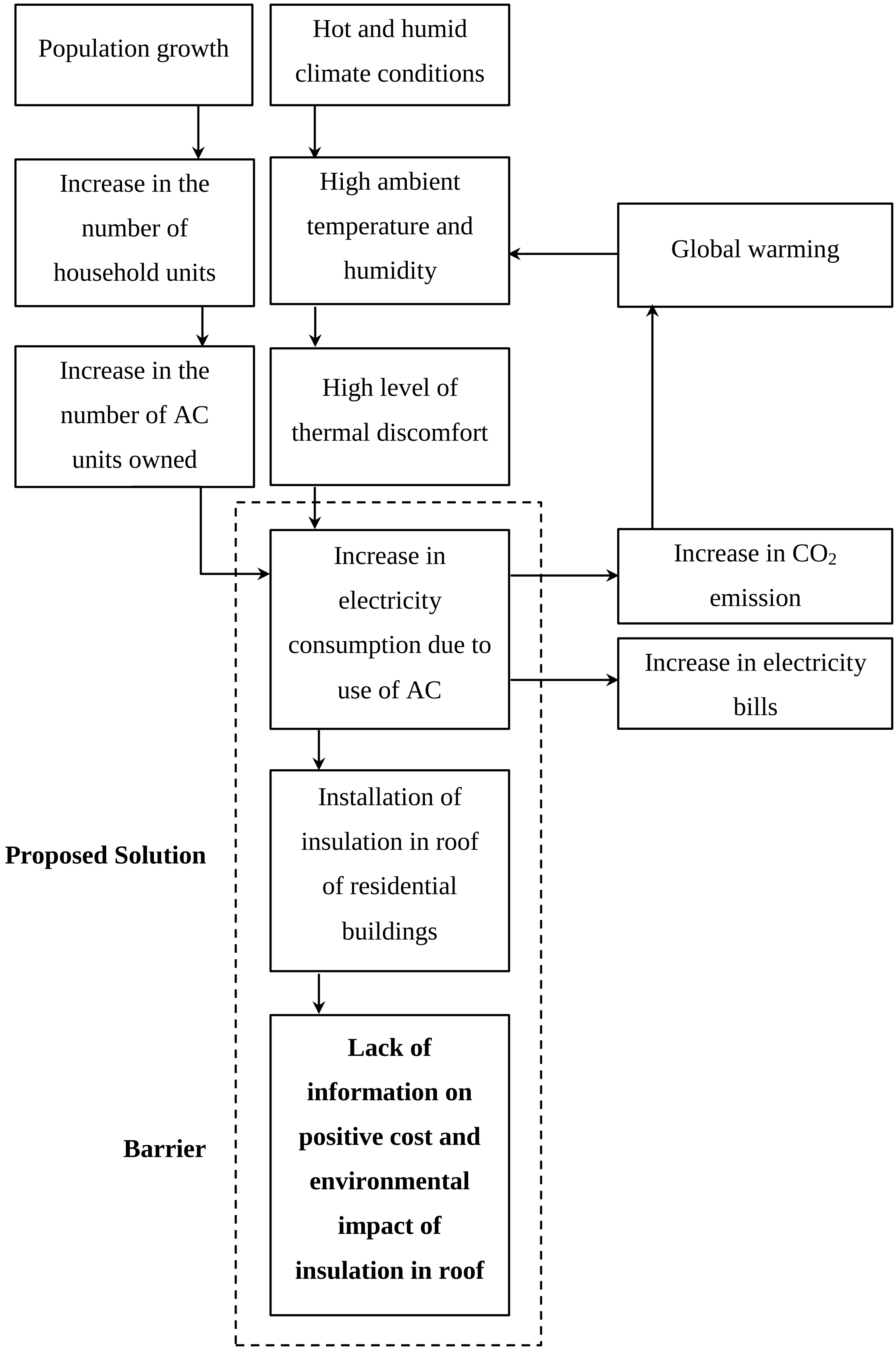


Figure 1.2: Schematic diagram of the research problem

1.3 Aim and Objectives

The research aim is to optimize thermal insulation in residential roofing system in hot-humid climate for maximum reduction in cost and CO_2 emission. The aim is supported by the following objectives:

i. To determine levels of awareness and preparedness and barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia
ii. To validate the effectiveness of thermal insulation in roof in hot-humid climate
iii. To evaluate the indoor temperature profiles of thermal insulation of varying material, thickness and placement in energy-efficient residential roofing system
iv. To project the cost and CO_2 emission of residential building for optimization of thermal insulation in roof

1.4 Scope of the Research

AC can be installed in residential, commercial and industrial buildings to improve thermal comfort and productivity of occupants. Some industrial buildings contain heavy machinery that contributes to high level of internal heat gain whereby in residential and commercial buildings the external heat gain is more predominant. In residential buildings, comfort of occupants is given higher priority compared to commercial and industrial buildings where productivity of employees is rated as more important than the level of comfort. The research focuses on reducing use of AC in residential buildings.

Insulation can be installed in buildings under various types of climates such as cold, temperate, hot-dry and hot-humid climates. In cold climate, insulation is commonly installed in walls to retard heat flow out of the building and improve level of thermal comfort by increasing indoor temperature. Contrarily, the research focuses on assessing the effectiveness of insulation in buildings under hot-humid climate. The research is conducted in Malaysia at high ambient temperature and relative humidity.

Other than utilizing AC, occupants can improve the level of thermal comfort by several methods such as operating fans to increase velocity of air flow, wearing thinner clothing to reduce effect of clothing insulation, sleeping or resting to reduce rate of metabolism and lower production of heat by the body, opening windows and door to increase velocity of air flow and rate of air ventilation as well as insulating the building envelope. The research focuses on reducing the dependence on AC by retarding heat transfer through the roof by insulation.

The building envelope consists of several components such as wall, window, roof and foundation. Insulation can be installed in window and wall to reduce heat gain through the building envelope. However, the roof is most exposed to solar radiation throughout the day compared other components of the building envelope. Accordingly, the research focuses on evaluating the thermal performance of insulation in roof.

1.5 Limitations of the Study

Data of higher relevance and accuracy can be obtained if insulation is evaluated in actual houses with actual conditions such as irregular building geometry, presence of occupants, arrangement of furniture and utilization of appliances. However, due to lack of resources, data is collected by conducting house model experiment and simulation.

During the experiment conducted with two (2) small-scaled house models, temperatures are taken at three (3) points for each house, which are the roof surface and indoor and outdoor air. With a larger set of instruments, a more complex analysis can be conducted by taking temperatures at more points such as the external and internal roof surfaces, air in the attic space, and top and bottom surfaces of the ceiling.

1.6 Research Contribution

The research has made contributions to the body of knowledge, society and research community. The body of knowledge on heat transfer is enhanced by the establishment of quantification and understanding of the effect of insulation materials on building heat transfer and thermal comfort parameters. Projection in cost savings and reduction of electricity consumption and CO_2 emission contribute towards inducing awareness and preparedness among the society to implement insulation in buildings and appreciate the benefits of conserving electricity. The research has contributed to the research community through the publication of indexed book chapters and conference items. Publications produced from this work are listed in Appendix A.

1.7 Thesis Outline

Chapter 1 is commenced with a discussion on the background of the research. The background highlights the issue concerning the sharp increase in electricity consumption and CO_2 emission due to dependence on AC among occupants in residential buildings. The problem statement is formulated based on issues raised in the background. Then, the aim and objectives of the research are presented. Subsequently, the scope, limitations and contribution of the research are discussed.

Chapter 2 firstly discusses components of the building envelope and energy-efficient solutions for each component. Then, a review of building insulation materials is presented. Subsequently, fundamental concepts of heat transfer and equations that govern them are discussed. After that, methods to determine the optimum thickness of building insulation materials are described. Then, the life cycle of CO_2 emission and the method to estimate it is explained. The chapter is ended with a review on previous similar studies conducted by other researchers.

Chapter 3 begins with an overview of the approach employed to achieve the research objectives. Then, it describes the survey methods implemented to determine levels of awareness and preparedness and barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia. Next, procedures to conduct the house model experiment and simulation are explained. Lastly, methods utilized to project the reduction in cost and CO_2 emission are presented.

Chapter 4 is commenced with a presentation and interpretation of the feedback from respondents obtained from the survey. Then, data collected from the house model experiment and simulation are presented and analyzed. Lastly, the reduction in cost and CO_2 emission obtained are presented and interpreted.

Chapter 5 begins with a review of the research aim and objectives. Then, conclusion remarks are discussed. Finally, recommendations are made to enhance the quality of findings of future research in this area.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is commenced with a discussion on components of the building envelope. Then, types, properties, mechanisms and benefits of building insulation materials are presented. Subsequently, fundamental concepts of heat transfer are described. Concept and calculation methods of optimum insulation thickness are then described. Then, background on CO_2 emission and methods to estimate it are explained. Lastly, previous researches that are similar to the present research are reviewed and gaps are highlighted.

2.2 Building Envelope

A building envelope is an assembly of building components that divides the indoor space from the outdoor environment. Main components of a building envelope are the roof, walls and fenestration, which consists of windows and doors. Other components include the foundation, insulation, shading devices, finishes and vapor retarders. This section discusses the roof, walls and windows and measures to improve their energy-efficiency.

2.2.1 Roof

The roof is the top-most component of the building that protects occupants from unfavourable weather elements such as rain and solar radiation. Other than that, the roof, depending on the architectural design, improves the aesthetic value of the building. Roofs can be categorized into two (2) types according to their slope, which are steep and low-slope roofs. Steep roofs possess slopes higher than 25% while on the contrary, low-slope roofs possess slopes of 25% or less. In common, steep roofs are assembled for residential buildings whereas low-slope roofs are assembled for commercial and industrial buildings. The purpose of a steep slope is to produce sufficient gravitational force to shed water off the roof. Insufficient slope reduces gravitational force and causes opposing forces produced by wind, head pressure and capillary action to push water up the slope and causes water to leak into the building through gaps in between roof tiles [40]. Other than slopes, roofs can be classified according to the method of construction. Types of roof discussed in this section are masonry, lightweight and advanced energy-efficient roofs, which are ventilated, solar-reflective and green roofs [41].

2.2.1.1 Masonry Roof

Masonry is a structure built of stone or brick. Concrete is a form of masonry because stone is its main constituent. An advantage of reinforced cement concrete (RCC) roofs is their resistance to pest and natural calamity [42]. Other advantages of concrete is its availability and cost-effectiveness [43]. However, a drawback of RCC roofs is the long heat retaining capacity of cement concrete under hot conditions that leads to thermal discomfort for occupants [44].

2.2.1.2 Lightweight Roof

Lightweight aluminium standing seam roofing system (LASRS) is a low-cost roofing system and is commonly used in commercial and government buildings [41]. However, it possesses weak seam-clip connections that make them vulnerable to wind forces. Furthermore, it does not resist heat flow efficiently and can lead to high level of thermal discomfort for occupants if no heat-resisting strategies are employed.

Thermal performance of LASRS can be improved by installing insulation and employing light-coloured roof paint [45].

2.2.1.3 Ventilated Roof

A ventilated roof employs a duct demarcated with two slabs as part of the roof structure. The duct provides a gap of flowing air which suppresses heat transfer through the roof. Flow of air through the duct can either be passively driven by stack effect or actively induced by ventilation fans. Ventilated roofs are generally more useful in low to mid-rise buildings located under hot climatic conditions where the solar heat gain through the roof is very high [41].

2.2.1.4 Solar-Reflective Roof

A solar-reflective roof is a type of roof that employs reflective surfaces that reflect solar radiation, emit infrared radiation and maintain low roof surface temperature [46]. The low roof surface temperature leads to significant reduction of heat transfer through the roof. Methods to increase the reflectivity of the roof surface include selecting materials with high Solar Reflectance Index (SRI) and applying reflective paint or coating.

2.2.1.5 Green Roof

A green roof is a roof structure that is covered with a composite layer of waterproofing membrane, growing medium and vegetation. Some green roofs also have a root barrier, drainage layer and an irrigation system. The vegetation provides thermal protection to the building by reflecting incident solar radiation, suppressing heat transfer through the roof and removing heat from the building by evapotranspiration from plants that constitute the vegetation [47].

2.2.2 Walls

Walls cover the largest portion of the building envelope and provide thermal and acoustic comfort to occupants and aesthetical value to the building. Walls also divide the building into sections to provide more convenience to occupants as a living space. Commonly, walls can be classified into three (3) main types according to materials used to construct them, which are wood-based, metal-based and masonry-based walls [41]. Other than that, walls can also be classified based on the system employed in the wall structure to improve certain characteristics of the wall. Improvement of the thermal performance of walls to enhance energy-efficiency of buildings can be realized by employing advanced wall systems such as passive solar, lightweight concrete and double skin walls [41].

2.2.2.1 Passive Solar Wall

A passive solar wall is designed to trap and transmit solar energy efficiently into the building. It is typically used in cold climate to diminish heat flow out of the building. A Trombe wall is a passive solar wall designed by Trombe *et al.* that transfers heat to the indoor by conduction through wall and convection through circulating air. There are several types of Trombe wall systems developed by researchers that include phase-change material (PCM) based, photovoltaic (PV) integrated and fluidized Trombe wall systems [48].

2.2.2.2 Lightweight Concrete Wall

A lightweight concrete wall is made of lightweight concrete material, which is concrete produced with density less than 2000 kg/m^3. Concrete that is utilized for structural functions possess density that typically ranges between 1600 kg/m^3 and 2000 kg/m^3 and a strength grade of 15 MPa. On the other hand, concrete used for thermal insulation often possess density that is lower than 1450 kg/m^3 and a strength grade of 0.5 MPa. Thermal insulation properties of lightweight concrete can be improved by including lightweight aggregates such as diatomite, expanded clay and foamed slag in the concrete mix. Other than that, use of low-conductivity aggregates can also improve insulation properties of concrete. Examples of low-conductivity concrete include polystyrene beads and vermiculite [49].

2.2.2.3 Double Skin Walls

Double skin walls comprise of an air gap between two layers of masonry walls braced with metal ties. The air gap improves the thermal performance of double skin walls by providing air ventilation that suppresses heat flow between external and internal walls. Air ventilation can either be actively induced or naturally present due to stack effect. Double skin walls are commonly installed in buildings located in hot climate to passively cool buildings and improve level of thermal comfort [50].

2.2.3 Windows

Windows are glass openings that improve level of thermal comfort, optimize illumination and enhance the aesthetical value of a building [41]. Energy-efficiency of buildings can be improved by employing advanced glazing technologies in window designs, which either provide high performance insulation, solar gain control or daylighting solutions or a combination of them [41]. This section presents several advanced glazing technologies, which are aerogel, vacuum and switchable reflective glazing and optimal design of frames and spacers.

2.2.3.1 Aerogel Glazing

Aerogel glazing consists of granular aerogel capsulized between polycarbonate panels. Aerogels are open-celled mesoporous solids with porosity greater than 50% by volume, density in the range of 1 kg/m^3 – 150 kg/m^3 and 90% – 99.8% air by volume. Aerogels can be made from a variety of materials, which includes silica, alumina, lanthanide and transition metal oxides, metal chalcogenides, organic and inorganic polymers and carbon. Aerogel glazing weighs less than 20% of the equivalent glass unit and has 200 times more impact strength. Application of aerogel glazing includes as fenestration in roof for roof-lighting because of its low density and ability to diffuse light effectively [51].

2.2.3.2 Vacuum Glazing

Vacuum glazing is formed by creating vacuum space in between two glass panes to obviate conductive and convective heat transfer between glass panes. In addition, low emissivity (low-e) coating can be applied on one or both glass panes to diminish re-radiation into the indoor space. However, a drawback of vacuum glazing is the need to maintain the vacuum for long periods [52].

2.2.3.3 Switchable Reflective Glazing

Switchable reflective glazing can be described as a glazing with variable tint. Application of switchable reflective glazing is preferred in buildings in hot climate where buildings experience high solar heat gain. Some types of switchable reflective glazing can change its optical properties according to the incident solar radiation by applying low direct current (DC) voltage or using hydrogen to change from bleached to coloured state. Other types of switchable reflective glazing employ switchable reflective light shelves to reflect solar radiation. However, marketability of switchable reflective glazing is hindered by cost, warranty, switching time, glare and colour rendering issues [53].

2.2.3.4 Optimal Design of Frames and Spacers

Optimal design of frames and spacers is an alternative approach to construct energy-efficient window glazing. Design combination of frames and spacers and selection of low conductance window frames can improve thermal performance of windows by minimizing thermal bridging and infiltration losses [54].

2.3 Building Insulation Materials

Thermal insulation is defined as “a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection and radiation due to its high thermal resistance”. This section is commenced with a conceptual review of the properties of insulation [55]. Then, mechanism of insulation materials is explained. Next, benefits of insulation materials are highlighted. Lastly, an overview on various types of building insulation materials available in the market today is presented.

2.3.1 Properties of Building Insulation Materials

2.3.1.1 Thermal Conductivity

Thermal conductivity (k-value) is “the time rate of steady state heat flow in Watts (W) through a unit area of 1 metre (m) thick homogeneous material in a direction perpendicular to isothermal planes induced by a unit 1 Kelvin (K) temperature difference across the sample” [56]. It is commonly expressed in units of W/m-K. The k-value of a material quantifies the effectiveness of that material in conducting heat flow. Material properties namely temperature, moisture content and density influence k-value. Materials with the same properties have the same k-value regardless of its thickness.

2.3.1.2 Thermal Resistivity

The thermal resistivity is a measure of the effectiveness of a material in resisting heat flow. It is the reciprocal of the thermal conductivity of the material as shown in Equation 2.1. Similar to thermal conductivity, the thermal resistivity of a material is not influenced by its thickness.

$$\sigma = \frac{1}{k} \tag{2.1}$$

Where σ is the thermal resistivity of the material expressed in m-K/W and k is the thermal conductivity of the material expressed in W/m-K.

2.3.1.3 Thermal Resistance

Thermal resistance (R-value) of a material is its thermal resistivity at a particular thickness. Therefore, unlike thermal resistivity, the R-value of a material is influenced by its thickness. R-value is commonly expressed in units of m^2K/W. It is used as a basis for quantitative comparison among thermal insulation materials. R-value of a material is derived from its thermal conductivity and thickness as presented in Equation 2.2. Since thermal resistivity is also derived from thermal conductivity, R-value can also be derived as shown in Equation 2.3.

$$R = \frac{X}{k} \tag{2.2}$$

$$R = \sigma X \tag{2.3}$$

Where R is the R-value of the material expressed in m^2K/W, X is its thickness expressed in *m*, *k* is its thermal conductivity expressed in W/m-K and σ is its thermal resistivity expressed in m-K/W.

.

2.3.1.4 Thermal Conductance

Thermal conductance (C-value) is “the rate of heat flow in *W* through a unit surface area of a component with unit 1 *K* temperature difference between the surfaces of the two sides of the component”. It is expressed in W/m^2K. It is calculated as in Equation 2.4.

$$C = \frac{1}{\sum R}$$

(2.4)

Where C is the C-value expressed in W/m^2K and ΣR is the sum of the thermal resistances of all layers composing that component.

2.3.1.5 Overall Heat Transfer Coefficient

When the temperature of a building component rises, layers of air adjacent to the surface on both sides of the component experience an increase in temperature at a higher rate than the surrounding air. The increase in temperature induces an upward movement of the air within the layers parallel to the surface of the component and hence, creating an air film which acts as a layer of insulation. The overall heat transfer coefficient (U-value) is the "rate of heat flow through a unit surface area of a component with unit 1 *K* temperature difference between the surfaces of the two sides of the component inclusive of the thermal resistances of the inside and outside air films". It is expressed in W/m^2K. It is calculated as in Equation 2.5.

$$U = \frac{1}{\sum R}$$

(2.5)

Where U is the U-value expressed in W/m^2K and ΣR is the sum of the thermal resistances of all layers composing that component plus the thermal resistances of the inside and outside air films.

2.3.2 Mechanism of Building Insulation Materials

Insulation materials possess innumerable microscopic dead air cells, which prevents movement of air within the material structure. Immobility of air within the insulation material enables it to retard heat transfer. Therefore, thermal resistance of an insulation material is not provided by the material itself, but by the air trapped within the material structure. Insulation materials also retard heat transfer by breaking paths of heat radiation into small distances. Long-wave infrared radiation is absorbed and scattered by the closed structure of small cells of the insulation material. Therefore, a high-density material with smaller cells can retard heat transfer by radiation more effectively. Contrarily, smaller cells do not retard heat transfer by conduction well due to the high rate of kinetic energy transfer between small cells that are in contact with each other. Thus, the thermal resistance of an insulation material is determined based on its ability to retard heat transfer by three modes which are conduction, convection and radiation [57].

2.3.3 Benefits of Building Insulation Materials

Installation of insulation materials in buildings results in many benefits. This section discusses three (3) main benefits, which are economic and environmental benefits, comfort and building protection [55-57].

2.3.3.1 Economic and Environmental Benefits

Insulation materials retard heat transfer into the building and reduce indoor cooling load. Consequently, operating cost of room AC is reduced. Less reliance on room AC leads to reduced electricity consumption and its associated emissions. As a result, electricity bills and pollutants from emissions are reduced.

2.3.3.2 Comfort

Reduced flow of heat into the building due to insulation enables occupants to achieve the desired level of indoor thermal comfort more frequently and for longer periods. Insulation materials also suppress movement of sound into the building. Therefore, noise from neighbours or outdoor environment is reduced, hence improving acoustical comfort.

2.3.3.3 Building Protection

Harsh climate conditions induce high temperature changes that can damage the building structure. High thermal resistance of insulation can minimize temperature fluctuations. Consequently, structural integrity of buildings is preserved and lifetime of building structures is increased. Furthermore, condensation of vapour on building surfaces can lead to penetration of moisture into the building structure. Insulation that is designed and installed correctly can contribute to prevention of vapour condensation. Moreover, in case of fire, insulation materials can prevent flame immigration into the building if the suitable insulation material is selected and installed correctly.

2.3.4 Traditional Building Insulation Materials

Types and forms of building insulation materials available are presented in Table 2.1 and Table 2.2 [57]. In this section, a number of traditional building insulation materials with relatively low thermal conductivity that are most commonly used today are described [58].

Table 2.1: Types of building insulation materials available today [57]

Types	**Sub-category**	**Examples**
Inorganic	Fibrous	Glass
		Rock
		Slag wool
	Cellular	Calcium silicate
		Bonded perlite
		Vermiculite
		Ceramic
Organic	Fibrous	Cellulose
		Cotton
		Wood
		Pulp
		Cane
	Cellular	Cork
		Foamed rubber
		Polystyrene
		Polyethylene
		Polyurethane
Reflective		Aluminium foil
		Ceramic coating

Table 2.2: Forms of building insulation materials [57]

Forms	**Sub-category**	**Examples**
Mineral fiber blankets	Batts	Fibreglass
	Rolls	Rock wool
Loose fill	Blown-in	Fibreglass
		Rock wool
	Mixed with concrete	Cellulose
		Perlite
		Vermiculite
Rigid boards		Polystyrene
		Polyurethane
		Polyisocyanurate
		Fibreglass
Foam		Polyurethane
		Polyisocyanurate
Spray		Polyurethane
		Polyisocyanurate
Boards or blocks		Perlite
		Vermiculite
Reflective materials		Aluminium foil
		Ceramic coating
		Reflective paint

2.3.4.1 Mineral Wool

Fibreglass (Figure 2.1) and rock wool (Figure 2.2) are two types of mineral wool. Fibreglass is made from borosilicate glass that is heated at around 1400°C and pulled through rotating nozzles to create fibres. On the other hand, rock wool is produced from stone such as diabase or dolerite that is heated at about 1500°C until it melts. Then, it is hurled out from a wheel or disc to create fibres. For both fibreglass and rock wool, fibres are bound together by adding dust abatement oil and phenolic resin to enhance their properties.

Figure 2.1: Fibreglass

Figure 2.2: Rock wool

2.3.4.2 Polystyrene

Two common types of polystyrene (Figure 2.3) discussed in this section are expanded polystyrene (EPS) and extruded polystyrene (XPS). EPS is formed from small spheres of polystyrene, which are made from crude oil containing an expansion agent, such as pentane (C_6H_{12}), which expand when heated with water vapour. The expanding spheres are attached together and casted as boards with a partly open pore structure. On the other hand, XPS is made from melted polystyrene by adding an expansion gas, such as HFC, CO_2 and C_6H_{12}, where the polystyrene mass is extruded through a nozzle with a release of pressure, which causes the mass to expand. It is formed in continuous lengths and cut after cooling. It has a closed pore structure.

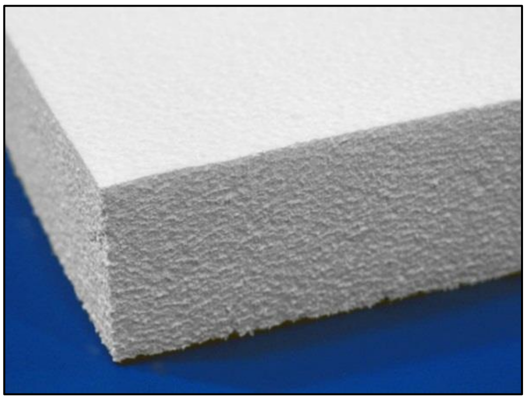


Figure 2.3: Polystyrene

2.3.4.3 Cellulose

Cellulose (Figure 2.4) or polysaccharide ($(C_6H_{10}O_5)_n$) is an insulation material formed from recycled paper or wood fibre with added boric acid (H_3BO_3) and borax or sodium borates ($Na_2B_4O_7 \cdot 10H_2O$ or $Na_2[B_4O_5(OH)_4] \cdot 8H_2O$) to enhance its properties.

Figure 2.4: Cellulose

2.3.4.4 Polyurethane

Polyurethane (PUR) (Figure 2.5) is formed by a chemical reaction between isocyanates and polyols, which are alcohols containing multiple hydroxyl groups. It is then expanded with an expansion gas such as HFC, CO_2 and C_6H_{12}.

Figure 2.5: PUR

2.3.4.5 Comparison between Traditional Building Insulation Materials

Production processes of traditional building insulation materials namely mineral wool, EPS and XPS, cellulose and PUR is described and their thermal conductivities are mentioned. Table 2.3 shows that PUR has the lowest thermal conductivity among the traditional building insulation materials described.

Table 2.3: Thermal conductivity of cellulose, mineral wool, polystyrene and PUR in order of descending values of thermal conductivity [58]

Material	Thermal conductivity (W/m-K)
Cellulose	0.04 to 0.05
Fibreglass	0.03 to 0.04
Rock wool	0.03 to 0.04
EPS	0.03 to 0.04
XPS	0.03 to 0.04
PUR	0.02 to 0.03

2.3.5 New Building Insulation Materials

Jelle (2011) [58] introduced new building insulation materials, which were referred to as state-of-the-art building insulation materials that was defined as "materials and solutions which are, or which are considered to be, the thermal building insulations with the lowest thermal conductivity today". This section describes a number of selected state-of-the-art building insulation materials, which are vacuum insulation panel (VIP), gas-filled panel (GFP) and aerogel. In addition, kapok fibre, or *Ceiba pentandra*, an insulation material that is utilized in textile products and not commonly used in buildings, is introduced as a potential building insulation of the future.

2.3.5.1 Vacuum Insulation Panel

VIP comprise of an open porous core of fumed silica enclosed in several metallized polymer laminate layers. Thermal conductivity of VIP in fresh condition and after 25 years of aging is in the range of 0.003 to 0.004 W/m-K and 0.008 W/m-K respectively. However, perforation, cutting and adjustments of VIP at the construction site causes an increase of the thermal conductivity to about 0.02 W/m-K [59].

2.3.5.2 Gas-Filled Panel

Mechanism of GFP is similar to VIP [60, 61]. The difference between GFP and VIP is the utilization of gases that possess thermal conductivity that are lower than air, such as argon (Ar), krypton (Kr) and xenon (Xe), instead of vacuum. However, vacuum possesses better thermal insulation performance than the gases utilized in VIP, which puts a question to the potential of GFP as a future insulation material. Consequently, measured thermal conductivity for prototype GFP is higher than VIP.

2.3.5.3 Aerogel

Aerogel (Figure 2.6) is a nano-material that can reach low thermal conductivity of 0.004 W/m-K at a pressure of 50 mbar. Main drawback of aerogel is the high production cost [62-65]. However, a new method of producing silica aerogel by extracting silica from rice husks [66], which is a waste raw material, provides a promising solution to reduce the production cost of aerogel substantially. This particular material is named Maerogel, which is the short form of Malaysian aerogel. Aerogels possess high compressive strength but very low tensile strength. Reinforcement of aerogel in a binding material (Figure 2.7) can increase its tensile strength and turn it into a high performance building insulation material [67, 68].

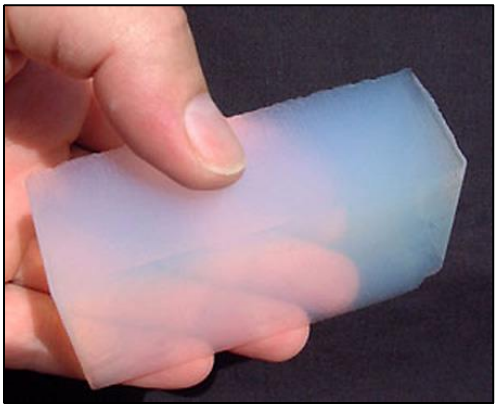


Figure 2.6: Aerogel block

Figure 2.7: Aerogel reinforced with silica felt

2.3.5.4 Comparison between State-of-the-Art Building Insulation Materials

VIPs, GFPs and aerogels have been identified in research literature as state-of-the-art building insulation materials with thermal conductivity much lower than the traditional building insulation materials commonly used today. Table 2.4 compares the thermal conductivity of the materials mentioned.

Table 2.4: Thermal conductivity of VIP, GFP and aerogel in order of descending values of thermal conductivity [58]

Material	Thermal conductivity (W/m-K)
VIP	0.003 to 0.004 (fresh) 0.008 (after 25-years of aging) 0.02 (after perforation, cutting and adjustments at site)
GFP	0.04 (prototype)
Aerogel	0.004

2.3.5.5 Kapok fibre

Kapok fibre (Figure 2.8) is extracted from kapok trees (Figure 2.9), which can be found abundantly in tropical countries such as Malaysia. The most popular application of kapok fibre is in pillows and mattresses because of its soft texture and durability. The potential application of kapok fibre as building insulation can be explored because of its high resistance to heat transfer [69, 70].

Figure 2.8: Kapok fibre

Figure 2.9: Fibre from kapok tree

2.4 Heat Transfer

2.4.1 Introduction

Heat transfers by three modes, which are conduction, convection and radiation. This section describes fundamental concepts of each mode of heat transfer and presents equations that govern them.

2.4.2 Heat Transfer by Conduction

Conduction occurs when heat transfer through a solid material is induced by a difference in temperature across the material. Rate of heat transfer by conduction is a function of the thermal conductivity and thickness of the material, temperature difference across the material and surface area available for heat transfer. Rate of heat transfer by conduction expressed in *W* is presented in Equation 2.6, which is known as Fourier's law [71].

$$Q_{conduction} = kA\frac{dT}{dx} \tag{2.6}$$

Where k is the thermal conductivity of the material expressed in W/m-K, A is the cross-sectional area perpendicular to heat flow expressed in m^2 and dT/dx is the difference in temperature with respect to thickness, or also referred to as the temperature gradient expressed in K/m.

2.4.3 Heat Transfer by Convection

Convection occurs when heat transfer through movement of fluid is induced by a difference in temperature across the fluid. Rate of heat transfer by convection is a function of the surface area available for heat transfer, difference in temperature across the fluid and conditions experienced by the surface of the fluid, which are wind conditions for outdoor surfaces, and air flow conditions over the surface for indoor surfaces. Rate of heat transfer by convection is presented in Equation 2.7, which is known as Newton's Law of Cooling [72].

$$Q_{convection} = h_c A(T_s - T_f) \tag{2.7}$$

Where h_c is the surface heat transfer coefficient, A is the surface area, T_s is the surface temperature and T_f is the fluid temperature.

2.4.4 Heat Transfer by Radiation

Radiation occurs when heat transfers by electromagnetic waves. Rate of heat transfer by radiation between two surfaces is a function of the absolute surface temperatures of the bodies exchanging heat and area of the body at the higher temperature. It is expressed as in Equation 2.8 and Equation 2.9 [73].

$$Q_{radiation} = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4) \tag{2.8}$$

$$Q_{radiation} = h_r A_1 (T_1 - T_2) \tag{2.9}$$

Where σ is the Stefan-Boltzmann constant, h_r is coefficient of heat transfer. A_1 is the area of the first surface, ε_1 is the emissivity of the first surface, T_1 is the absolute temperature of the first surface and T_2 is the absolute temperature of the second surface.

2.5 Optimization of Thermal Insulation Thickness in Roof

2.5.1 Introduction

Different insulation materials are priced differently and can be purchased at various thicknesses. An increase in insulation thickness leads to a decrease in the cost of energy consumed to cool the indoor space at the expense of an increase in the cost to purchase and install insulation. The thickness is optimized when the total cost, which is the summation of the cost to purchase and install insulation and the cost of energy consumed to cool the indoor space, is at its minimum. Optimization of insulation thickness takes into account ongoing cost savings over the expected service lifetime of the insulation material [74]. Conceptual graphs are presented in Figure 2.10 and Figure 2.11 to illustrate the approach employed to optimize thermal insulation thickness [57]. This section describes the calculations and presents the equations [75, 76] involved to optimize insulation thickness.

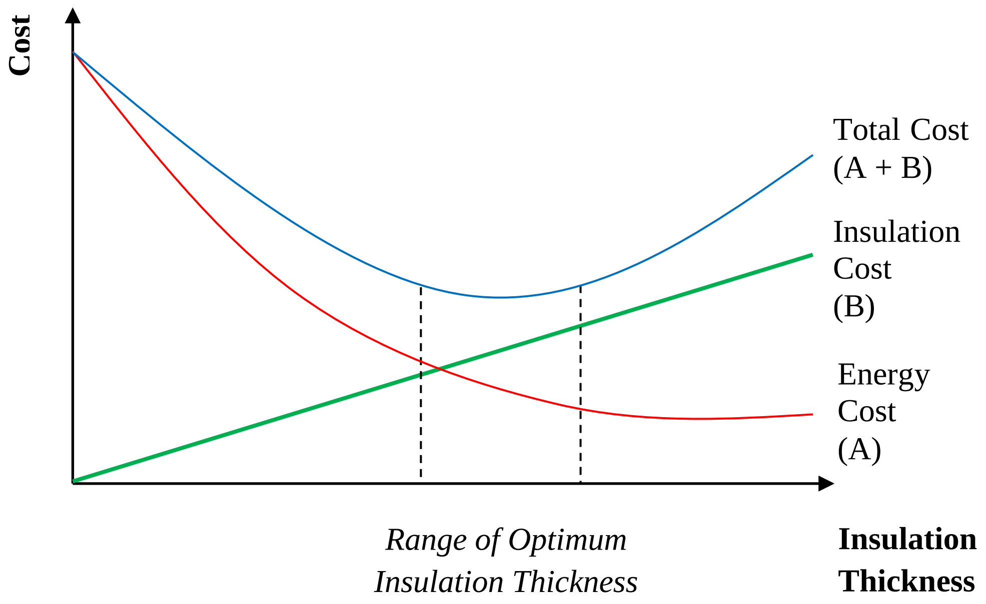


Figure 2.10: Effect of insulation thickness on energy, insulation and total cost [57]

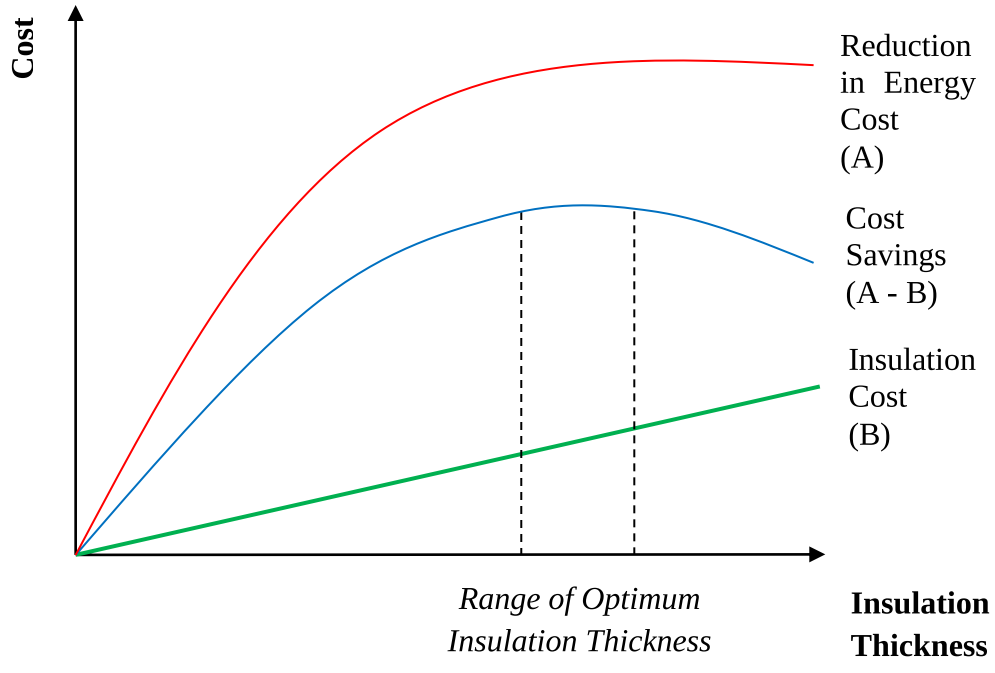


Figure 2.11: Effect of insulation thickness on insulation cost, cost savings and reduction in energy cost [57]

2.5.2 Cost of Insulation

Cost of insulation, $C_{insulation}$, is the summation of costs incurred by the supplier to supply the material and the contractor to install it. It can be calculated as in Equation 2.10.

$$C_{insulation} = C_{supply}A_{insulation}X_{insulation} + C_{install}A_{insulation} \tag{2.10}$$

Where C_{supply} is the cost rate incurred by the supplier to supply the insulation material in RM/m^3, $C_{install}$ is the cost rate incurred by the contractor to install the insulation material in RM/m^2, $A_{insulation}$ is the total area covered by insulation in m^2 and $X_{insulation}$ is the thickness of insulation in m.

2.5.3 Heat Transfer through the Roof

Heat transfer through the roof can be calculated as in Equation 2.11.

$$Q_{roof} = U_{roof}A_{roof}\left(T_{outdoor-design} - T_{indoor-design}\right) = U_{roof}A_{roof}\Delta T \tag{2.11}$$

Where Q_{roof} is the heat transfer through the roof, U_{roof} is U-value of the roof, A_{roof} is the surface area of the roof, $T_{outdoor\text{-}design}$ is the design temperature of the outdoor air and $T_{indoor\text{-}design}$ is the design temperature of the indoor air. Accordingly, ΔT represents the difference between design temperatures of outdoor and indoor air. The method to calculate the U-value of a building component is explained in Section 2.3.1.5. The total R-value of a roof is equal to the summation of the R-values of all layers of the roof, which can be calculated as in Equation 2.12.

$$R_{roof} = \frac{X_1}{k_1} + \frac{X_2}{k_2} + \cdots + \frac{X_n}{k_n} \tag{2.12}$$

Where R_{roof} is the total R-value of the roof, X_1, X_2 and etc. are thicknesses of each layer and k_1, k_2 and etc. are the thermal conductivity of each layer.

The difference between U-values of uninsulated and insulated roofs can be expressed as in Equation 2.13.

$$\Delta U_{roof} = U_{roof-uninsulated} - U_{roof-insulated} = \frac{1}{R_{roof}} - \frac{1}{R_{roof} + R_{insulation}} = \frac{1}{R_{roof}} - \frac{1}{R_{roof} + \frac{X_{insulation}}{k_{insulation}}} \tag{2.13}$$

Accordingly, the amount of heat transfer reduced due to the installation of insulation in roof, ΔQ_{roof}, can be quantified using the difference between the overall heat transfer coefficients of uninsulated and insulated roofs as in Equation 2.14.

$$\Delta Q_{roof} = \Delta U_{roof} A_{roof} \left(T_{outdoor-design} - T_{indoor-design} \right) = \Delta U_{roof} A_{roof} \Delta T \tag{2.14}$$

Furthermore, effect of insulation thickness in relation to heat transfer through roof can be obtained by differentiating ΔU_{roof} with respect to $X_{insulation}$ as in Equation 2.15.

$$\frac{\partial(\Delta U_{roof})}{\partial X_{insulation}} = \frac{R_{roof} k_{insulation}}{\left(R^2{}_{roof} k_{insulation} + R_{roof} X_{insulation} \right)^2} \tag{2.15}$$

2.5.4 Hours of Operation for Indoor Cooling

The equivalent hours of operation for indoor cooling can be formulated in terms of time period of full load hours which can be calculated by Equation 2.16.

$$t_{equivalent} = t_{full} \frac{T_{outdoor-average} - T_{indoor-design}}{T_{outdoor-design} - T_{indoor-design}} \tag{2.16}$$

Where $t_{equivalent}$ is the equivalent hours of operation for indoor cooling, t_{full} is the time period of full load hours and $T_{outdoor-average}$ is the average temperature of outdoor air.

2.5.5 Energy Consumption for Air-Conditioner under Roof Insulation

The total amount of energy consumption for AC, E_{AC}, can be calculated using Equation 2.17. Accordingly, the reduction in energy consumption due to insulation in roof, ΔE_{AC} can be expressed in Equation 2.18. E_{AC} and ΔE_{AC} are commonly expressed in kWh. COP_{AC} is the coefficient of performance (COP) of the AC.

$$E_{AC} = \frac{Q_{roof} t_{equivalent}}{COP_{AC}} \tag{2.17}$$

$$\Delta E_{AC} = \frac{\Delta Q_{roof} t_{equivalent}}{COP_{AC}} \tag{2.18}$$

2.5.5.1 Coefficient of Performance of Air-Conditioner

The COP of a room AC, COP_{AC}, is a measure of how efficiently it performs and can be obtained from its cooling capacity and power consumption. It can be calculated as in Equation 2.19. The cooling capacity and power consumption are commonly expressed in *kW*. Common values of COP used in past studies are 2.5 [77-81], 2.9 [82], 2.93 [75, 83-85].

$$COP_{AC} = \frac{Cooling\ capacity}{Power\ consumption} \tag{2.19}$$

2.5.5.2 Cost of Energy Consumption of Air-Conditioner

The cost of energy consumption for AC, C_{AC}, can be calculated by multiplying E_{AC} with the cost of electricity, $C_{electricity}$, as in Equation 2.20. Accordingly, reduction in cost of energy consumption due to insulation, ΔC_{AC}, can be quantified and expressed as in Equation 2.21. Cost of electricity for domestic usage in Malaysia in 2012 is presented in Table 2.5.

$$C_{AC} = E_{AC} C_{electricity}$$

(2.20)

$$\Delta C_{AC} = \Delta E_{AC} C_{electricity} = \frac{\Delta Q_{roof} t_{equivalent} C_{electricity}}{COP_{AC}} = \frac{\Delta U_{roof} A_{roof} \Delta T t_{equivalent} C_{electricity}}{COP_{AC}}$$

(2.21)

Table 2.5: Cost of electricity for domestic usage in Malaysia in 2012 [86]

Tariff Category	**Rate (sen/kWh)**
For the first 200 kWh (1 - 200 kWh) per month	21.8
For the next 100 kWh (201 - 300 kWh) per month	33.4
For the next 100 kWh (301 - 400 kWh) per month	40.0
For the first 100kWh (401 - 500 kWh) per month	40.2
For the next 100 kWh (501 - 600 kWh) per month	41.6
For the next 100 kWh (601 - 700 kWh) per month	42.6
For the next 100 kWh (701 - 800 kWh) per month	43.7
For the next 100 kWh (801 - 900 kWh) per month	45.3
For the next kWh (901 kWh onwards) per month	45.4

2.5.6 Cost Savings from Use of Insulation

Cost savings from use of insulation in roof, *S*, can be calculated as in Equation 2.22.

$$S = \Delta C_{AC} P_1 - C_{insulation} P_2 = \frac{\Delta U_{roof} A_{roof} \Delta T t_{equivalent} C_{electricity} P_1}{COP_{AC}} - (C_{supply} A_{insulation} X_{insulation} + C_{install} A_{insulation}) P_2$$

(2.22)

Where P_1 and P_2 are ratios of life cycle energy and life cycle expenditures incurred due to the additional capital investment. Methods to calculate P_1 and P_2 are presented in Section 2.5.6.1.

The optimum thickness of insulation can be obtained by differentiating S with respect to $X_{insulation}$ and making it equal to zero as in Equation 2.23 and Equation 2.24.

$$\frac{\delta S}{\delta X_{insulation}} = \frac{\delta(\Delta U_{roof})}{\delta X_{insulation}} \frac{A_{roof} \Delta T t_{equivalent} C_{electricity} P_1}{COP_{AC}} - C_{supply} A_{insulation} P_2$$

(2.23)

$$X_{insulation-optimum} = \frac{\left[\sqrt{\left(\frac{R^2{}_{roof} k_{insulation} \Delta T t_{equivalent} C_{electricity} P_1}{COP_{AC} C_{supply} P_2 10^3}\right)} - R^2{}_{roof} k_{insulation}\right]}{R_{roof}}$$

$$when\ \frac{\delta S}{\delta X_{insulation}} = 0$$

(2.24)

2.5.6.1 Ratio of Life Cycle Energy and Expenditures

The accuracy of the projection of cost feasibility of insulation can be enhanced by including the ratio of life cycle energy, P_1 and the ratio of life cycle expenditures incurred due to the additional capital investment to the initial investment, P_2, in the calculation. Equation 2.25 and Equation 2.26 presents the method to calculate P_1, whereas Equation 2.27 presents the method to calculate P_2.

$$P_1 = \frac{1}{d - i}\left[1 - \left(\frac{1 + i}{1 + d}\right)^N\right]\ if\ i \neq d$$

(2.25)

$$P_1 = \frac{N}{1 + i}\ if\ i = d$$

(2.26)

$$P_2 = D + (1 - D)P_1 + MP_1 - \frac{R_v}{(1+d)^N} \tag{2.27}$$

Where d is the market discount rate for the value of money expressed in percentage, i is the inflation rate for the cost of energy expressed in percentage, N is the lifetime period of the insulation expressed in years, D is the ratio of the down payment to the initial investment, M is the ratio of the first year miscellaneous costs such as maintenance, insurance and other incidental costs to the initial investment and R_v is the ratio of the resale value at the end of the economic period of the initial investment. However, if there is no additional capital investment to the initial investment, then P_2 is equal to *1*. Determination of the values for i and d is explained in Section 2.5.6.2.

2.5.6.2 Discount and Inflation Rates

Discount and inflation rates vary from one country to another depending on the economic condition of that country. The majority of previous studies assume their values to ease calculation with reference to economic report. Several studies assume the values of inflation rate to be 1% [87], 3.5% [88], 5% [74, 82, 85, 89-91], 7% [84] and 7.50% [77, 78], whereas for the discount rate, some studies assumed it to be 4% [89-91], 5% [82], 7% [74], 8% [85] and 8.75% [77, 78].

2.5.6.3 Lifetime Period of Insulation Material

Lifetime period of insulation materials vary from one another depending on their material properties. It can be accurately determined by conducting laboratory experiments. For studies where accurate determination of it is unnecessary, an assumption of its value is made. Several past studies assumed its values to be 10 years [91-94], 20 years [75, 84, 87, 95], 25 years [96] and 30 years [83, 85, 97].

2.5.7 Payback Period

By making the cost savings, *S*, equal to zero, the payback period, $N_{payback}$, can be expressed as in Equation 2.23 and 2.24.

$$N_{payback} = \frac{P_2 C_{supply}\left(R_{roof}X_{insulation} + R^2{}_{roof}k_{insulation}\right)10^3 COP_{AC}(1+i)}{C_{electricity}\Delta T t_{equivalent}}$$

$$if\ i = d, when\ S = 0$$

(2.28)

$$N_{payback} = \frac{\ln\left[1 - \left(\frac{P_2 C_{supply}\left(R_{roof}X_{insulation} + R^2{}_{roof}k_{insulation}\right)10^3 COP_{AC}(1-d)}{C_{electricity}\Delta T t_{equivalent}}\right)\right]}{\ln\left(\frac{1+d}{1+i}\right)}$$

$$if\ i \neq d, when\ S = 0$$

(2.29)

2.6 CO_2 Emission

Generation and consumption of electricity from various activities lead to emission of CO_2, which contribute towards global warming and climate change. This section explains how CO_2 is emitted from generation and consumption of electricity and explains methods to estimate CO_2 emission.

Electricity is generated from combustion of fossil fuels, which produces heat energy. The heat energy is converted into kinetic energy, which drives the mechanism that generates electricity. Complete combustion of fossil fuels is governed by the following chemical equation (Equation 2.30) [98]:

$$Fuel + O_2 \rightarrow CO_2 + H_2O + Heat\ Energy$$

(2.30)

2.6.1 CO_2 Emission from Electricity Generation

Main sources of energy supply in Malaysia are crude oil and petroleum products, natural gas, coal and coke and hydro. Figure 2.12 shows the percentage distribution of energy supply in Malaysia by fuel source.

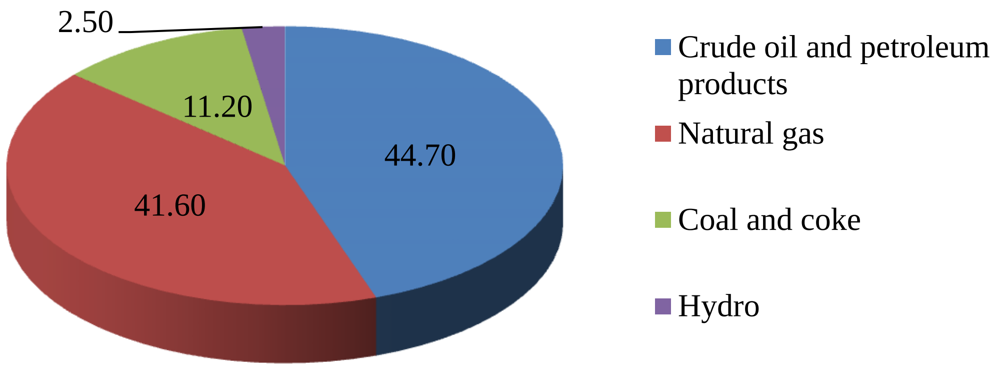


Figure 2.12: Percentage distribution of energy supply in Malaysia by source [99]

CO_2 emission from electricity generation from each source can be computed using Equation 2.31 [98].

$$Emission_{CO_2-Fuel} = Consumption_{Fuel} \times Emission\ Factor_{CO_2-Fuel} \tag{2.31}$$

Where $\text{Emission}_{\text{CO2}}$ is the CO_2 emission by a source in *kg* CO_2, $\text{Consumption}_{\text{Fuel}}$ is the amount of fuel combustion in *J* that emits CO_2 and $\text{Emission Factor}_{\text{CO2-Fuel}}$ is the rate of CO_2 emission per unit of fuel combustion in *kg* CO_2/J. CO_2 emission factor for each source in Malaysia is presented in Table 2.6. CO_2 emission factor of the overall fuel mix is the combination of CO_2 emission factors of each source with consideration of the percentage distribution of energy supply by each source.

Table 2.6: CO_2 emission factor for each source in Malaysia [99, 100]

Source	CO_2 Emission Factor (kg CO_2/kWh)
Coal	0.95
Gas	0.59
Hydro	0.00
Overall Fuel Mix	0.65

2.6.2 CO_2 Emission from Cars

Other than electricity generation, CO_2 is also emitted from cars. Cars are mobilized by the kinetic energy produced from fuel combustion in the engine. As a result of this combustion, CO_2 is emitted into the atmosphere. Rate of CO_2 emission from cars varies according to several factors, which includes type of car, rate of fuel consumption of car, type of fuel, distance travelled and style of driving. Table 2.7 reveals the rate of fuel consumption of selected cars from 2010 to 2012. Table 2.8 shows the average rate of CO_2 emission of selected cars in selected years between 1980 and 2012.

Table 2.7: Rate of fuel consumption (km/litre) of selected cars from 2010 to 2012 [101]

Manufacturer	**Make**	**Rate of Fuel Consumption (km/litre)**		
		2010	*2011*	*2012*
Toyota	Toyota	17.09	15.73	17.64
Toyota	Lexus	12.50	12.63	13.14
Honda	Honda	15.30	15.26	16.45
Honda	Acura	12.37	12.71	12.97
BMW	BMW	11.10	11.82	12.10
BMW	Mini	15.98	16.71	16.49
Ford	Ford	13.18	13.52	15.18
Daimler	Mercedes-Benz	10.42	10.59	12.03
Daimler	Smart	20.87	20.70	21.38
GM	Chevrolet	13.05	13.18	13.65

Table 2.8: Average rate of CO_2 emission (kg CO_2/km) of selected cars in selected years between 1980 and 2012 [102]

Model Year	**Rate of CO_2 Emission (kg CO_2/km)**			
	Laboratory		*Adjusted*	
	City	*Highway*	*City*	*Highway*
1980	0.2728	0.1914	0.3032	0.2455
1985	0.2411	0.1616	0.2678	0.2069
1990	0.2361	0.1535	0.2703	0.2013
1995	0.2361	0.1479	0.2784	0.1982
2000	0.2392	0.1516	0.2908	0.2069
2005	0.2268	0.1454	0.2852	0.2032
2010	0.2007	0.1317	0.2554	0.1852
2012	0.1895	0.1230	0.2417	0.1734

2.6.3 CO_2 Sequestration from Trees

Trees sequester CO_2 from the atmosphere to produce food through the process of photosynthesis. Consequently, effect of global warming can be reduced by protecting existing trees and planting new trees. Rate of CO_2 sequestration from trees varies according to several factors including the type, growth rate and age of tree. Table 2.9 presents the types and growth rates of selected trees. Table 2.10 reveals CO_2 sequestration rates of common urban trees.

Table 2.9: Types and growth rates of selected trees [103]

Species	**Type**		**Growth Rate**		
	Hardwood	Conifer	Slow	Moderate	Fast
Ailanthus altissima	/				/
Alnus glutinosa	/				/
Betula papyrifera	/			/	
Ginkgo biloba	/		/		
Magnolia acuminata	/				/
Pinus strobus		/			/
Populus deltoides	/			/	
Populus grandidentata	/			/	
Tsuga canadensis		/		/	
Ulmus parvifolia	/			/	

Table 2.10: CO_2 sequestration rates of common urban trees (kg CO_2/tree/year) [104]

Tree Age (years)	**CO_2 Sequestration Rate (kg CO_2/tree/year)**					
	Hardwood			*Conifer*		
	Slow	*Moderate*	*Fast*	*Slow*	*Moderate*	*Fast*
5	1.452	2.767	4.581	0.8618	1.678	2.903
10	2.495	5.080	8.754	1.588	3.357	5.988
20	4.899	10.52	18.60	3.357	7.575	13.97
50	13.79	30.75	55.66	10.84	25.54	48.22

2.7 Review of Previous Researches

This section reviews previous researches and is divided into two parts. The first part reviews previous researches on thermal performance of building insulation materials. Then, the second part reviews previous researches on determination of optimum insulation thickness.

2.7.1 Thermal Performance of Building Insulation Materials in Roof

Existing building insulation materials and solutions can be classified into two categories, which are traditional and state-of-the-art building insulation materials [58]. It states that the most common traditional building insulation materials of today with low thermal conductivity are mineral wool, EPS, XPS, cellulose, cork and PUR. State-of-the-art building insulation materials presented in this review are VIP, GFP, aerogels and PCM. This review concluded that it is important to initiate research which explores possibilities of discovering and developing novel high performance insulation materials and solutions with properties that are superior to all of the existing building insulation materials and solutions. Nano insulation materials (NIM), dynamic insulation materials (DIM) and the load bearing insulation material, NanoCon, are highlighted as potential high performance insulation materials of the future.

Ong (2011) [36] compared the thermal performances of uninsulated and insulated tiled and metal deck roof designs as shown in Figure 2.13. The experimental setup comprises of six (6) laboratory-sized units placed next to each other in a walled-up open area as shown in Figure 2.14. Each unit was supported by a 2-m long and 1-m wide frame. Each base frame was inclined by 15° from the horizontal plane. The base frames rested at 0.3-m height from the ground on 50-mm long by 50-mm wide by 3-mm thick aluminium angles. The side walls of the base frames were constructed from 50-mm thick rock wool laminated with 0.5-mm thick aluminium sheets on both sides. For the tiled roof designs, 25-mm thick cement roof tiles were utilized. While, for the metal deck roof designs, 0.5-mm thick galvanized roofing sheets were used. The insulation material used for the insulated roofs was aluminium foil-backed 50-mm rock wool. The difference between the insulated metal deck roof and roof solar collector is the presence of a 50-mm air gap formed between the galvanized roofing sheet, the insulation material and an opening on the opposite side of the roof. The function of the air gap and opening is to provide air circulation. Temperatures of the roof, attic and ceiling were recorded at 5-min intervals continuously over 24 hours for several weeks. Results obtained concluded that the roof solar collector results in the coolest attic and ceiling, with temperatures ranging between 37°C - 38°C and 36°C - 37°C for the attic and ceiling respectively. The insulated metal deck roof resulted in the highest roof temperature. However, the ceiling of the insulated metal deck roof is cooler than the uninsulated metal deck roof. This indicates that the insulation material underneath the roofing sheet absorbs the heat and retards the flow of heat to the ceiling. A comparison between the temperatures obtained for the two (2) insulated tiled roof designs indicated that placement of insulation below tiles is preferred to above the ceiling.

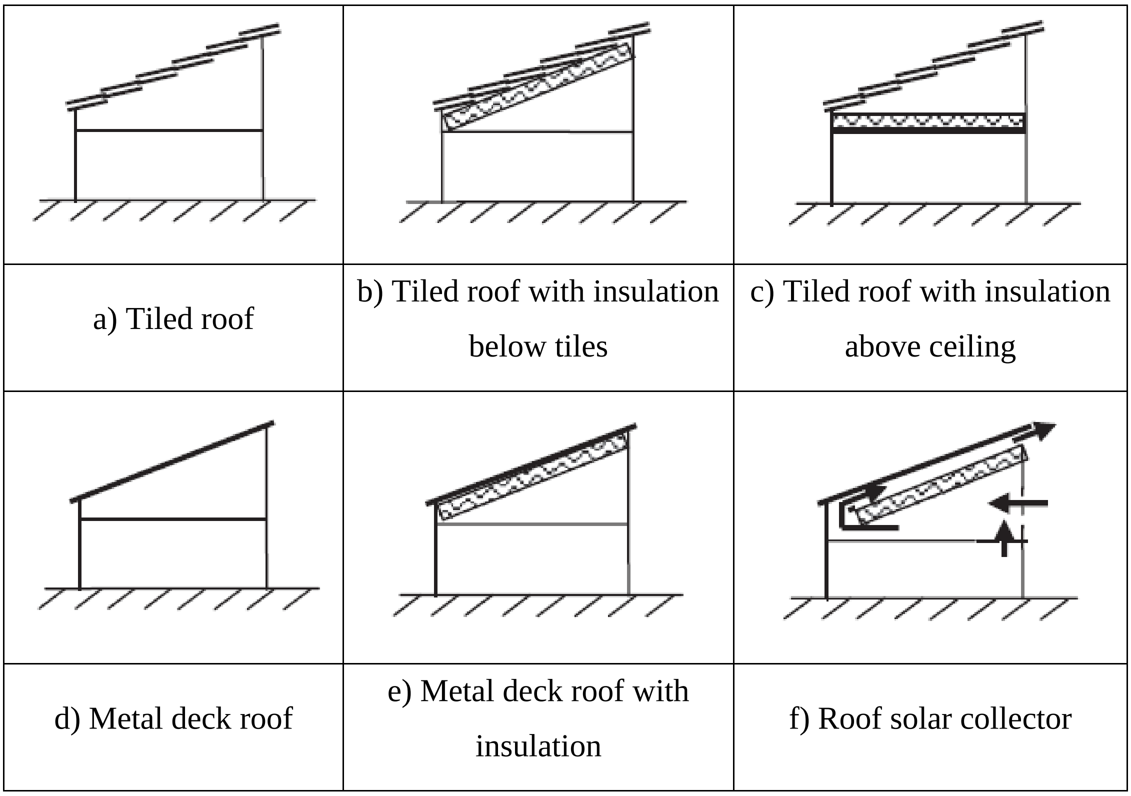


Figure 2.13: Roof designs evaluated in Ong (2011) [36]

Figure 2.14: Roof units fabricated in Ong (2011) [36]

In another study [39], an experimental setup consisting of two identical naturally ventilated 4-m long by 4-m wide by 3-m high test cells placed next to each other as shown in Figure 2.15 were employed to evaluate the thermal performance of insulation placed underneath roof tiles and above the ceiling. Selection of materials and method of construction of both test cells are conventional. The roof of one cell is uninsulated, while the roof of the other cell is insulated. For the insulated roof, firstly, a 75-mm thick mineral wool is placed underneath the roof tiles for 5 days. Later on, the mineral wool is removed and a 100-mm thick fibreglass is placed above the ceiling for 10 days. Outdoor and indoor temperatures of both cells were recorded at 10-minute intervals with opened windows that cover 20% of the floor area. Results show that the mineral wool placed under the roof tiles lower the indoor temperature at daytime up to 0.8°C, while the fibreglass placed above the ceiling lower the indoor temperature at daytime up to 0.6°C. It is concluded that the positive impact of the mineral wool placed under the roof tiles is more significant than the fibreglass placed above the ceiling.

Figure 2.15: Test cells fabricated in Morris *et al.* (2011) [39]

A computer simulation [105] using IES was performed to investigate the benefits of insulation installed below the roof pitch and above the ceiling for air-conditioned buildings in Malaysia. The building model created for the simulation is shown in Figure 2.16. Three (3) models were created as described in Table 2.11. A 950-W split AC was installed in the indoor space of each model. The insulation material employed in the insulated models is fibreglass. The Subang weather data for the month of March is used in the simulation. The reduction in attic and indoor space temperature due to the placement of insulation below the roof pitch is up to 6.9°C and 0.4°C respectively. Contrarily, the attic temperature is raised by up to 2.2°C due to the placement of insulation above the ceiling, but results in the reduction in indoor space temperature by up to 0.8°C. Monthly savings on the cooling load due to insulation ranges between 6% - 24%.

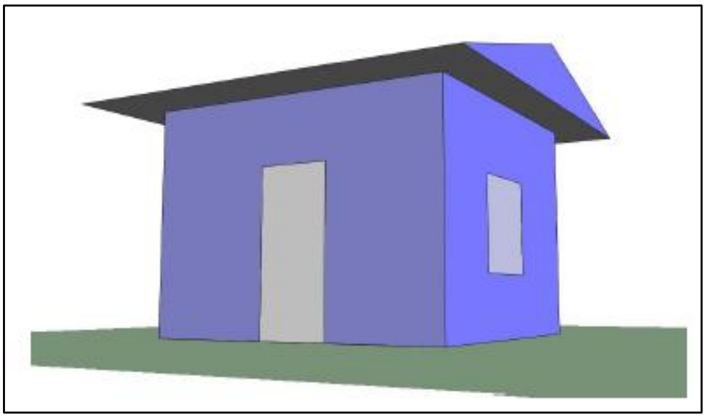


Figure 2.16: 3-D image of building model created in Halim *et al.* (2011) [105]

Table 2.11: Description of building models created in Halim *et al.*(2011) [105]

Model Number	Model Name	Description
1	BASE	Non-insulated
2	CEILING	Insulation laid on the ceiling
3	PITCH	Insulation installed underneath the roof pitch

2.7.2 Determination of Optimum Insulation Thickness

Previous researches reveal that two (2) main methods, which are the Life Cycle Cost (LCC) and P_1-P_2 methods, were utilized to determine optimum insulation thickness. [83, 84, 92, 106, 107] employed the LCC method and [75, 80, 87, 90, 108] employed the P_1-P_2 method.

2.7.2.1 Life Cycle Cost

Mahlia and Iqbal (2010) [84] studied the optimum insulation thicknesses of fibreglass-urethane, fibreglass (rigid), urethane (rigid), perlite, XPS and urethane (roof deck) with varying thickness of air gaps for building walls in Maldives and found that the optimum insulation thicknesses range from 0.015 m - 0.06 m depending on the insulation material and thickness of air gap. In this research, adoption of insulation resulted in emission reduction of 65% - 77%.

In another study, Yildiz *et al.* (2008) [106] calculated the optimum insulation thicknesses of two (2) types of mineral wool, which are fibreglass and rock wool in the cities of Izmir and Ankara, which are located in Turkey, at varying types of fuel used to heat the indoor space during heating days. Types of fuel considered in this study are coal, natural gas, oil and liquefied petroleum gas (LPG). Consumption of electricity due to operation of room AC during cooling days is also considered. Optimum insulation thicknesses obtained for fibreglass range from 0.05 m to 0.12 m depending on the type of fuel used in the calculation. It is highlighted that the emission reduction from use of coal as fuel is approximately 35% for Ankara.

Sisman *et al.* (2007) [92] determined the optimum thicknesses of rock wool for application in external walls and ceilings in Turkey in cities with various heating and cooling degree days (DD). The locations considered in this study are the cities of Izmir, Bursa, Eskisehir and Erzurum in Turkey and Tehran in Iran. The fuel type used in the calculation to determine the optimum thickness of rock wool is coal. Optimum insulation thicknesses obtained for external walls are 0.033 m, 0.047 m, 0.061 m and 0.080 m.

Another research [107] studied the optimum thickness of polystyrene for insulation in building walls in a total of 16 cities in Turkey. The 16 cities comprise of four (4) cities for each DD region. Fuel types for heating used in the calculation are natural gas, coal, oil and LPG. Optimum insulation thicknesses obtained vary widely from 0.019 to 0.172 m depending on the cities and fuel types used for heating.

Daouas *et al.* (2010) [83] determined optimum thickness of EPS and rock wool for application in building walls in Tunisia. Consumption of electricity for cooling of indoor space is considered in the calculation. The optimum insulation thickness obtained is 0.057 m.

Table 2.12 presents the comparison between previous studies on optimum thickness of insulation materials that adopted the LCC method.

2.7.2.2 P_1-P_2

Another research [108] conducted also in Turkey determined the optimum thicknesses of XPS foam and rock wool. Fuel types used for heating are natural gas and fuel oil. Four (4) DD regions were considered in the calculation. Optimum insulation thicknesses obtained vary between 0.0364 m to 0.087 m depending on the DD regions for XPS foam. Emission reductions obtained are 51% of CO_2 for natural gas and 55% of CO_2 and SO_2 for fuel oil.

Ucar and Balo (2009) [90] studied the optimum thicknesses of Foamboard 1500, Foamboard 3500, XPS and fibreglass in the cities of Kocaeli, Aydin, Elazig and Agri in Turkey. The fuel types used for heating are natural gas, coal, fuel-oil and LPG. Consumption of electricity for indoor cooling is also considered. Optimum insulation thicknesses obtained vary between 0.0106 m to 0.0764 m depending on the cities and fuel types used for heating.

A study by Yu *et al.* (2009) [87] on optimum thicknesses of EPS, XPS, foamed PUR, perlite and foamed polyvinyl chloride (PVC) is conducted in the cities of Shanghai, Changsha, Shaoguan and Chengdu in China. Optimum insulation thicknesses generated range from 0.053 m to 0.236 m.

Mahlia *et al.* (2007) [75] conducted a study in Malaysia that determines the optimum insulation thickness of fibreglass-urethane, fibreglass (rigid), urethane (rigid), perlite, XPS and urethane (roof deck). The values obtained vary between 0.04 to 0.10 m.

Bolatturk (2008) [80] determines the optimum insulation thickness of XPS board when applied in building walls in the warmest zone of Turkey. Zone of study covers cities of Adana, Antalya, Aydin, Hatay, Iskanderun, Izmir and Mersin. Natural gas is used for indoor heating and consumption of electricity is considered for indoor cooling. Results vary between 0.032 m to 0.038 m for cooling degree hours (CDH) and between 0.016 m to 0.027 m for heating degree hours (HDH).

Table 2.13 presents the comparison between previous studies on optimum thickness of insulation materials that adopted the P_1-P_2 method.

Table 2.12: Comparison between previous studies on optimum thickness of insulation materials that adopted the LCC method

Reference	**Location of Study**	**Insulation Materials**	**Placement of Insulation Materials**	**Varying Parameters**	**Optimum Insulation Thicknesses**	**Reduction in Emission**
Mahlia and Iqbal (2010) [84]	Maldives	Fibreglass, Urethane, Perlite, Polystyrene	Walls	Thickness of air gap	Vary from 0.015 m to 0.06 m	65% to 77%
Yildiz *et al.* (2008) [106]	2 cities in Turkey	Fibreglass, Rock wool	-	Types of fuel for heating	Vary from 0.05 m to 0.12 m for fibre glass	35% for coal for Ankara
Sisman *et al.* (2007) [92]	4 cities in Turkey, Tehran in Iran	Rock wool	Walls and Ceiling	Heating and cooling DD of cities	0.033 m, 0.047 m, 0.061 m and 0.0080 m for walls	-
Bolatturk (2006) [107]	16 cities in Turkey	Polystyrene	Walls	Climate zones, Types of fuel for heating	Vary 0.019 m to 0.172 m	-
Daouas *et al.* (2010) [83]	Tunisia	Polystyrene, Rock wool	Walls	-	0.057 m	-

Table 2.13: Comparison between previous studies on optimum thickness of insulation materials that adopted the P_1-P_2 method

Reference	**Location of Study**	**Insulation Materials**	**Placement of Insulation Materials**	**Varying Parameters**	**Optimum Insulation Thicknesses**	**Reduction in Emission**
Ozkan and Onan (2011) [108]	Turkey	Polystyrene, Rock wool	Window	DD of regions	Vary from 0.0364 m to 0.087 m for polystyrene	51% CO_2 for natural gas and 55% CO_2 and SO_2 for fuel oil
Ucar and Balo (2009) [90]	4 cities in Turkey	Foamboard 1500, Foamboard 3500, Polystyrene, Fibreglass	-	DD of regions	Vary from 0.0106 m to 0.0764 m	-
Yu *et al.* (2009) [87]	4 cities in China	Polystyrene, PUR, Perlite, PVC	Walls	-	Vary from 0.053 m to 0.236 m	-
Mahlia *et al.* (2007) [75]	Malaysia	Fibreglass, Urethane, Perlite, Polystyrene	Walls	Thermal conductivity of insulation material	Vary from 0.04 m to 0.10 m	-
Bolatturk (2008) [80]	7 cities in Turkey	Polystyrene	Walls	CDH and HDH of regions	Vary between 0.032 m and 0.038 m for CDH and 0.016 m and 0.027 m for HDH	-

2.8 Gap Analysis

Although there are many researches that study the optimum thickness of insulation [75, 80, 83, 84, 87, 90, 92, 106-108], but to the researcher’s knowledge, all of them employed traditional insulation materials such as polystyrene, rock wool and fibreglass and none employed novel insulation materials that are not commonly used today. Therefore, a study on the optimum thickness of novel insulation materials with high performance is essential in order to prove their potential as insulation materials of the future. This research employs alternative insulation materials such as kapok fibre, elastomeric nitrile rubber (ENR) and reinforced aerogel as well as traditional insulation materials such as polystyrene, rock wool, fibreglass and cellulose. A number of researches worked on developing kapok fibre and reinforced aerogel as novel building insulation materials and determining their insulation properties in the laboratory [63, 66-70].

To the researcher’s knowledge, previous researches employ either house model measurement [36, 39] or simulation [105] to validate effectiveness of insulation in building components such as walls or roof. House model measurement can validate the effectiveness of insulation materials but it has many constraints that limit the scope of research. Simulation can widen the scope of research, but conducting simulation alone presents a gap where data generated from simulation is not validated in actual climate conditions. Thus, utilizing both house model measurement and simulation data is a better approach that can generate a wider range of data that is more reliable. Also, application of building energy performance simulation tools needs to be further investigated to develop the body of knowledge in this area. This research validates the effectiveness of insulation from house model measurement and explores the potential of both traditional and novel insulation materials from simulation.

Most of the previous researches that study optimum insulation thickness concentrated on placement of insulation in walls [75, 80, 83, 84, 87, 92, 107] and there is a lack of research in this area that focuses on the placement of insulation in the roof, either beneath the roof pitch or above the ceiling. The roof is the most exposed building component because of its position at the top-most part of the building, which is closest to the sun [37, 38]. Hence, more research that determines the optimum insulation thickness for roof insulation is required. In this research, insulation is placed beneath roof tiles and above the ceiling.

Furthermore, in previous research on optimum insulation thickness, only the cost to supply insulation is considered. In this research, another component in the calculation of insulation, which is the cost to install insulation, is included in the calculation. The cost rate to install insulation is obtained from local contractors. This approach improves the practicality of the result.

Moreover, some researches in this area attempt to calculate the reduction in CO_2 emission as a result of implementing insulation [84, 106, 108]. However, to the researcher's knowledge, there is no research that quantifies the impact of CO_2 emission reduction in values that people outside the research community can better understand. This research determines the impact of the reduction in CO_2 emission by calculating the number of cars being removed from the road and the number of trees being planted that can result in the same reduction in CO_2 emission. As a result, awareness on impact of insulation can be recognized not only by academicians and researchers, but also the public.

Table 2.14 and Table 2.15 illustrate the gap that is currently present in this research area and highlights how the present research fills that gap.

Table 2.14: Research gap based on placement of insulation

Research	**Placement of Insulation**			
	Wall	*Window*	*Roof*	
			Pitch	*Ceiling*
Ozkan and Onan (2011)		√		
Daouas *et al.* (2010)	√			
Mahlia and Iqbal (2010)	√			
Yu *et al.* (2009)	√			
Bolatturk (2008)	√			
Sisman *et al.* (2007)	√			√
Mahlia *et al.* (2007)	√			
Bolatturk (2006)	√			
Present Research			√	√

Table 2.15: Research gap based on insulation material

Research	Insulation				
	Traditional			New	
	Polystyrene	*Rock Wool*	*Fibreglass*	*Kapok Fibre*	*Reinforced Aerogel*
Ozkan and Onan (2011)	√	√			
Daouas *et al.* (2010)	√	√			
Mahlia and Iqbal (2010)	√		√		
Yu *et al.* (2009)	√				
Bolatturk (2008)	√				
Sisman *et al.* (2007)		√			
Mahlia *et al.* (2007)	√		√		
Bolatturk (2006)	√				
Present Research	√	√	√	√	√

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes research methods and approaches employed to accomplish the research objectives. Firstly, an overview of the research process is presented. Then, all methods employed are explained.

3.2 Overview of Research Process

Firstly, to achieve the first objective, a survey was conducted. The survey consists of two (2) sets of questionnaire and an online interview targeted for house owners, developers and professionals. Then, to achieve the second and third objectives, a house model experiment and simulation were carried out. Lastly, to achieve the fourth objective, calculations were performed to quantify the cost and environmental impacts of thermal insulation in residential roofing system. Figure 3.1 presents an overview of the research process and Figure 3.2 illustrates the research methodology flow.

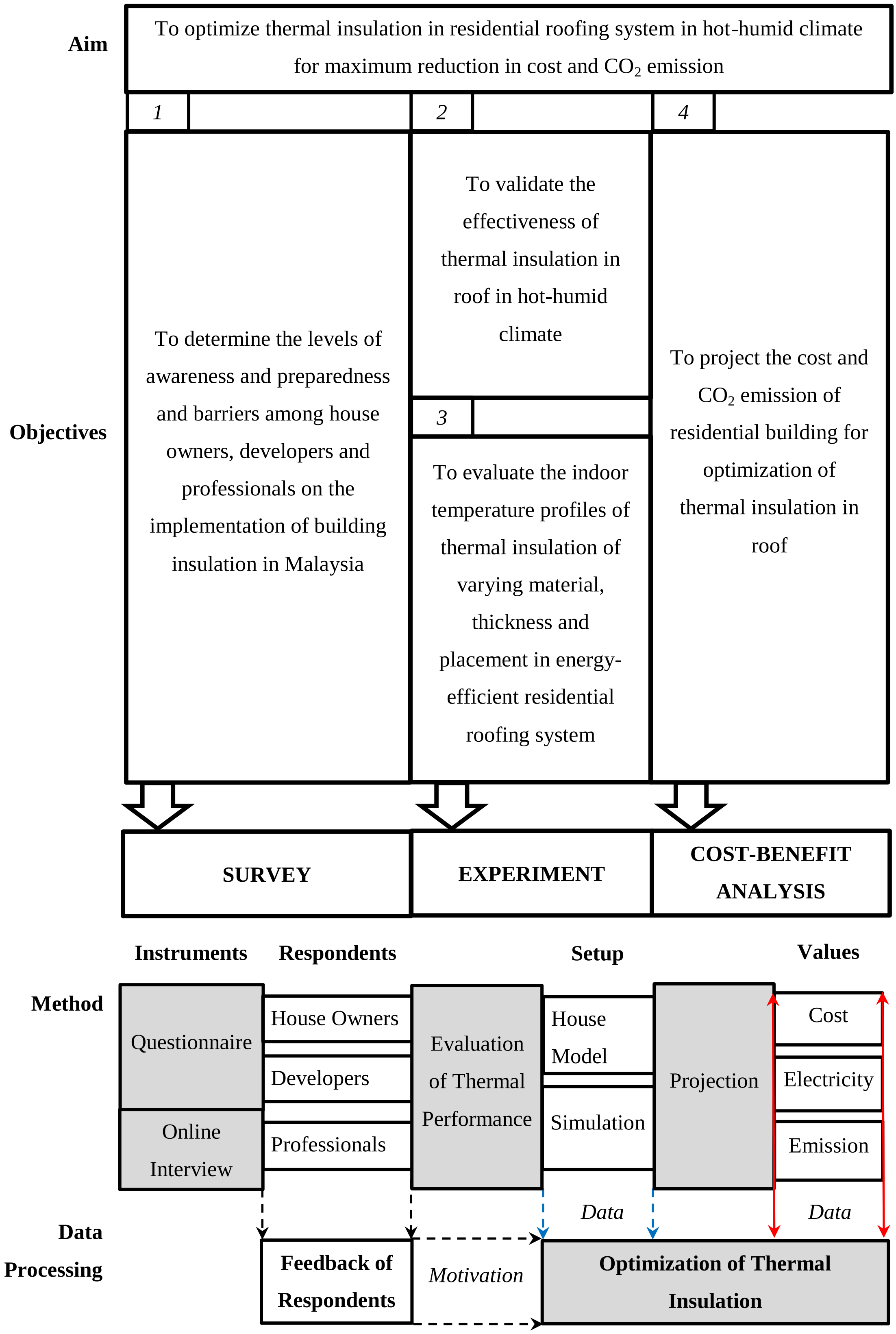


Figure 3.1: Overview of the research process

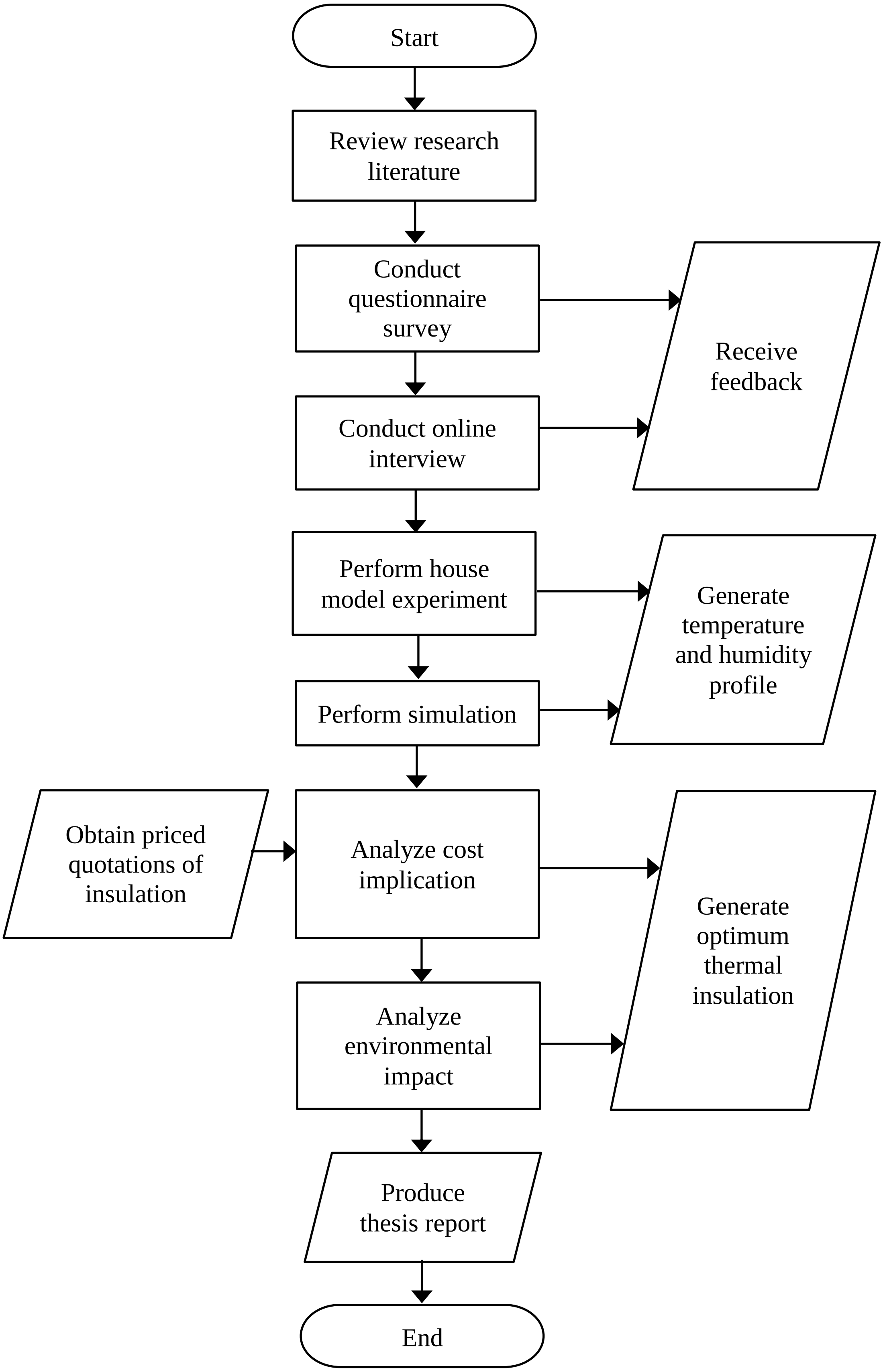


Figure 3.2: Research methodology flow

3.3 Survey

The first objective of the research is to determine the levels of awareness and preparedness and identify the barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia. To achieve this objective, a survey was conducted. Two (2) survey methods were employed, which are the questionnaire and interview methods.

3.3.1 Questionnaire

A questionnaire is a paper instrument that contains questions and prompts with a choice of answers, prepared for the purpose of gathering specific data from targeted respondents. To determine the set of questions to be included in the questionnaires, a preliminary research was conducted. The preliminary research comprises of the following activities:

- Gathering of information at the International Greentech & Eco Products Exhibition & Conference Malaysia 2010 (IGEM 2010) at KL Convention Centre (KLCC), Malaysia, which presented latest news, knowledge and inventions in the field of green technology

- Study on statistical reports produced by Malaysian Insulation Manufacturers Group (FMM-MIMG), which was formed under the guidance of the Federation of Malaysian Manufacturers (FMM), on the understanding of homeowners' awareness levels and usage experience of building insulation

- Gathering of information online

Then, with reference to the results of the preliminary research, the questions to be included in the questionnaire are determined. The strategy employed in the questionnaires is presented in Figure 3.3.

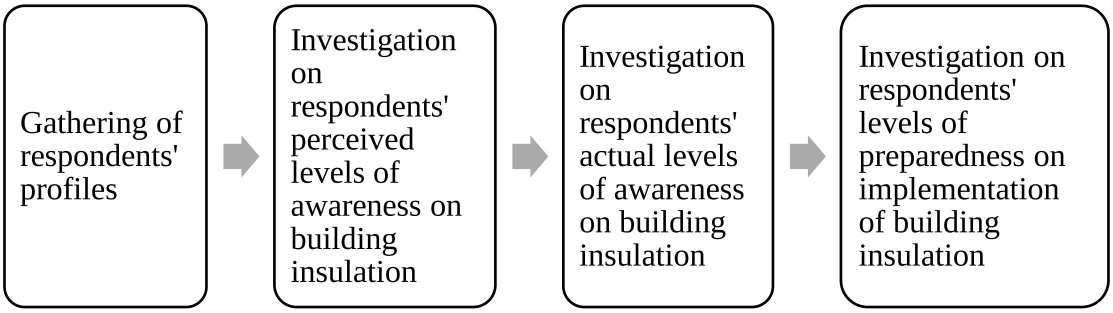


Figure 3.3: Strategy employed in the questionnaires

Two (2) sets of questionnaires were produced. The first set determines the preference of housing insulation among house owners and factors that can drive its implementation. 50 copies were sent to 50 random house owners at property exhibitions. The respondents' profiles were checked to ensure respondents' involved come from various age, race and occupation groups. If the respondents' profile distribution is unsatisfactory, the number of copies distributed is to be increased accordingly. The choice of property exhibitions as the location to distribute the questionnaires is to ensure that the respondents' consist of interested house buyers. The questionnaire is enclosed in Appendix B.

The second set of questionnaires is targeted for developers. It is divided into four (4) parts. In Part 1, details of developers were gathered for future reference. In Part 2, the level of preference of housing insulation was determined based on information obtained on projects completed by developers. Part 3 determines factors that contribute to the lack of preparedness on implementation of housing insulation and awareness of its importance. Part 4 gathers comments and suggestions from developers on the issue of housing insulation.

For the second set of questionnaires, a request for endorsement was sent to recognized agencies that play important roles in the field of insulation, which are Real Estate and Housing Developers' Association of Malaysia (REHDA), FMM-MIMG and Pertubuhan Arkitek Malaysia (PAM), as a measure to improve the rate of feedback from respondents. REHDA responded positively to the request and the survey was named the REHDA Property Industry Survey for 2nd Half of 2010.

The REHDA directory was purchased to obtain contacts of developers registered under her. 600 copies of the second set of questionnaires were sent to 600 developers by email with assistance from REHDA. Calls were made to each respondent as a measure to increase the rate of feedback. Approximately 500 copies were sent through REHDA to developers registered under her and 100 copies were sent personally. However, out of the 600 copies sent, only 30 developers, which represent only 5% of the respondents, responded. The low rate of feedback is an indication that most housing developers were not aware of the importance of the issue. The questionnaire is attached in Appendix C.

Questionnaires were filled in and compiled. Answers provided by respondents are presented and analyzed qualitatively. Further statistical analysis of the results is not necessary because the purpose of the survey is only to address one supporting objective of the research, which is to determine the levels of awareness and preparedness among house owners and developers on building insulation.

3.3.2 Online Interview

Online interviews were conducted with 15 professionals from various fields to obtain opinions and identify barriers on the implementation of housing insulation in Malaysia. Answers provided by interviewees were written down and arranged accordingly. Details of the interviewees are attached in Appendix D. Table 3.1 summarizes the methodology discussed in this section.

Table 3.1: Summary of questionnaire and online interview surveys implemented

Survey Type	Set	Part	Focus Areas	Targeted Respondents
Questionnaire	1		1. Preference of housing insulation among house owners 2. Factors that can drive implementation of housing insulation	House owners
	2	1	Details of developers	Developers
		2	Preference of housing insulation based on projects	
		3	1. Factors that contribute to the lack of preparedness on the implementation of housing insulation 2. Factors that contribute to the lack of awareness of the importance of housing insulation	
		4	Comments and suggestions on the issue of housing insulation	
Online Interview			Barriers on the implementation of housing insulation	Professionals from various fields

3.4 House Model Experiment

The second objective of the research is to validate the effectiveness of thermal insulation in roof in hot-humid climate. A house model experiment is employed to achieve this objective. Data was collected from instruments installed in two (2) small-scaled house models.

3.4.1 Construction of House Models

Two (2) small-scaled house models were constructed and placed at an open area near Building 13, Universiti Teknologi PETRONAS (UTP). The location is as shown in Figure 3.4. House dimensions are 60-cm length by 60-cm breadth by 50-cm height with 45°-sloped doubled-pitched roofs, which is exactly five times smaller than the house model dimensions used for the simulation, which were determined based on previous studies [36, 39, 105] and the fixed minimum dimensions for a room as mentioned in Uniform Building By-Laws (UBBL) 1984 [109, 110]. Cement roof tiles of dark grey colour were utilized. Selection of dark grey as the colour of roof tiles is to allow maximum absorption of solar radiation. The roof tiles were supported by a timber roof structure underneath. The timber roof structure is shown in Figure 3.5. It is placed on top of a 125-mm thick concrete brick wall with no finishing as shown in Figure 3.6, Figure 3.7 and Figure 3.8. The internal wall was insulated with polystyrene to reject all heat transmission through the wall and provide a condition where all heat transmission is only through the roof for a more accurate evaluation. The roof of one house was not insulated, while insulation was installed in the roof of the other house as shown in Figure 3.9. The houses were placed on top of wood pellets. The roof pitch was aligned with the West-East axis for maximum exposure to solar radiation as shown in Figure 3.10 and Figure 3.11.

Not to scale

Figure 3.4: Location of small-scaled house models

Figure 3.5: Timber roof structure

Figure 3.6: 125-mm thick concrete brick wall with no finishing

Figure 3.7: Placement of roof structure on top of brick wall (interior side view)

Figure 3.8: Placement of roof structure on top of brick wall (interior top view)

Figure 3.9: Installation of insulation material in roof structure

Figure 3.10: Placement of small-scaled house models

Not to scale

Figure 3.11: Alignment of roof pitch of house models

3.4.2 Insulation Material

The insulation material utilized in this experiment is kapok fibre. In this case, it is not necessary for this experiment to be conducted with many types of insulation materials because the purpose of this experiment is only to validate the effectiveness of insulation in general. Comparison between effectiveness of various types of insulation materials is conducted during the simulation.

Front and top views of the kapok fibre sample are shown in Figure 3.12 and Figure 3.13. Firstly, 50-mm thick kapok fibre was installed in the timber roof structure of one house, while the other house was left uninsulated. Then, thermal performances of both experimental houses were compared. After that, thickness of kapok fibre installed in the insulated house was increased to 100 mm. Similarly, the performance of the 100-mm thick kapok fibre was evaluated.

Figure 3.12: Kapok fibre (front view)

Figure 3.13: Kapok fibre (top view)

3.4.3 Instrumentation

Instruments used were single input thermometer with surface probe (Figure 3.14) and hygro-thermometers (Figure 3.15). The single input thermometer with surface probe measures the roof surface temperature, while the hygro-thermometers measure indoor and outdoor air temperatures and indoor relative humidity. The model and specifications of each instrument are highlighted in Table 3.2. Two (2) hygro-thermometers were installed inside the houses to measure indoor air temperature and relative humidity simultaneously as shown in Figure 3.16 and 3.17. Hygro-thermometers were positioned in the middle of room to obtain values that represent the average values for the whole room.

Figure 3.14: Single input thermometer with surface probe

Figure 3.15: Hygro-thermometer with a built-in temperature and relative humidity sensor

Table 3.2: Model and specifications of instruments

Instrument	**Model**	**Specifications**
Single Input Thermometer with Surface Probe	Extech TM100	Measuring Range: Temperature (Type K): -200 to 1372°C Temperature (Type J): -210 to 1100°C Accuracy: ± (0.15% of reading + 1°C) Resolution: 0.1°/1° Dimensions: 220 mm x 63 mm x 28 mm Weight: 200 g
Hygro-Thermometer with a Built-In Temperature and Relative Humidity Sensor	Kimo KH100	Measuring Range: Relative Humidity: 5% to 95% Temperature: -20°C to 70°C Accuracy: Relative Humidity: ± 2.95% between 18°C and 28°C Temperature: ± 1% of value displayed, ±0.4°C at (5°C<T<70°C), ± 2% of value displayed, ±0.6°C at (20°C<T<5°C) Response Time: Relative Humidity: $t_{0,63}$ = 50s (V_{air} = 2 m/s) Temperature: $t_{0,63}$ = 25s (V_{air} = 2 m/s) Dimensions: 91 mm x 65 mm x 33 mm Weight: 85 g

Figure 3.16: Position of hygro-thermometers inside house model (front view)

Figure 3.17: Position of hygro-thermometers inside house model (side view)

Roof surface temperatures, indoor and outdoor air temperatures and indoor relative humidity for each house model were recorded hourly from 10AM until 4PM for five (5) hot-humid days. The period 10AM until 4PM is chosen because generally, within this period, the sun radiates the most amount of heat due to its high position in the sky. Furthermore, five (5) hot-humid days is sufficient since it is not necessary for the experiment to be conducted for many weeks or months because the climate in Malaysia is hot and humid throughout the year with no major seasonal changes.

3.5 Simulation

The simulation aims to address the third objective, which is to evaluate the indoor temperature profiles of thermal insulation of varying material, thickness and placement in energy-efficient residential roofing system. Figure 3.18 illustrates the simulation process flow. Firstly, the appropriate simulation tool is selected. The selection process is elaborated further in Section 3.5.1. Next, the appropriate climate is selected. Then, a control house model is developed and its indoor temperature profile is generated. The specification of the control house model is discussed in Section 3.5.2. Next, roof elements of the control house model, which consist of roof tile colour and pitch orientation, are modified to create least energy-efficient (L), typical (T) and most energy-efficient (T) house models. The modification details are explained in Section 3.5.3. After that, the indoor temperature profiles are generated accordingly. Subsequently, a number of different types of insulation materials with varying thickness and placement are selected to develop modified M house models. Accordingly, indoor temperature profiles for modified M house models are generated.

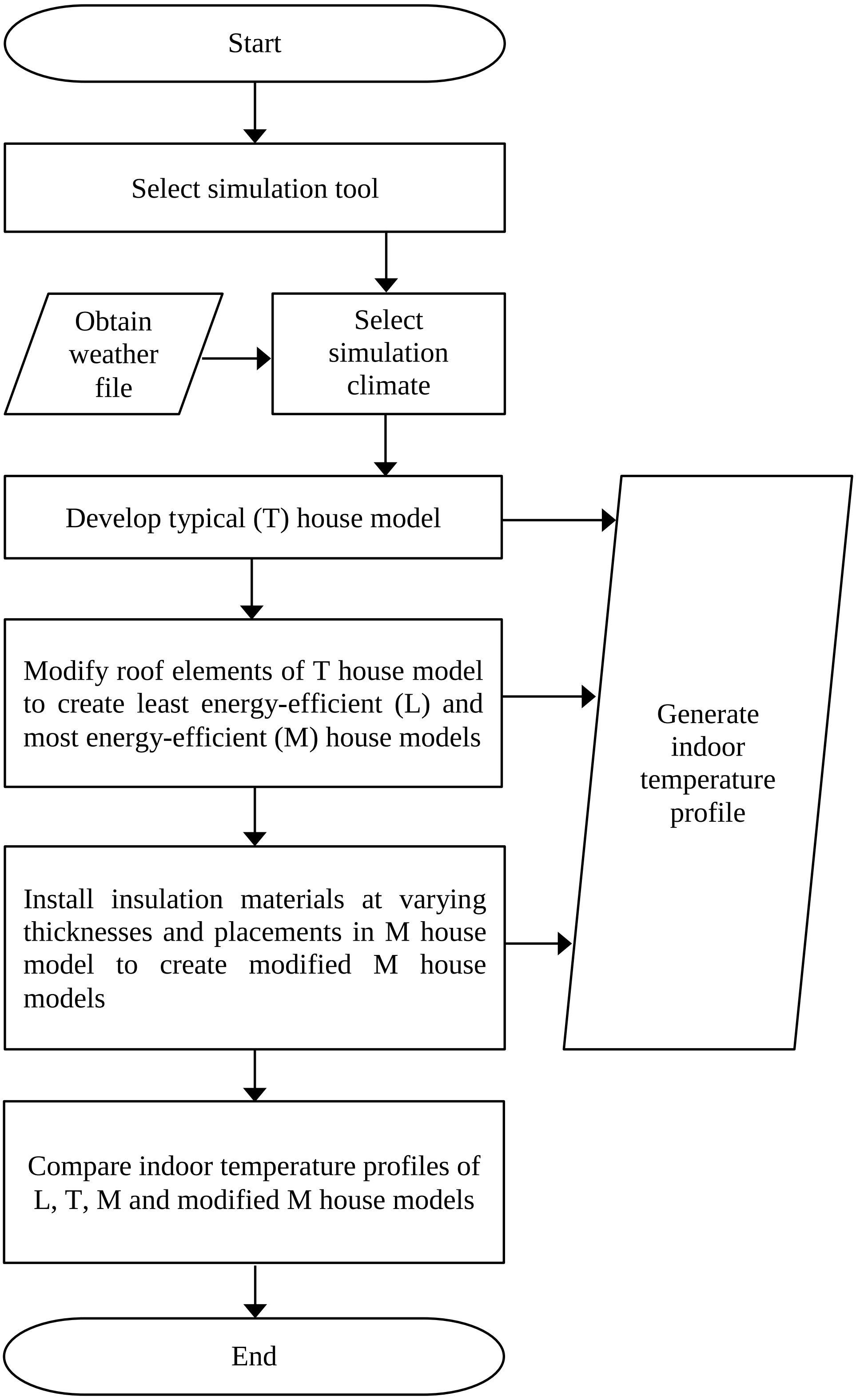


Figure 3.18: Simulation process flow

3.5.1 Selection of Simulation Tool

Advancement in computer technology allows students, researchers and industry practitioners from the building energy field to utilize simulation tools for building design and construction. Hundreds of building energy performance simulation tools have been developed. Building performance indicators such as energy use and demand, temperature, humidity and cost can be determined and analyzed using these tools.

A comparative survey of twenty (20) major building energy simulation programs [111] is studied. Based on this comparative survey, eQUEST, EnergyPlus, IES <VE>, TRNSYS and ECOTECT simulation tools fulfill the requirements of the research. This section describes the main features of these tools and justifies the selection of simulation tool for the research.

3.5.1.1 eQUEST

eQUEST is a user-friendly building energy use analysis tool which comprises of a building creation and an energy efficiency measure (EEM) wizards and a graphical results display module. It can create multiple simulations simultaneously and enables users to view the results simultaneously. It can conduct estimation of energy and cost, control of daylighting and lighting systems and implement energy efficiency measures.

3.5.1.2 EnergyPlus

EnergyPlus is a simulation engine with input and output of text files. It can conduct calculation on heating and cooling systems and electrical system response in plants. It provides accurate space temperature prediction for system and plant sizing and occupant comfort and health calculations. It can also evaluate system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems and interzone air flow.

3.5.1.3 IES <VE>

IES <VE> is an integrated suite of applications linked by a common user interface and a single integrated data model. The modules includes ModelIT for geometry creation and editing, ApacheCalc for loads analysis, ApacheSim for thermal analysis, MacroFlo for natural ventilation analysis, ApacheHVAC for component-based HVAC analysis, SunCast for shading visualization and analysis, MicroFlo for 3D computational fluid dynamics analysis, FlucsPro/Radiance for lighting design, DEFT for model optimization, LifeCycle for life-cycle energy and cost analysis and Simulex for building evacuation analysis. This program can design, evaluate and optimize building system designs with regard to comfort criteria and energy use.

3.5.1.4 TRNSYS

TRNSYS is a transient system simulation program with a modular structure that implements a component-based approach. Components can be as simple as a pump or pipe, or as complex as a multi-zone building model, which can be configured and assembled with a fully integrated visual interface known as the TRNSYS Simulation Studio. Input data is entered through a visual interface known as the TRNBuild. The program can solve all HVAC-system components simultaneously. Components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration and fuel cells are included in the TRNSYS library. The modular structure enables users to add new mathematical models to the program.

3.5.1.5 ECOTECT

Ecotect is a highly visual architectural design and analysis tool that links a comprehensive 3D modeler with a wide range of performance analysis functions covering thermal, energy, lighting, shading, acoustics and costs aspects. Standard graphs and table-based reports can be generated. Results of analyses can be mapped over building spaces or displayed directly within the spaces. Results of volumetric and spatial analysis can be visualized. Acoustic and solar ray tracing can be animated in real-time with changes to building geometry and material properties.

ECOTECT possesses the features and capabilities required to achieve the third objective of the research. Therefore, ECOTECT is selected as the tool to be used for the simulation. Features and capabilities that were considered in the selection of ECOTECT are highlighted below:

- Visualization of building geometry
- Assignment of materials on building elements
- Utilization of actual weather data
- Generation of hourly temperature profiles

3.5.2 Development of Control House Model

A control house model with dimensions of 3-m length by 3-m breadth by 2.5-m height and 45°-sloped double-pitched roof was developed as shown in Figure 3.19. Red clay tiles were employed for the roof pitch. 125-mm thick brick wall was adopted. A door and window were installed on the south wall. Kuala Lumpur climate data was used for simulation (Figure 3.20).

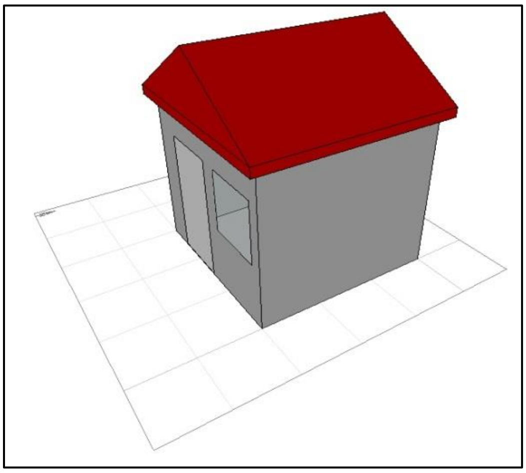


Figure 3.19: Control house model

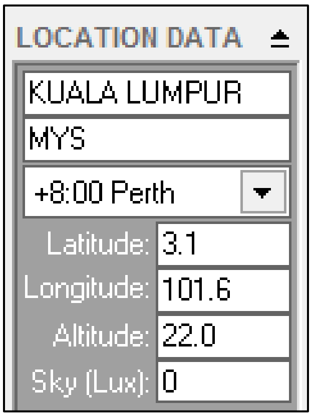


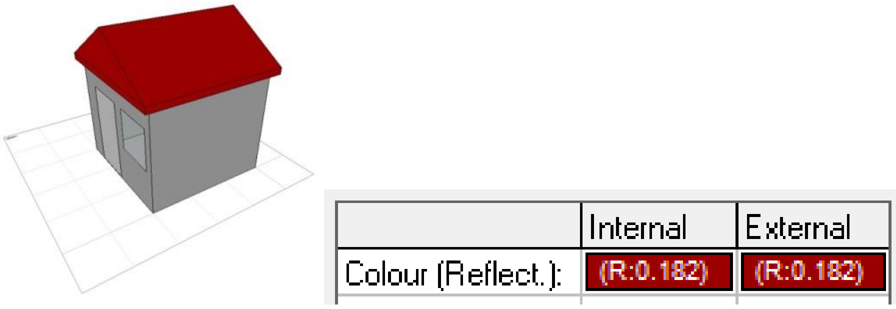
Figure 3.20: Selection of Kuala Lumpur climate data

3.5.3 Modification of Roof Elements

Roof elements of the control house model were modified to simulate least and most energy-efficient house models. As a result, three (3) house models were developed. The least energy-efficient house model was labelled *L*, the typical house model was labeled *T* and the most energy-efficient house model was labeled *M*, as shown in Table 3.3. Modification of roof elements, which are the colour of roof tiles and orientation of roof pitch, are presented in Figure 3.21, Figure 3.22, Figure 3.23, Figure 3.24 and Figure 3.25.

Table 3.3: Modification of roof elements

Roof Elements	**House Model**		
	Least energy-efficient house model, *L*	Typical house model, *T*	Most energy-efficient house model, *M*
Colour of Roof Tiles	Black	Dark Red	White
Orientation of Roof Pitch	Aligned with West-East axis	Aligned with North-South axis	Aligned with North-South axis
Degree of Energy-Efficiency	**Low**	**Medium**	**High**

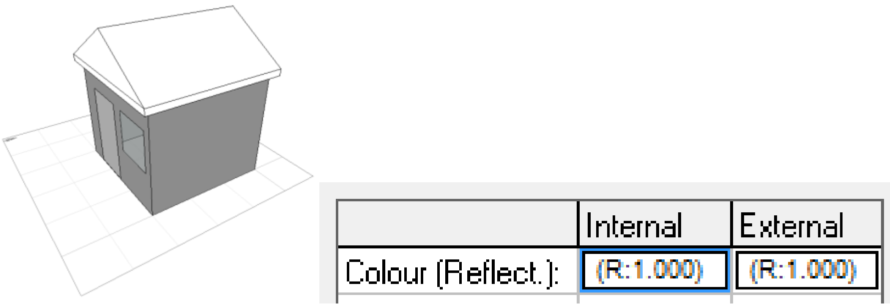


	Internal	External
Colour (Reflect.):	(R:0.182)	(R:0.182)

Figure 3.21: Modification of colour of roof tiles to red with SRI value of 0.182

	Internal	External
Colour (Reflect.):	(R:0.000)	(R:0.000)

Figure 3.22: Modification of colour of roof tiles to black with SRI value of 0.000



	Internal	External
Colour (Reflect.):	(R:1.000)	(R:1.000)

Figure 3.23: Modification of colour of roof tiles to white with SRI value of 1.000

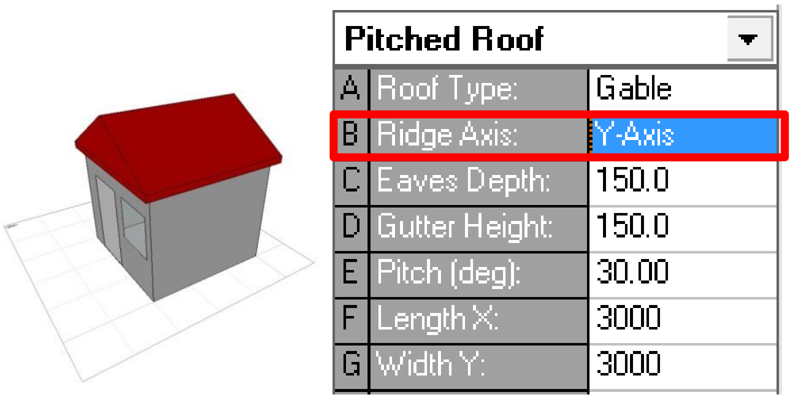


Figure 3.24: Modification of orientation of roof pitch to be aligned with West-East axis

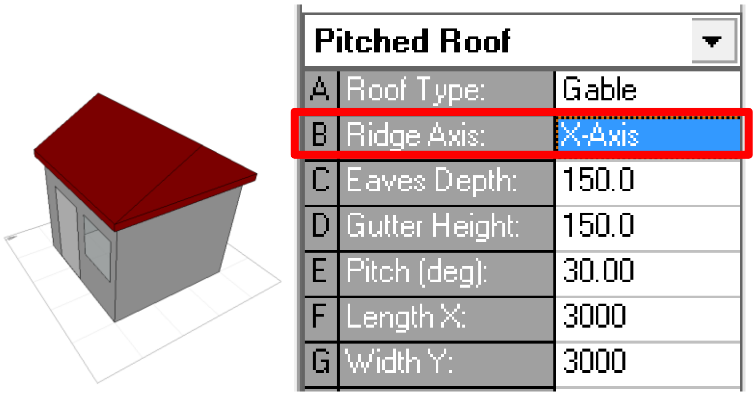


Figure 3.25: Modification of orientation of roof pitch to be aligned with North-South axis

3.5.4 Selection of Insulation

Traditional and new insulation materials extracted partly from Jelle (2011) [58], which is reviewed in Section 2.3.4 and Section 2.3.5, were employed in the simulation. Properties of the insulation materials are presented in Table 3.4.

Table 3.4: Properties of insulation materials used in the simulation

Insulation Material	**Density kg/m^3**	**Specific Heat J/kg-K**	**Thermal Conductivity W/m-K**	**Reference**
Vermiculite	260	880	0.069	ECOTECT library
Cellulose	43	1380	0.042	ECOTECT library
Polystyrene	100	1130	0.035	ECOTECT library
Rock Wool	200	710	0.034	ECOTECT library
Kapok Fibre	179	1158	0.034	[69]
PUR	40	1674	0.032	ECOTECT library
Reinforced Silica Aerogel	110	1000	0.013	[62]

Insulation materials listed in Table 3.4 with thicknesses of 10 mm, 30 mm, 50 mm and 100 mm were installed in house model *M* and labelled as shown in Table 3.5 and Table 3.6. Hence, 56 insulated house models were developed. Inclusive of the three (3) uninsulated house models, *L*, *T* and *M*, a total of 59 house models were developed for the simulation.

Table 3.5: Labelling of insulated *M* house models (Model number 1 – 24)

Model Number	Insulation	Thickness (mm)	Placement	Label
1	Vermiculite	10	Beneath tiles	M_{V10T}
2		10	On top of ceiling	M_{V10C}
3		30	Beneath tiles	M_{V30T}
4		30	On top of ceiling	M_{V30C}
5		50	Beneath tiles	M_{V50T}
6		50	On top of ceiling	M_{V50C}
7		100	Beneath tiles	M_{V100T}
8		100	On top of ceiling	M_{V100C}
9	Cellulose	10	Beneath tiles	M_{C10T}
10		10	On top of ceiling	M_{C10C}
11		30	Beneath tiles	M_{C30T}
12		30	On top of ceiling	M_{C30C}
13		50	Beneath tiles	M_{C50T}
14		50	On top of ceiling	M_{C50C}
15		100	Beneath tiles	M_{C100T}
16		100	On top of ceiling	M_{C100C}
17	Polystyrene	10	Beneath tiles	M_{PS10T}
18		10	On top of ceiling	M_{PS10C}
19		30	Beneath tiles	M_{PS30T}
20		30	On top of ceiling	M_{PS30C}
21		50	Beneath tiles	M_{PS50T}
22		50	On top of ceiling	M_{PS50C}
23		100	Beneath tiles	M_{PS100T}
24		100	On top of ceiling	M_{PS100C}

Table 3.6: Labelling of insulated *M* house models (Model number 25 – 56)

Model Number	Insulation	Thickness (mm)	Placement	Label
25	Rock Wool	10	Beneath tiles	M_{R10T}
26		10	On top of ceiling	M_{R10C}
27		30	Beneath tiles	M_{R30T}
28		30	On top of ceiling	M_{R30C}
29		50	Beneath tiles	M_{R50T}
30		50	On top of ceiling	M_{R50C}
31		100	Beneath tiles	M_{R100T}
32		100	On top of ceiling	M_{R100C}
33	Kapok Fibre	10	Beneath tiles	M_{K10T}
34		10	On top of ceiling	M_{K10C}
35		30	Beneath tiles	M_{K30T}
36		30	On top of ceiling	M_{K30C}
37		50	Beneath tiles	M_{K50T}
38		50	On top of ceiling	M_{K50C}
39		100	Beneath tiles	M_{K100T}
40		100	On top of ceiling	M_{K100C}
41	PUR	10	Beneath tiles	M_{PU10T}
42		10	On top of ceiling	M_{PU10C}
43		30	Beneath tiles	M_{PU30T}
44		30	On top of ceiling	M_{PU30C}
45		50	Beneath tiles	M_{PU50T}
46		50	On top of ceiling	M_{PU50C}
47		100	Beneath tiles	M_{PU100T}
48		100	On top of ceiling	M_{PU100C}
49	Reinforced Silica Aerogel	10	Beneath tiles	M_{S10T}
50		10	On top of ceiling	M_{S10C}
51		30	Beneath tiles	M_{S30T}
52		30	On top of ceiling	M_{S30C}
53		50	Beneath tiles	M_{S50T}
54		50	On top of ceiling	M_{S50C}
55		100	Beneath tiles	M_{S100T}
56		100	On top of ceiling	M_{S100C}

Figure 3.26 and Figure 3.27 displays the arrangement of layers of the uninsulated and insulated roof pitch and Table 3.7 presents the material properties of each layer. Figure 3.28 and Figure 3.29 displays the arrangement of layers of the uninsulated and insulated plaster ceiling and Table 3.8 presents the material properties of each layer.

Hourly indoor and outdoor temperature profiles were generated for both attic and indoor space for each house model during the hottest day of the year, which was determined by accessing data from ECOTECT on the average and maximum monthly temperatures for Kuala Lumpur.

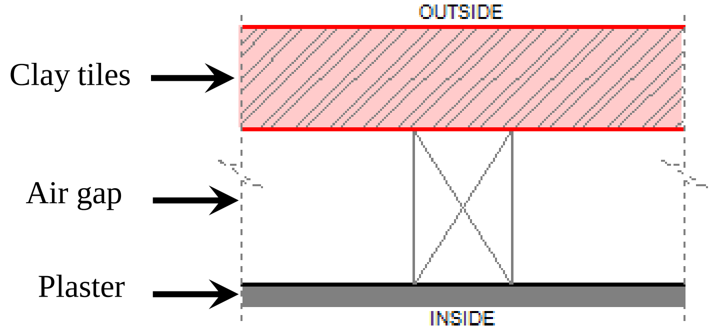


Figure 3.26: Arrangement of layers in uninsulated clay-tiled roof

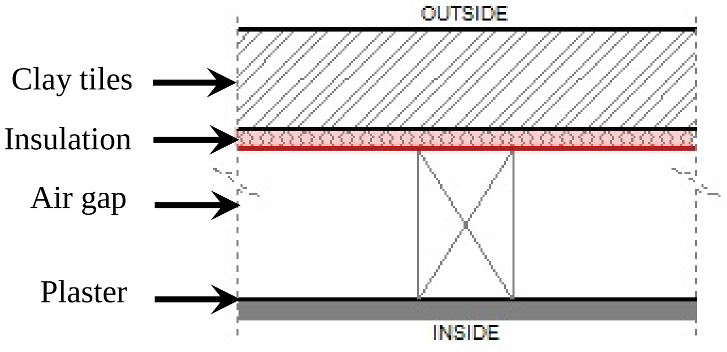


Figure 3.27: Arrangement of layers in insulated clay-tiled roof

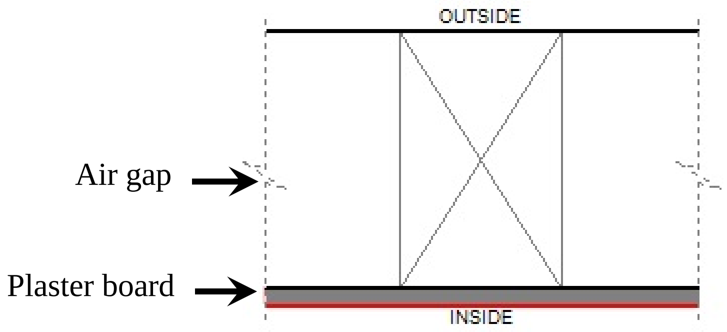


Figure 3.28: Arrangement of layers in uninsulated plaster ceiling

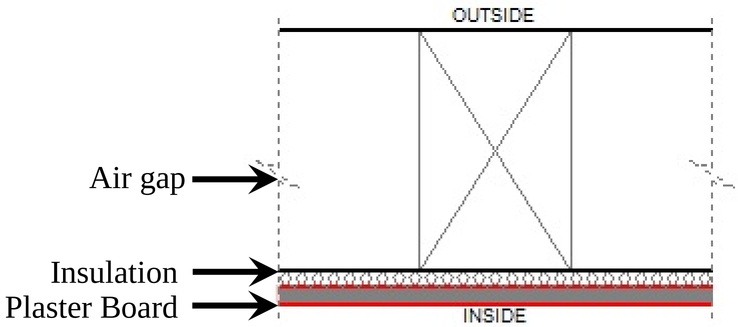


Figure 3.29: Arrangement of layers in insulated plaster ceiling

Table 3.7: Properties of layers in uninsulated clay-tiled roof

Number	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
1	Clay Tiles	50.00	2760.00	836.80	18.828
2	Air Gap	75.00	1.300	1004.00	5.560
3	Plaster Board	10.00	1250.00	1088.00	0.431

Table 3.8: Properties of layers in uninsulated plaster ceiling

Number	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
1	Air Gap	150.00	1.300	1004.00	5.560
2	Plaster Board	10.00	1250.00	1088.00	0.431

3.6 Cost-Benefit Analysis

This method aims to address the fourth objective, which is to project the cost and CO_2 emission of residential building for optimization of thermal insulation in roof. Electricity consumption, cost elements and CO_2 emission at varying thicknesses, material types and placements of insulation were determined. Then, optimum insulation thicknesses of several materials at varying placements were computed. The methods used to determine electricity consumption, cost savings, payback period and optimum insulation thickness is presented in Section 2.5. This section explains how the unknown variables were obtained and varied.

3.6.1 Cost Rate of Insulation Supply and Installation

Five (5) types of traditional insulation materials were considered in the calculation namely EPS, fibreglass, cellulose and rock wool. To add to that, three (3) new insulation materials, which are ENR, kapok fibre and reinforced aerogel were explored. Based on market prices of several insulation products quoted from local and foreign manufacturers, the cost rate to supply and install insulation were determined.

3.6.2 Insulation Thickness and Placement

Increment in thickness of insulation is expected to improve its effectiveness in resisting heat transfer at the expense of higher cost of insulation. At the same time, improved effectiveness of insulation will lead to further cost reduction of electricity consumption by room AC. The main purpose of varying the thickness of insulation is to determine the optimum insulation thickness that lead to the highest cost savings. In addition, other values such as electricity consumption, payback period and CO_2 emission were also calculated at varying insulation thickness. The thickness of insulation is varied from 0 mm to 100 mm at increments of 5 mm.

Placement of insulation above the ceiling and beneath the roof pitch as shown in Figure 3.30 and Figure 3.31 were considered. Variation of insulation placement affects cost of insulation and the U-value of roof. The cost of insulation placed beneath the roof pitch is higher than above the ceiling because of two (2) factors. The first factor is the area of insulation beneath the roof pitch is larger than above the ceiling because of its slope. The second factor is the ease of installation of insulation below the roof pitch is less than above the ceiling. On the other hand, the effectiveness of insulation below the roof pitch is expected to be higher than above the ceiling based on the outcome of previous researches [36, 39, 105].

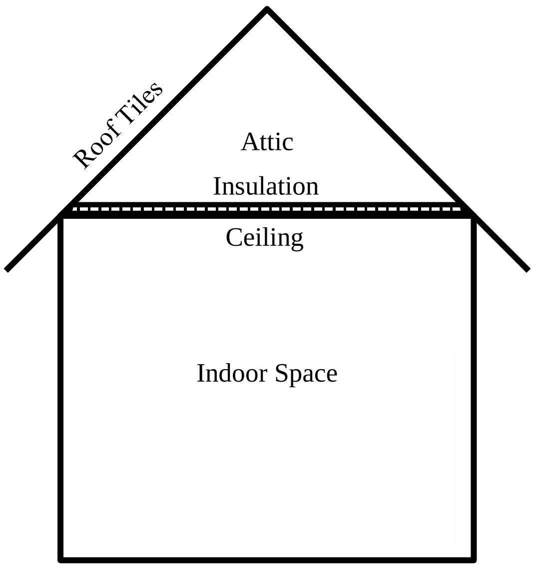


Figure 3.30: Placement of insulation above the ceiling

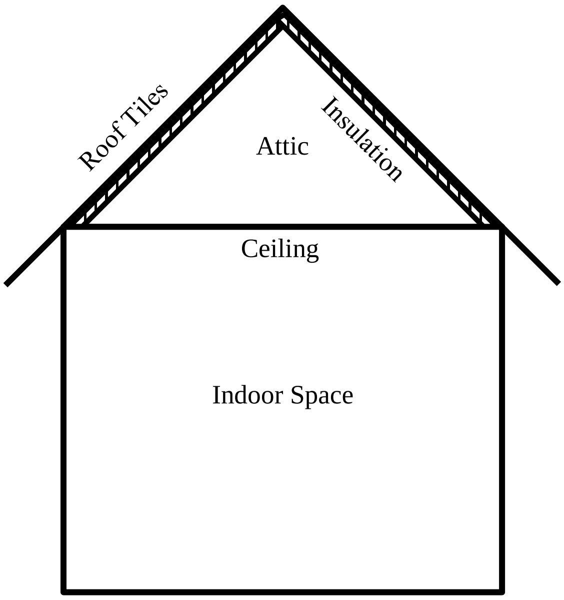


Figure 3.31: Placement of insulation beneath roof tiles

3.6.3 CO_2 Emission and Environmental Impact

CO_2 emission reduction was calculated by multiplying the electricity consumption reduction in kWh with the emission factor of the overall fuel mix in Malaysia, which is 0.65 kg CO_2/kWh as explained in Section 2.6.1 (Equation 3.1).

$$CO_2 emission\ reduction\ (kg\ CO_2) = Electricity\ consumption\ reduction\ (kWh) \times 0.65\ kg\ CO_2/kWh \tag{3.1}$$

Then, to quantify the environmental impact, CO_2 emission reduction was expressed in terms of the number of cars that are removed from the road and the number of trees that are planted that can result in the equivalent CO_2 emission reduction.

A typical car has an average rate of fuel consumption of about 15 km/litre as discussed in Section 2.6.2 and was assumed to drive about 20,000 km/year. 2.35 kg of CO_2 is emitted for every litre of petrol combusted [112]. Thus, amount of CO_2 emitted from a car per year can be estimated as in Equation 3.2.

$$Amount\ of\ CO_2\ emitted\ from\ a\ car\ per\ year = \frac{Distance\ travelled\ per\ year \times Rate\ of\ CO_2\ emission}{Rate\ of\ fuel\ consumption} \tag{3.2}$$

$$= \frac{20{,}000\ km}{1\ year} \times \frac{1\ litre}{15\ km} \times \frac{2.35\ kg\ CO_2}{1\ litre} = 3133.33\ kg\ CO_2/car/year$$

Hence, the number of cars that can be removed from the road to reduce a given amount of CO_2 emission per year can be calculated as in Equation 3.3.

$$Number\ of\ cars\ removed\ from\ the\ road\ (car) = \frac{CO_2\ emission\ reduction\ per\ year\ (kg\ CO_2/year)}{3133.33\ kg\ CO_2/car/year} \tag{3.3}$$

For calculation of CO_2 sequestration from trees, the trees were assumed to be of hardwood type, have a moderate growth rate and are ten (10) years old. Based on the assumptions, the annual sequestration rate of a tree is about 5.08 kg CO_2/tree/year as discussed in Section 2.6.3 [104]. Thus, the number of new trees that can be planted to sequester a given amount of CO_2 emission per year can be computed as in Equation 3.4.

$$Number\ of\ new\ trees\ planted\ (tree) = \frac{CO_2\ emission\ reduction\ per\ year\ (kg\ CO_2/year)}{5.08\ kg\ CO_2/tree/year} \tag{3.4}$$

In addition, the total environmental impact of installing insulation in most urban houses in Malaysia was projected. The number of households in Malaysia in 2012 was projected to be 6 554 113 [1], as discussed in Section 1.1. With reference to this value, CO_2 emission reduction and environmental impact of insulation for a set of assumed number of households were computed as in Equation 3.5.

$$
\begin{aligned}
&CO_2 emission\ reduction\ for\ a\ given\ number\ of\ households\ (kg\ CO_2) \\
&\quad = Electricity\ consumption\ reduction\ per\ household\ (kWh \\
&\quad /household) \times 0.65\ kg\ CO_2/kWh \\
&\quad \times Number\ of\ households\ (household)
\end{aligned}
\tag{3.5}
$$

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

Feedback of respondents from the survey is revealed. Then, results from the house model experiment and simulation are presented. Subsequently, cost savings, reduction in electricity consumption and CO_2 emission and environmental impacts of thermal insulation in residential roofing system are highlighted.

4.2 Survey

This section is divided into two (2) main parts. The first part presents results obtained from the questionnaire and the second part presents results obtained from the online interview. The first part is further divided into two (2) sections. The first section presents results obtained from the first set of questionnaires, which are targeted at house owners, and the second section presents results obtained from the second set of questionnaires, which are targeted at developers.

4.2.1 Questionnaire for House Owners

This section presents and discusses respondents' feedback for selected questions from the questionnaire for house owners. Feedback for all questions from this questionnaire is attached in Appendix E.

Questions 1 to 6 gather background information on the respondents. Results show that the age range of respondents is wide. There is a fairly good balance between male and female respondents. In terms of race, most of the respondents comprise of either Malay or Chinese. Occupations of respondents vary widely. Most of the respondents are planning to buy houses in 3 years' time and possess house budgets between RM200,000 to RM300,000.

Question 7 is "Do you know what 'insulation' is?". Figure 4.1 shows that 54% responded "Yes" and 46% responded "No". The 54% who responded "Yes" were prompted with Question 8, which is "How do you judge your understanding about housing insulation?".

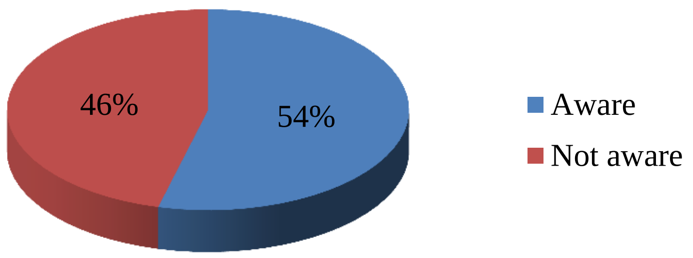


Figure 4.1: Percentages of respondents based on awareness on insulation

Question 8 is "How do you judge your understanding about housing insulation?". Figure 4.2 shows that 63% responded "Medium", 15% responded "High" and 22% responded "Low".

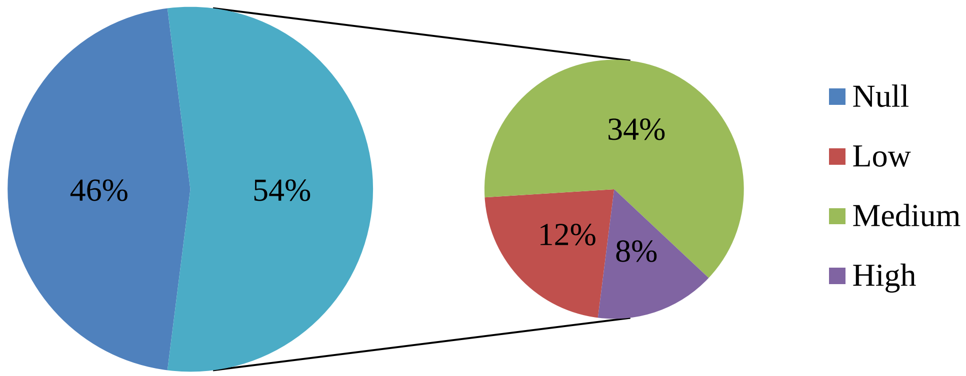


Figure 4.2: Percentages of respondents based on level of understanding on insulation

Question 10 is "Will you consider installing housing insulation after the reading the above paragraph?", which refers to the following paragraph:

"The insulation layer absorbs sound and heat, hence it is commonly used as sound barrier and to produce cooler indoor environment in hot climate country. With cooler indoor temperature, less energy is used and this leads to greener environment. Besides that, insulation is a great fire retardant as it can resist up to 800 degree Celsius."

Figure 4.3 indicates that most of them are willing to consider installing housing insulation after knowing the benefits, with 90% responding "Yes".

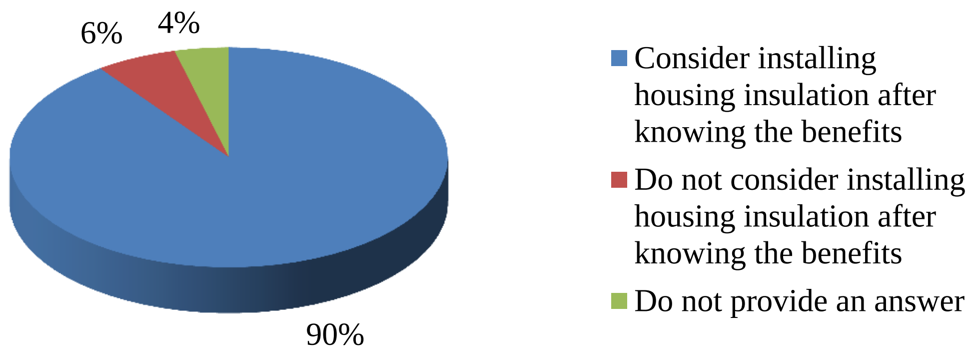


Figure 4.3: Percentages of respondents based on acceptance level on housing insulation after knowing the benefits

4.2.2 Questionnaire for Developers

This section presents and discusses respondents' feedback for selected questions from the questionnaire for developers. Feedback for all questions from this questionnaire is attached in Appendix F.

Question 2 is "How many of the residential projects completed implement insulation?". Feedback for Question 2 is presented in Figure 4.4, which shows that 60% of the projects do not utilize insulation. This shows that the preference of housing insulation among developers is low.

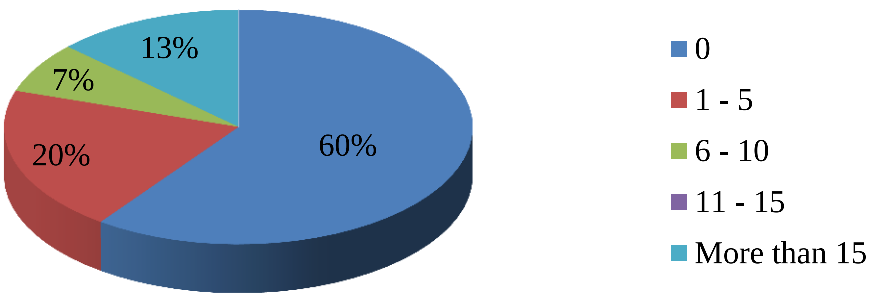


Figure 4.4: Percentages of respondents based on the amount of residential projects completed in the last 20 years with insulation

Question 5 is "Which do you think is/are the benefits of insulation?". All the benefits of insulation are listed out as the choice of answers and they are allowed to choose more than one answer. The question aims to assess their level of knowledge on insulation. The uneven distribution of percentages revealed in Figure 4.5 proves that the level of knowledge among developers on housing insulation is low.

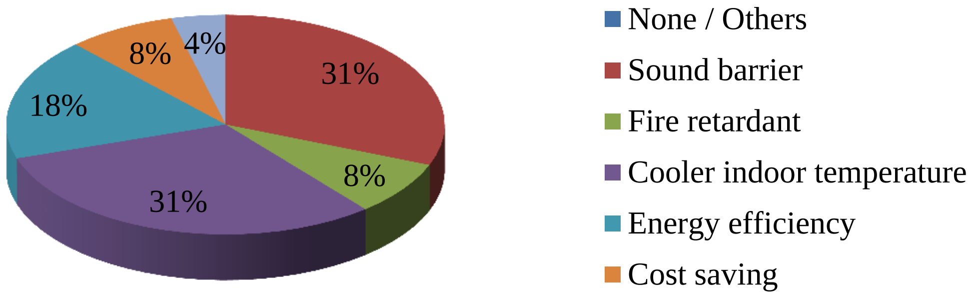


Figure 4.5: Percentages of respondents based on perceived benefits of insulation

Questions 6 and 7 asked "What do you think about the (i) knowledge/understanding level, (ii) acceptance level towards insulation usage by architects, engineers, clients and government (approving) authorities?". Figure 4.6 and Figure 4.7 reveals that levels of knowledge, understanding and acceptance towards insulation usage by architects, engineers, clients and government (approving) authorities as perceived by developers are medium.

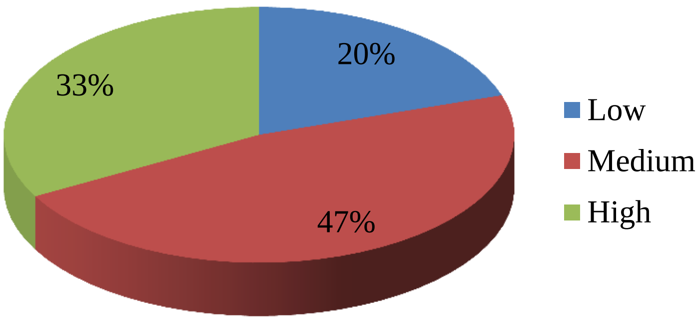


Figure 4.6: Percentages of respondents based on perception on the level of knowledge/understanding towards usage of insulation by architects, engineers, clients and government/approving authorities

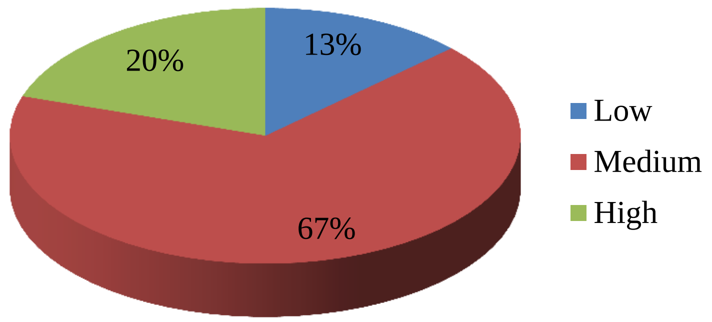


Figure 4.7: Percentages of respondents based on perception on the level of acceptance towards usage of insulation by architects, engineers, clients and government/approving authorities

Question 8 is "Do you think there are enough insulation manufacturers in Malaysia?". Figure 4.8 shows that 80% responded with "Not sure", 13% responded "Yes" and 7% responded "No".

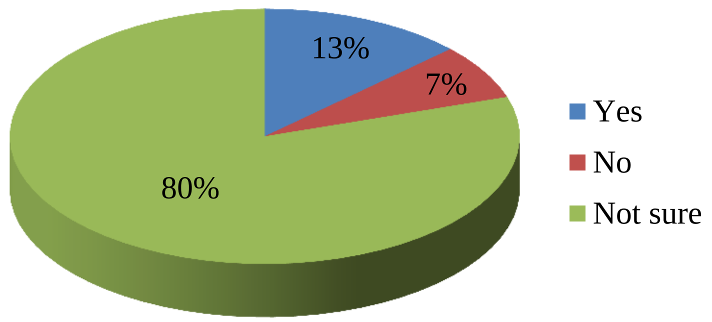


Figure 4.8: Percentages of respondents based on perception on the sufficiency of insulation manufacturers in Malaysia

Question 9 is "If given a choice, will you consider using insulation in future construction projects? If no, why?". Figure 4.9 shows that 80% are willing to consider using insulation in future construction projects and 20% are not willing to consider using insulation in future projects due to additional cost of acquiring and installing insulation and absence of legal requirement for its implementation.

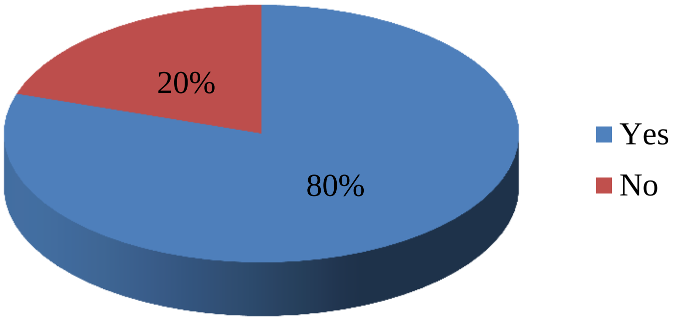


Figure 4.9: Percentages of respondents based on willingness to consider using insulation in future construction projects

Question 10 is “If there is a request from the architect, will you consider using insulation in particular project?”. Figure 4.10 presents that 60% answered “Yes”, 40% answered “Depends on cost” and none of them answered “No”. Among the 40% who answered “Depends on cost”, 80% stated that RM1.00/ft^2 is the reasonable cost and the rest are uncertain about the cost. The result demonstrates that the cost of installing insulation has a high influence on the decision of developers on whether to install insulation or not.

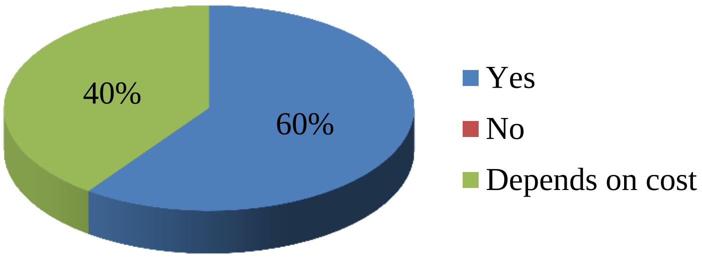


Figure 4.10: Percentages of respondents based on willingness to consider using insulation in particular projects if there is a request from the architect

Question 11 is “If there is a demand on good quality insulation from some client/potential house buyers, will you consider using insulation in whole projects?” All respondents answered “Yes” as shown in Figure 4.11. This indicates that demand from clients and potential house buyers highly influence the decision of developers on implementation of insulation.

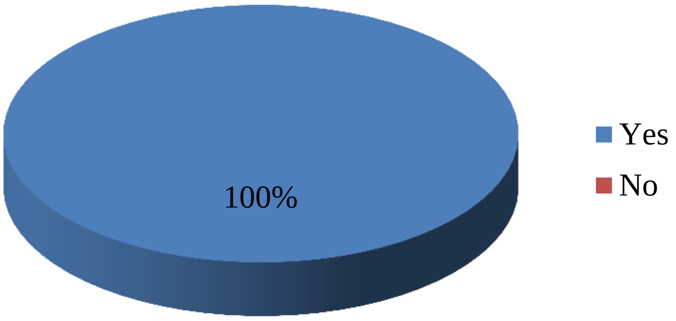


Figure 4.11: Percentages of respondents based on willingness to consider using insulation in whole projects if there is demand on good quality insulation from client/potential house buyers

Question 13 is “Would you adopt insulation after knowing the benefits of it, even though no law stated that it is compulsory to be implemented? If no, why? Figure 4.12 shows that 70% responded “Yes” and 30% responded “No”. Those who responded “No” stated that they will not adopt housing insulation because it increases project cost, the market demand is low and there is no statutory requirement.

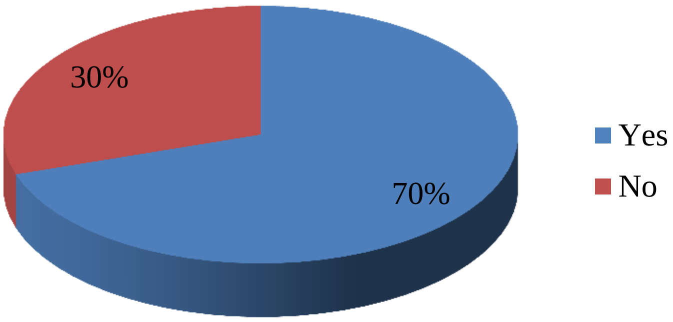


Figure 4.12: Percentages of respondents based on willingness to adopt insulation after knowing the benefits even without legal requirement

Question 14 is “Have you ever thought of / would you consider using insulation as a gimmick in promoting your projects? Are there any particular reasons for the choice?”. Figure 4.13 reveals that 53% responded “Yes” and 47% responded “No”. Respondents who answered “No” claimed that house buyers are more interested in the price and design of houses rather than presence of insulation.

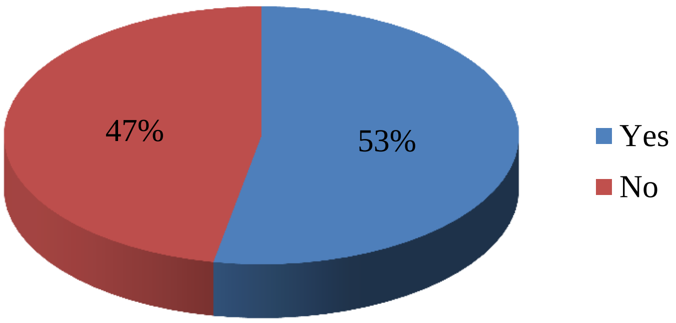


Figure 4.13: Percentages of respondents based on willingness to consider using insulation as a gimmick in promoting projects

The final part of this questionnaire, which is Part 4, consists of three (3) questions, which gathered comments and suggestions from respondents on several issues on housing insulation. The questions are the following:

1. What is your opinion on making insulation compulsory in construction?
2. Any suggestions to promote insulation in the Malaysian construction industry?
3. What do you think about the government subsidizing on the insulation industry?

1. What is your opinion on making insulation compulsory in construction?

Majority of respondents do not think it is viable to make insulation compulsory in construction due to low market demand and additional cost. If insulation is installed, they feel that house buyers should bear the cost, not them.

2. Any suggestions on how to promote insulation in the Malaysian construction industry?

Respondents suggested means to promote insulation, which are summarized as the following:

- Incentives should be provided for developers who construct buildings that fulfill the Green Building Index (GBI) criteria
- Insulation manufacturers should do more to promote benefits of insulation
- Comparison between cost and energy savings of insulation should be highlighted by insulation manufacturers
- Benefits of insulation should be introduced to architects, contractors and developers

3. What do you think about the government subsidizing on the insulation industry?

Most respondents are keen on having the government subsidizing on insulation because it reduces project cost. However, a small number of respondents do not think the idea is workable. They feel that the government is unlikely to commit on the subsidy and house owners prefer other subsidies, such as petrol, rather than insulation.

4.2.3 Online Interview

Online interviews were conducted with 15 professionals from various fields. Main points gathered from the feedback of interviewees are elaborated. Three (3) main questions were asked:

1. Housing insulation is quite common in Western countries but not in the Malaysian construction industry. What is your opinion or what are the factors that lead to this phenomenon?
2. Although insulation brings benefits to occupants, it is not widely used. What would you suggest to promote it?
3. Do you think insulation is economically feasible for the public?

4.2.3.1 Feedback for Question 1

Most respondents stated cost infeasibility for developers as the main reason why housing insulation is not as common in Malaysia as it is in Western countries. Developers decide to not install insulation because it leads to additional cost, despite the benefits. If insulation is installed, they feel that house buyers should pay for it because the benefits of insulation are for house buyers, not them. In contrast, developers in Western countries that implement insulation do so because they see the long-term positive impact insulation could bring to their company in terms of branding and reputation.

Another main reason is that in Malaysia, there is no legal requirement to install insulation. In Western countries, insulation is highly relied on to reduce cooling and heating loads of buildings. Differently, design of buildings in Malaysia and other tropical countries tend to focus on natural ventilation as the main method to reduce cooling load rather than insulation. As Malaysia develops, design of buildings also changes. Selection of materials in new buildings is similar to the design of Western buildings and is adopted as standards. Even so, insulation in housing is still not stressed in local codes and regulation, which is not up to date with current trends and technologies.

A factor highlighted by the respondents is that the electricity tariff in Malaysia is low compared to many countries. As a result, the public can afford the bill even though they switched on the AC for long periods. The current electricity tariff in Malaysia is 21.8 sen/kWh for residential consumers [113]. This rate is rather low compared to other countries [114].

4.2.3.2 Feedback for Question 2

Preference of building insulation can be enhanced by active promotion. Execution of exhibition and interviews and publication of articles and magazines that discuss insulation have been conducted in recent years in Malaysia. However, awareness on insulation has only just started in Malaysia and is steadily growing.

Many interviewees suggested making housing insulation a legal requirement rather than brainstorming methods to promote insulation. By doing so, developers have no option but to implement insulation in projects. However, some respondents objected to this idea and explained that showing the benefit of insulation to the public is a better long-term plan. The collaboration among the government, consumer associations, professional bodies, real estate agents, education centres and property exhibitions to promote insulation is suggested. Furthermore, the promotion should focus on highlighting the energy efficiency, return on investment and thermal comfort.

Alternatives to making insulation compulsory include the improvement of industry standards to lower the Overall Thermal Transfer Value (OTTV) of buildings. The implementation of this alternative can be initiated by the collaboration between the government and Green Building Index (GBI).

4.2.3.3 Feedback for Question 3

All respondents agreed that insulation is economically feasible to the public. However, more effort must be done to prove the economic feasibility of insulation and quantify its cost and environmental impact. The public must be made aware not only on the benefits of insulation, but also on the selection of insulation to be purchased.

4.2.4 Critical Analysis

In the questionnaire survey for house owners, feedback from Question 7 reveals that 54% of house owner respondents are aware of the term ‘insulation’, whereas 46% are not. When further questioned on their understanding of insulation in Question 8, 12%, 34% and 8% of them have low, medium and high levels of understanding respectively. However, due to the subjective nature of this question, the feedback only provides the judgement of the respondents on their levels of understanding, which may not be their actual levels of understanding. Then, prior to answering Question 10, they are informed about the benefits of insulation. The effect of this is positive.

Feedback from Question 10 reveals that 90% of them would like to consider installing insulation in their homes. This shows that the preparedness level among house owners to implement insulation in their homes can be dramatically increased by promoting its benefits.

In the questionnaire survey for developers, Question 2 reveals that 60% of residential projects in the last 20 years did not utilize insulation, which shows that installation of building insulation is not popular among developers. Then, Question 5 tests them on their level of knowledge on insulation by questioning them on the benefits of insulation and providing answer choices that are all correct. They are allowed to choose more than one answer. If they are aware of the benefits of insulation, they would know that all of the answer choices are correct and they would have opted for all of them. Their feedbacks reveal that the percentage distribution between answer choices is not even, which shows that most of them did not choose all answers. This is an indication that their level of knowledge on insulation is low. In addition, their feedback in Question 8 reveals that 80% of them are not sure whether there is enough insulation manufacturers in Malaysia or not. This is an indication that their level of knowledge and also concern on insulation is low. However, they are willing to consider installing insulation in their house projects provided that there is demand from house owners. Therefore, once again, the implementation of building insulation must be driven by the promotion of awareness among house owners on the long term benefits of insulation.

4.3 House Model Experiment

This section presents the results of the house model experiment. Throughout this section, notations as listed in Table 4.1 and Table 4.2 are used.

Table 4.1: Notations used to present house model experiment results (Notation number 1-15)

Notation Number	Notation	Variable
1	$T_{i,u}$	Indoor temperature of uninsulated house
2	$T_{i,k50}$	Indoor temperature of house insulated with 50-mm kapok fibre
3	$T_{i,k100}$	Indoor temperature of house insulated with 100-mm kapok fibre
4	$T_{o,u}$	Outdoor temperature of uninsulated house
5	$T_{o,k50}$	Outdoor temperature of house insulated with 50-mm kapok fibre
6	$T_{o,k100}$	Outdoor temperature of house insulated with 100-mm kapok fibre
7	$T_{r,u}$	Roof surface temperature of uninsulated house
8	$T_{r,k50}$	Roof surface temperature of house insulated with 50-mm kapok fibre
9	$T_{r,k100}$	Roof surface temperature of house insulated with 100-mm kapok fibre
10	$\Delta T_{o-i,u}$	Outdoor-indoor temperature difference of uninsulated house
11	$\Delta T_{o-i,k50}$	Outdoor-indoor temperature difference of house insulated with 50-mm kapok fibre
12	$\Delta T_{o-i,k100}$	Outdoor-indoor temperature difference of house insulated with 100-mm kapok fibre
13	$\Delta T_{r-i,u}$	Roof surface-indoor temperature difference of uninsulated house
14	$\Delta T_{r-i,k50}$	Roof surface-indoor temperature difference of house insulated with 50-mm kapok fibre
15	$\Delta T_{r-i,k100}$	Roof surface-indoor temperature difference of house insulated with 100-mm kapok fibre

Table 4.2: Notations used to present house model experiment results (Notation number 16-21)

16	$RH_{i,u}$	Indoor relative humidity of uninsulated house
17	$RH_{i,k50}$	Indoor relative humidity of house insulated with 50-mm kapok fibre
18	$RH_{i,k100}$	Indoor relative humidity of house insulated with 100-mm kapok fibre
19	$RH_{o,u}$	Outdoor relative humidity of uninsulated house
20	$RH_{o,k50}$	Outdoor relative humidity of house insulated with 50-mm kapok fibre
21	$RH_{o,k100}$	Outdoor relative humidity of house insulated with 100-mm kapok fibre

Outdoor and indoor temperatures of uninsulated and insulated house models are compared to validate the effectiveness of insulation. Relative humidity is presented to justify the consistency of outdoor and indoor air conditions throughout data collection. Figure 4.14 reveals that the highest $T_{o,u}$ is 40.33°, obtained in Day 2 at 1400 hours. The corresponding $T_{i,u}$ obtained is 36.71°C, which presents a temperature reduction of 3.62°C.

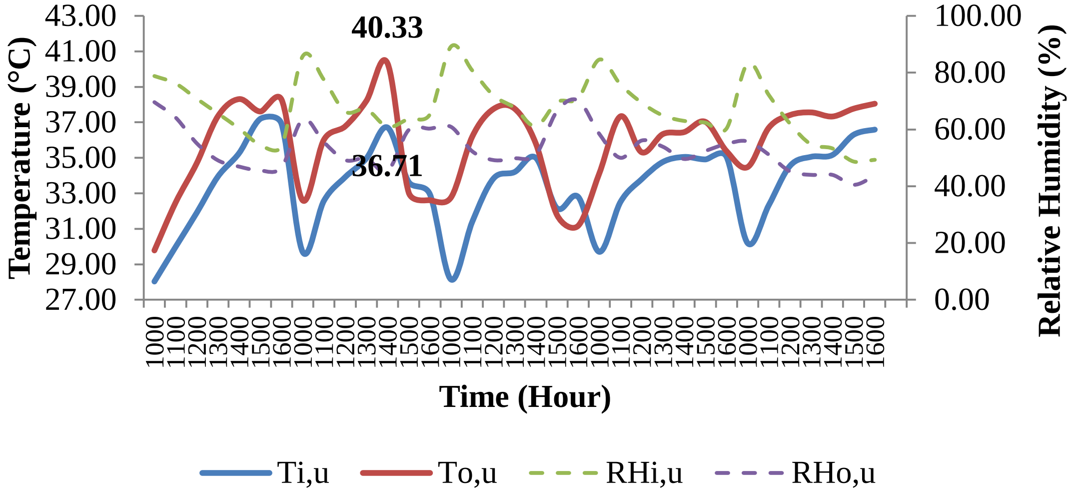


Figure 4.14: $T_{i,u}$, $T_{o,u}$, $RH_{i,u}$ and $RH_{o,u}$ profiles from Day 1 to Day 5

Then, Figure 4.15 shows that the highest $T_{o,k50}$ is 41.62°, obtained in Day 1 at 1400 hours. The corresponding $T_{i,k50}$ obtained is 36.63°C, which is a temperature reduction of 4.99°C.

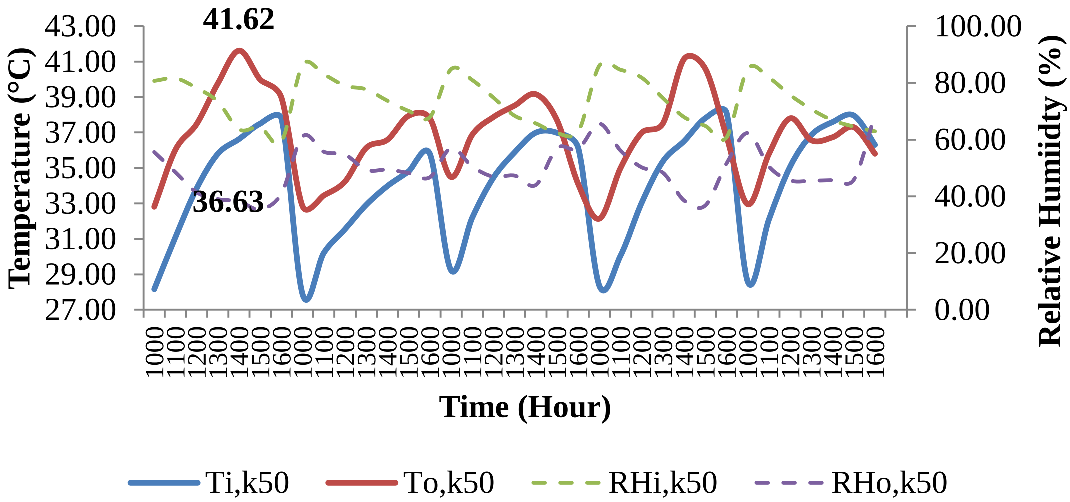


Figure 4.15: $T_{i,k50}$, $T_{o,k50}$, $RH_{i,k50}$ and $RH_{o,k50}$ profiles from Day 1 to Day 5

Figure 4.16 shows that the highest $T_{o,k100}$ is 41.11°, obtained in Day 2 at 1300 hours. The corresponding $T_{i,k100}$ obtained is 35.23°C, which is a temperature reduction of 5.88°C.

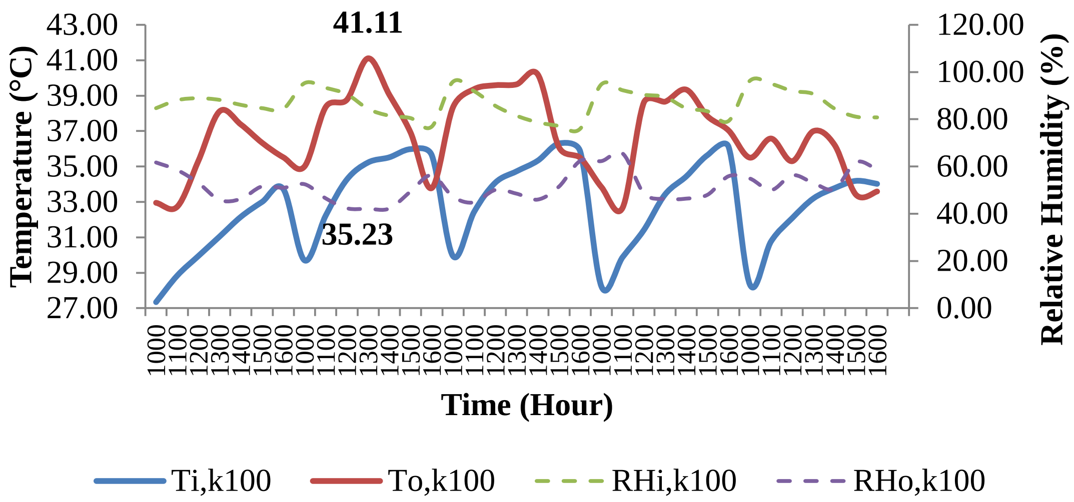


Figure 4.16: $T_{i,k100}$, $T_{o,k100}$, $RH_{i,k100}$ and $RH_{o,k100}$ profiles from Day 1 to Day 5

Furthermore, roof surface and indoor temperatures of uninsulated and insulated house models are compared. Figure 4.17 demonstrates that the highest $T_{r,u}$ is 42.50°C, obtained in Day 2 at 1400 hours. At this time, $T_{i,u}$ is 36.71°C, which represents a temperature reduction of 5.79°C.

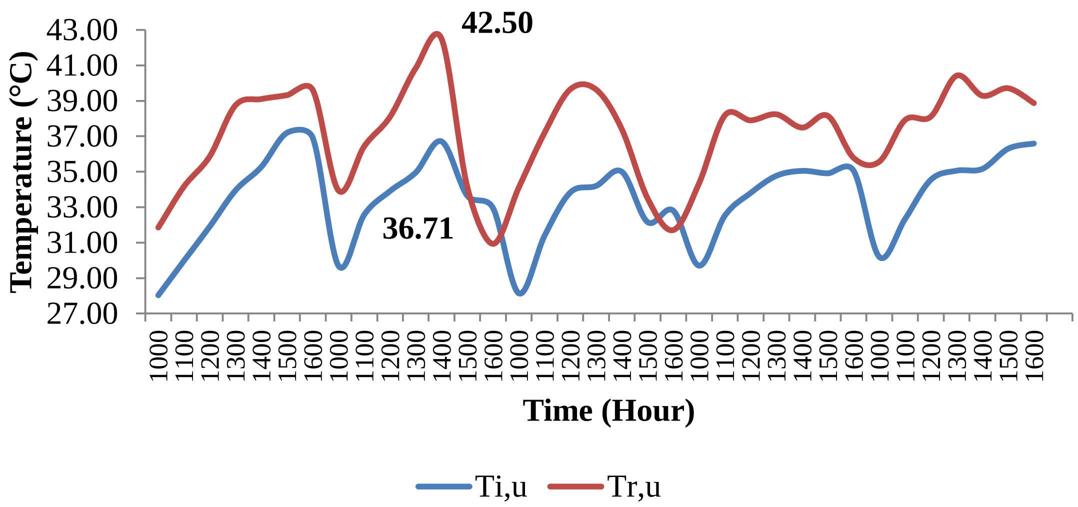


Figure 4.17: $T_{i,u}$ and $T_{r,u}$ profiles from Day 1 to Day 5

Next, Figure 4.18 reveals that the highest $T_{r,k50}$ is 43.89°C, obtained in Day 1 at 1400 hours. The corresponding $T_{i,k50}$ is 36.63°C, which presents a temperature reduction of 7.26°C.

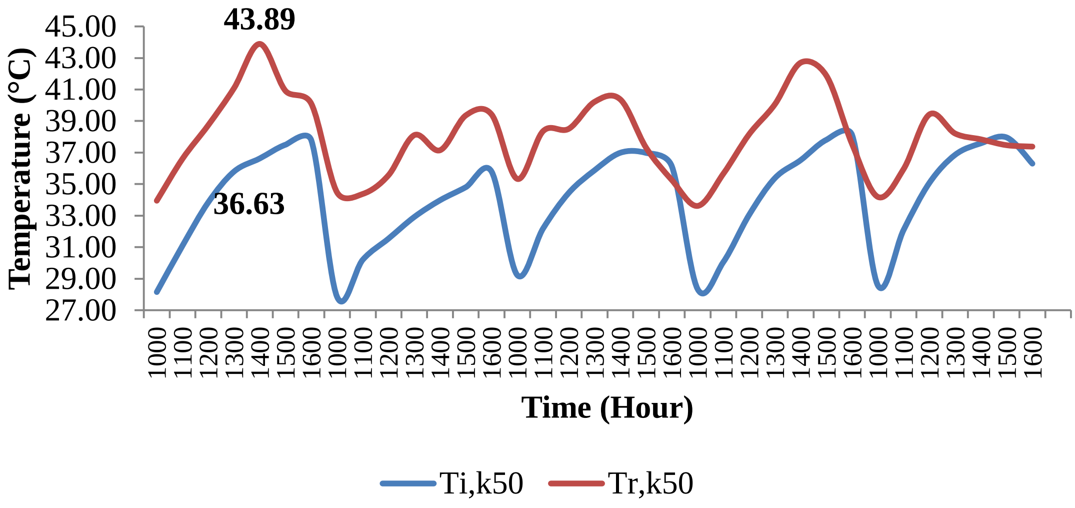


Figure 4.18: $T_{i,k50}$ and $T_{r,k50}$ profiles from Day 1 to Day 5

Then, Figure 4.19 shows that the highest $T_{r,k100}$ is 43.85°C, obtained in Day 2 at 1300 hours. The corresponding $T_{i,k100}$ is 35.23°C, which is a temperature reduction of 8.62°C.

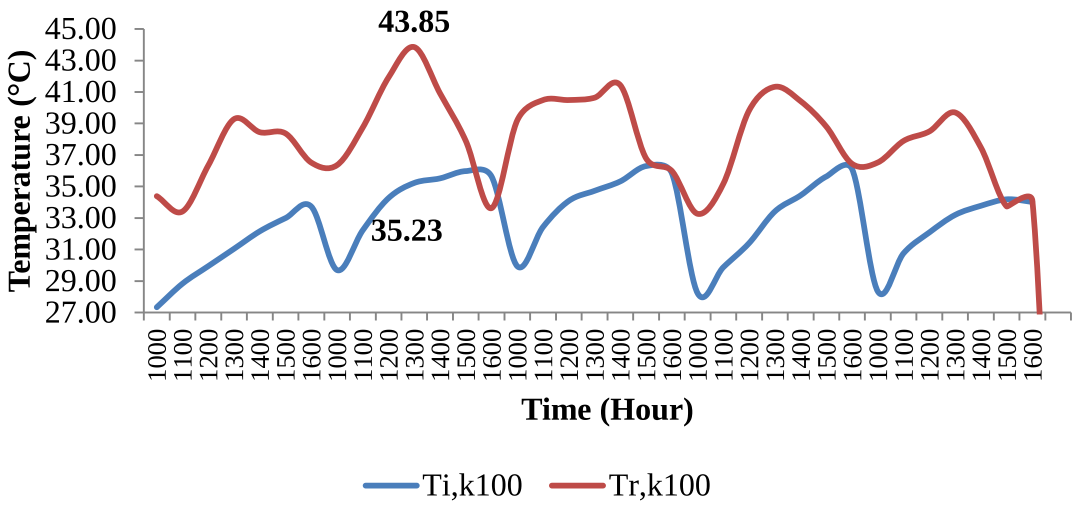


Figure 4.19: $T_{i,k100}$ and $T_{r,k100}$ profiles from Day 1 to Day 5

Figure 4.20 and Figure 4.21 reveal that the highest temperature reductions were $\Delta T_{o-i,k100}$ and $\Delta T_{r-i,k100}$ in Day 3 at 1000 hours, which were 8.40°C and 9.27°C respectively.

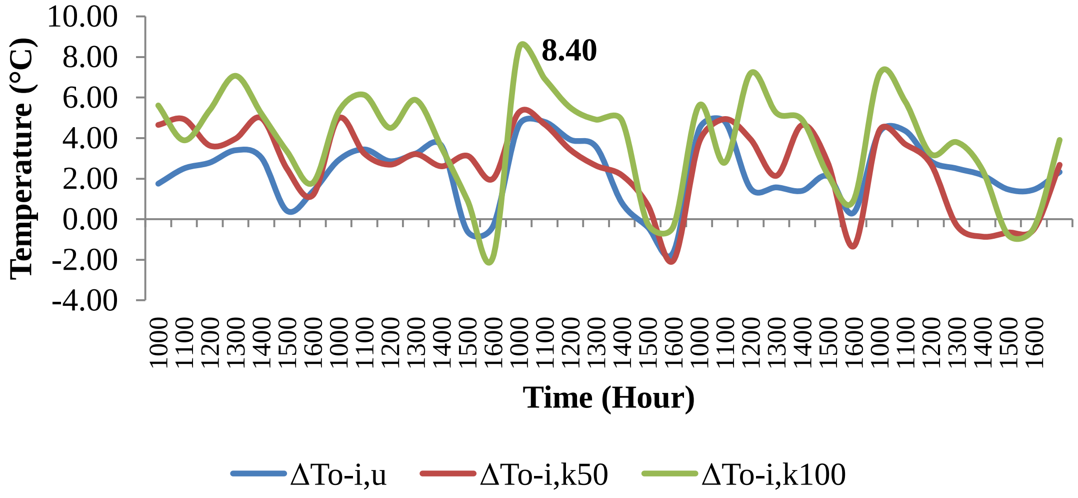


Figure 4.20: $\Delta T_{o-i,u}$, $\Delta T_{o-i,k50}$ and $\Delta T_{o-i,k100}$ profiles from Day 1 to Day 5

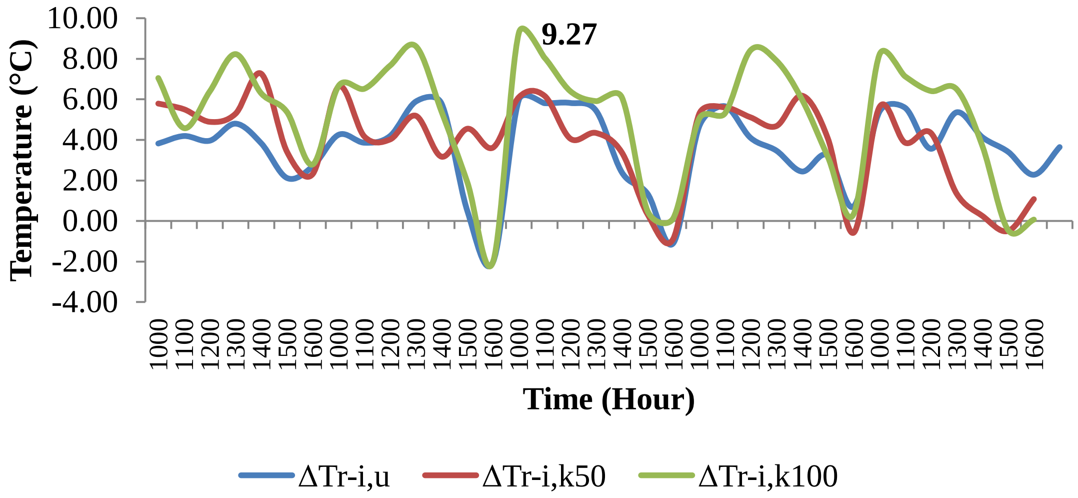


Figure 4.21: $\Delta T_{r-i,u}$, $\Delta T_{r-i,k50}$ and $\Delta T_{r-i,k100}$ profiles from Day 1 to Day 5

Figure 4.22 and Figure 4.23 reveal that on average, values of temperature reduction of house insulated with 100-mm kapok fibre are higher than 50-mm kapok fibre, followed by uninsulated house.

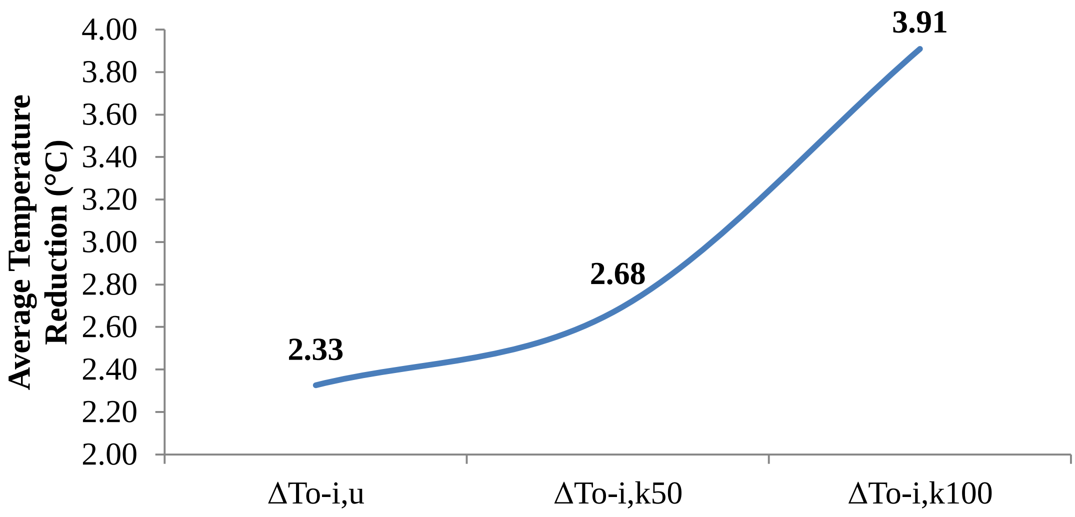


Figure 4.22: Average values of $\Delta T_{o\text{-}i,u}$, $\Delta T_{o\text{-}i,k50}$ and $\Delta T_{o\text{-}i,k100}$

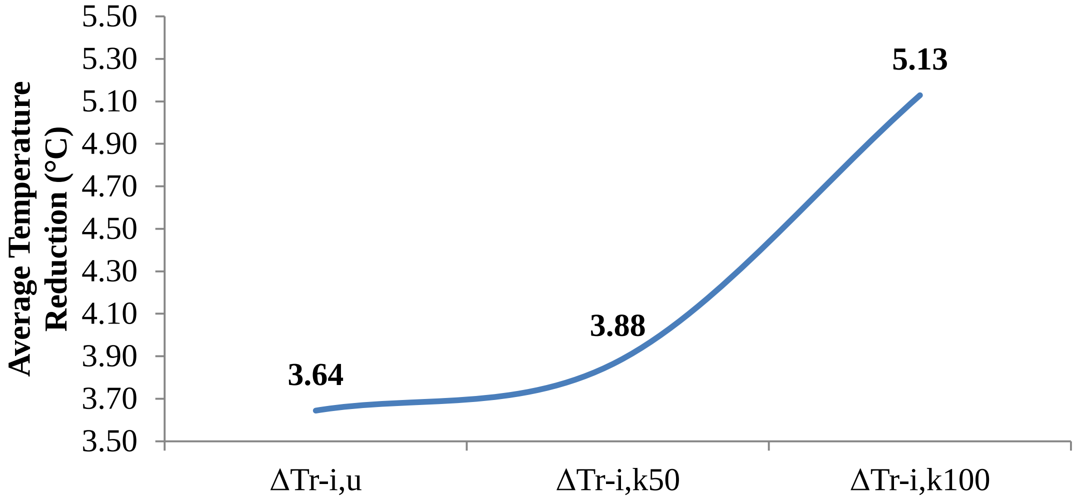


Figure 4.23: Average values of $\Delta T_{r\text{-}i,u}$, $\Delta T_{r\text{-}i,k50}$ and $\Delta T_{r\text{-}i,k100}$

Therefore, based on the results, the effectiveness of insulation in reducing indoor temperature is validated. Temperature reduction values indicate that increase in thickness of insulation further improves the thermal performance. The findings are in agreement with [36, 39, 105].

4.4 Simulation

4.4.1 Selection of Simulation Period

Monthly average and maximum temperatures for Kuala Lumpur is obtained from ECOTECT weather file. Figure 4.24 presents monthly average and maximum temperatures for Kuala Lumpur. The highest monthly average temperature is obtained in June, which is 27.80°C. However, the highest monthly maximum temperature is obtained in July, which is 35.80°C. This indicates that June and July are the two (2) hottest months of the year. Daily temperature records for Kuala Lumpur from ECOTECT weather file reveal that the maximum temperature of 35.80°C occurred on 6 July. Hence, 6 July is selected as the period of simulation. This is to allow evaluation of insulation to occur under the harshest climate condition. Appendix G reveals the data presented in Figure 4.24.

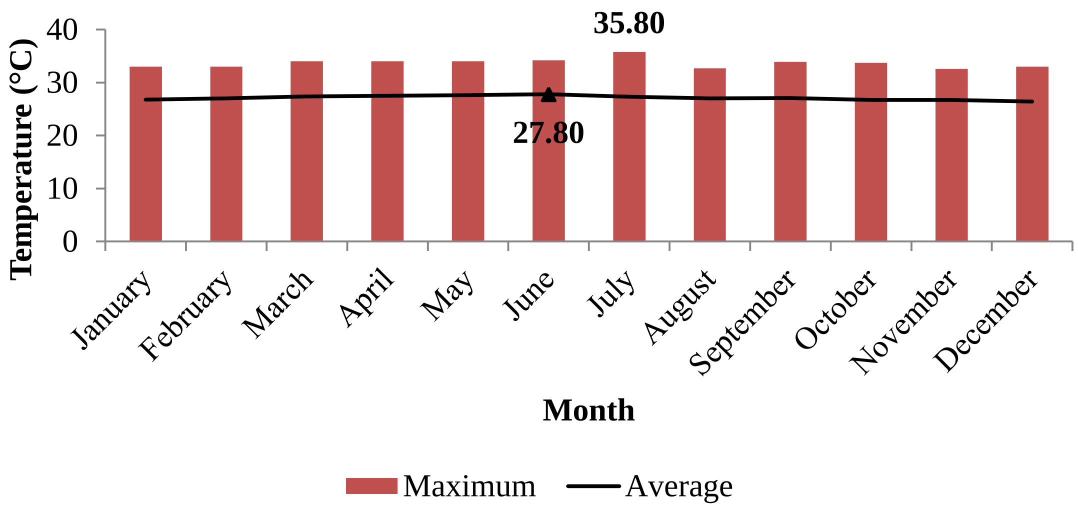


Figure 4.24: Monthly average and maximum temperatures in Kuala Lumpur

4.4.2 Performance of Roof Elements

This section presents simulation results for roof modification of uninsulated house models. While, Section 4.4.3 presents simulation results for insulated house models. Throughout this section and also Section 4.4.3, system of notations as in Table 4.3 is used.

Table 4.3: Notations used to present simulation results

Notation Format	Variable
T_o	Outdoor temperature
$T_i(X)$	Indoor temperature of house model X
$T_a(X)$	Attic temperature of house model X
$\Delta T_{o-i}(X)$	Difference between outdoor and indoor temperatures for house model X
$\Delta T_{o-a}(X)$	Difference between outdoor and attic temperatures for house model X

A comparison between outdoor temperatures and indoor and attic temperatures of house models *L*, *T* and *M* as in Figure 4.25 and Figure 4.26 reveal that the highest T_o is 35.80°C, which occurred at 1600 hours. At that time, house model *M* showed the best thermal performance with lowest values of $T_i(M)$ and $T_a(M)$ of 31.50°C and 35.60°C respectively.

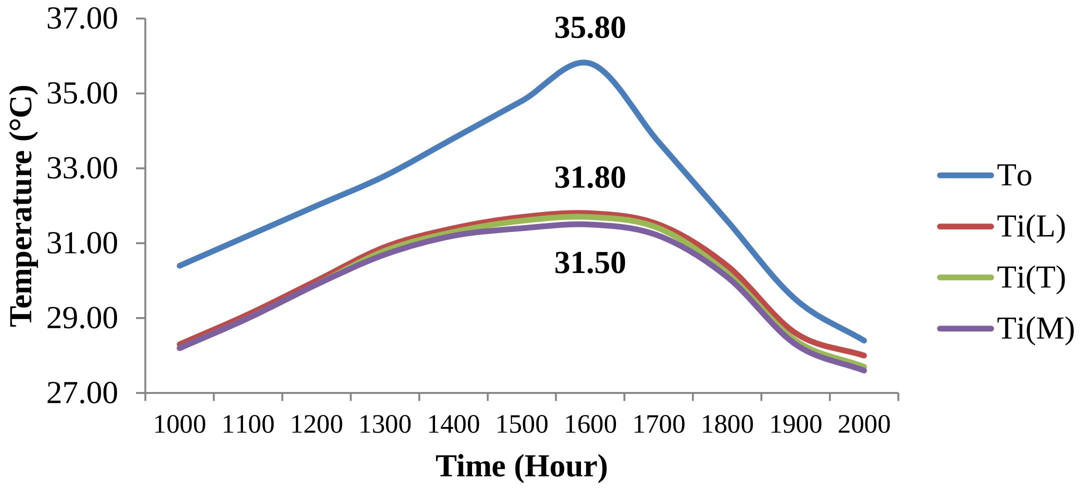


Figure 4.25: T_o, T_i(L), T_i(T) and T_i(M) profiles

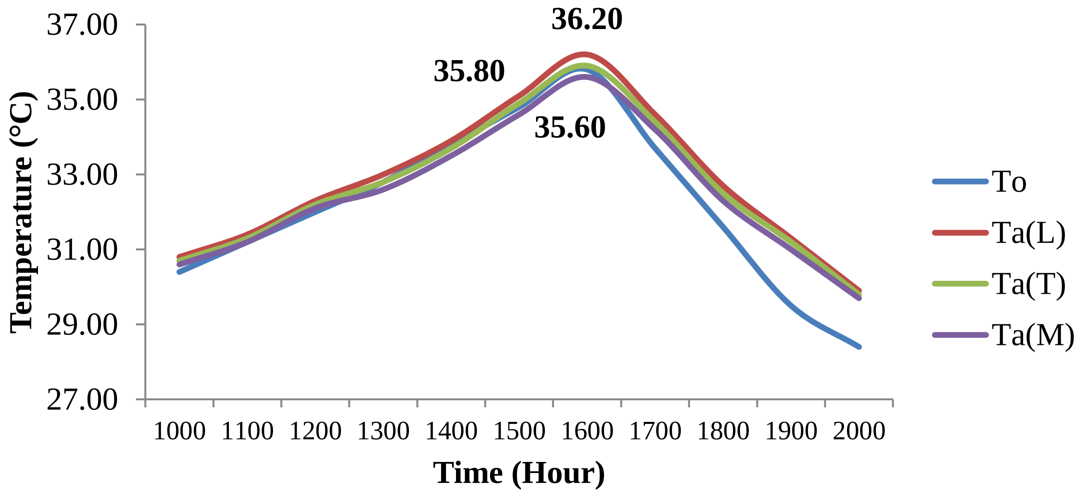


Figure 4.26: T_o, T_a(L), T_a(T) and T_a(M) profiles

Figure 4.27 and Figure 4.28 show that the highest outdoor-indoor and outdoor-attic temperature reductions were achieved by ΔT_{o-i}(M) and ΔT_{o-a}(M) with with 4.10°C and 0.30 °C respectively.

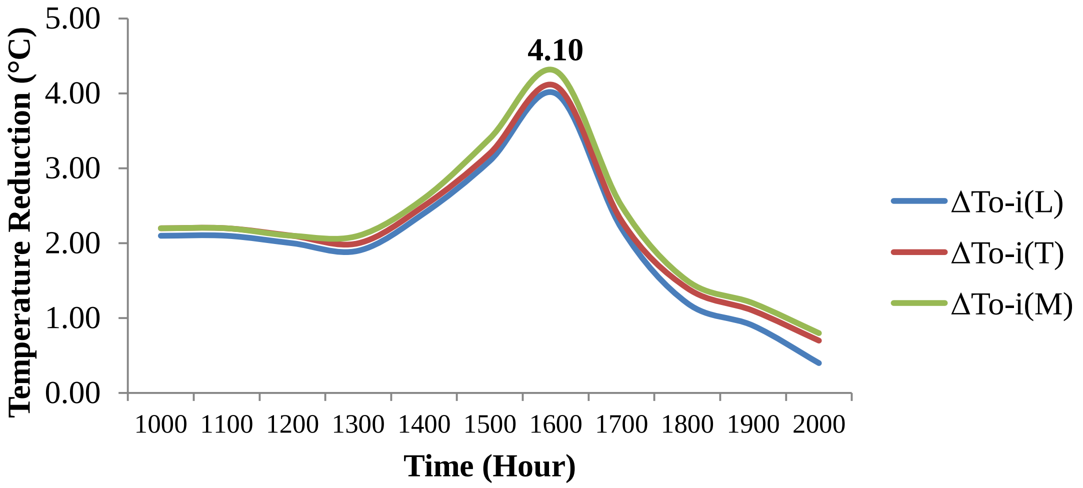


Figure 4.27: $\Delta T_{o\text{-}i}$(L), $\Delta T_{o\text{-}i}$(T) and $\Delta T_{o\text{-}i}$(M) profiles

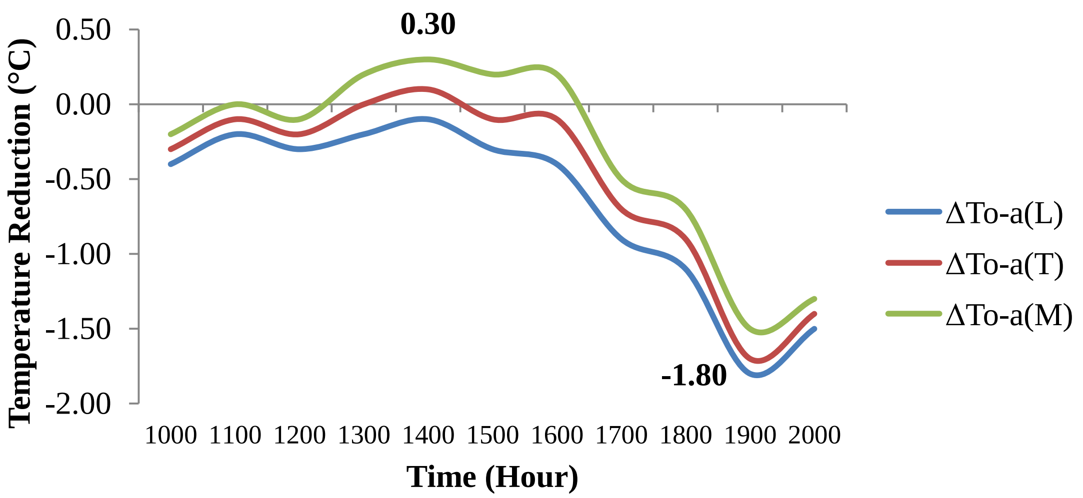


Figure 4.28: $\Delta T_{o\text{-}a}$(L), $\Delta T_{o\text{-}a}$(T) and $\Delta T_{o\text{-}a}$(M) profiles

In addition, Figure 4.29 and Figure 4.30 reveal average temperature reductions for all house models. The outdoor-attic temperatures are generally very small or negative because of the intense heat radiation from roof tiles and trapping of heat occurring within the enclosed attic space. The adoption of white roof tiles and minimum exposure to solar radiation through adjustment of roof pitch orientation in the design of house model *M* improves the roof thermal performance. Similarly in [115-117], adoption of white roof tiles is proven to reduce heat transfer through the roof. Moreover, installation of insulation in house model *M* is expected to further enhance thermal performance.

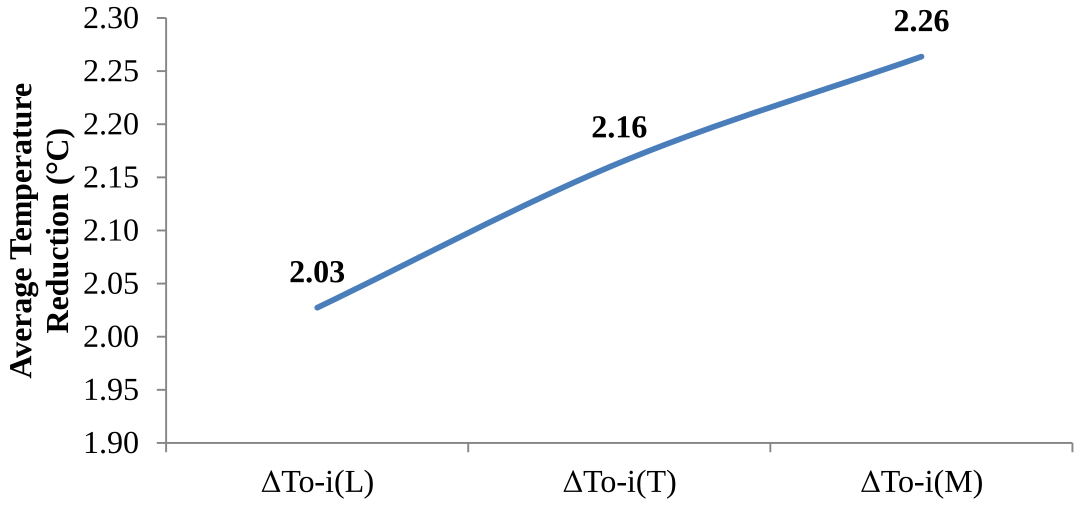


Figure 4.29: Average values of $\Delta T_{o\text{-}i}$(L), $\Delta T_{o\text{-}i}$(T) and $\Delta T_{o\text{-}i}$(M)

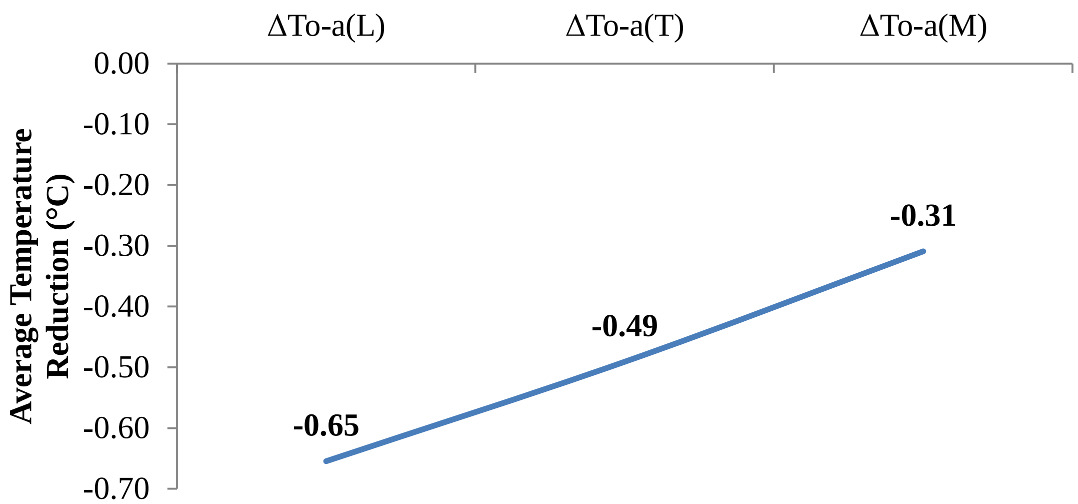


Figure 4.30: Average values of $\Delta T_{o\text{-}a}$(L), $\Delta T_{o\text{-}a}$(T) and $\Delta T_{o\text{-}a}$(M)

4.4.3 Performance of Insulation

This section is divided into four (4) parts. The first part assesses the effectiveness of insulation in relation to uninsulated house models. The second part evaluates the effect of thickness on the performance of insulation. The third part evaluates the effect of placement on the performance of insulation. Lastly, the fourth part compares the performance of traditional and new insulation materials.

Figure 4.31 compares the indoor temperature profiles of insulated house model M_{R50C} with uninsulated house models *L*, *T* and *M*. Results show that adoption of 50-mm rock wool insulation in house model M_{R50C} reduces indoor temperature by 3.50°C, which is from 31.80°C to 28.30°C, relative to the *L* house model.

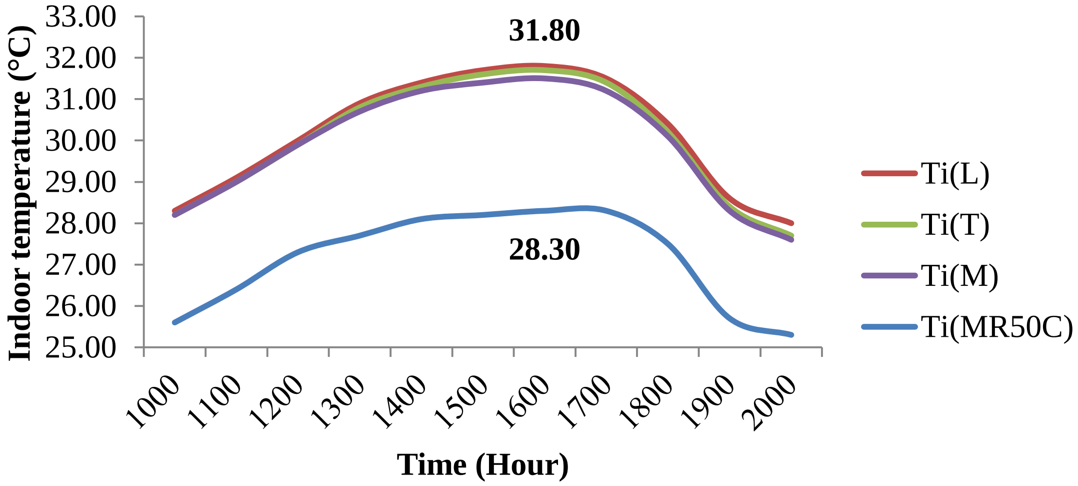


Figure 4.31: T_i(L), T_i(T), T_i(M) and $T_i(M_{R50C})$ profiles

Figure 4.32 presents indoor temperature profiles of house models of house models insulated with rock wool at 10-mm, 30-mm, 50-mm and 100-mm thicknesses. Results indicate that increase in thickness of insulation improves thermal performance. Accordingly, increase from 10-mm to 100-mm thickness results in the decrease in indoor temperature by 1.30°C, which is from 29.30°C to 28.00°C.

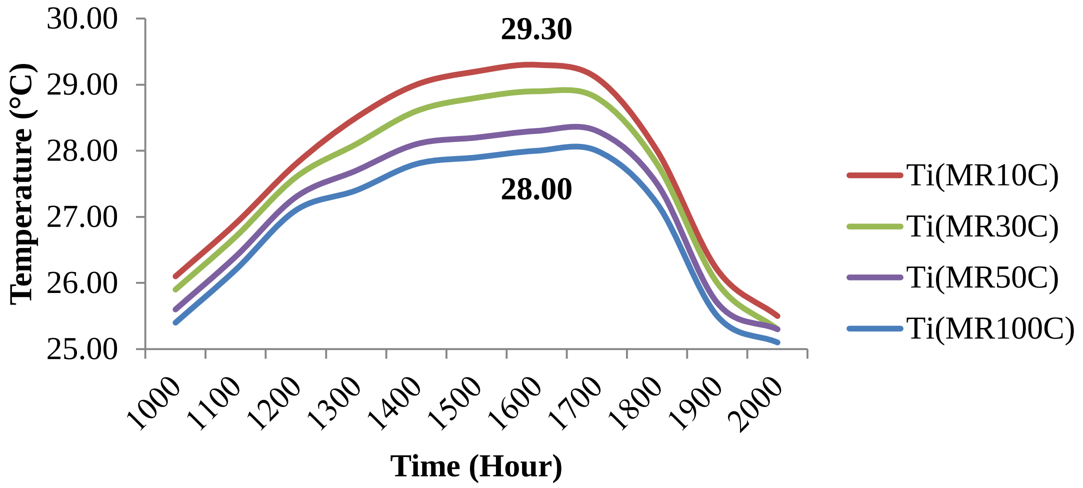


Figure 4.32: $T_i(M_{R10C})$, $T_i(M_{R30C})$, $T_i(M_{R50C})$ and $T_i(M_{R100C})$ profiles

Most insulation products in the market today are designed to be placed above the ceiling due to ease of installation. However, installation beneath roof tiles is expected to provide better insulation performance because of the larger insulation area and resistance of heat at first point of entry. Figure 4.33 proves that 50-mm rock wool insulation placed beneath roof tiles performs better than above the ceiling, which is in agreement with the results obtained in [36, 39]. Temperature reduction obtained in the present research due to placement of insulation beneath tiles as compared to above the ceiling is 0.60°C, which is from 28.30°C to 27.70°C. Contrarily, in [105], insulation above the ceiling performed better than beneath the roof tiles. Hence, more research on this subject matter is needed to further validate results of existing researches and develop a better understanding.

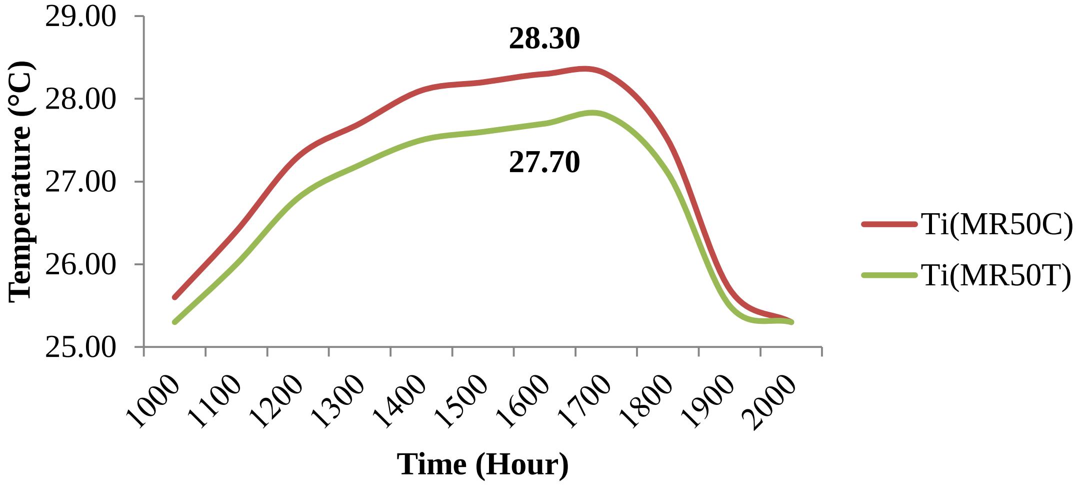


Figure 4.33: $T_i(M_{R50C})$ and $T_i(M_{R50T})$ profiles

Lastly, Figure 4.34 compares the thermal performances of different insulation materials. Potential of reinforced aerogel as a future common insulation material is proven with $T_i(M_{S50C})$ at peak hour 1600 hours reaching the lowest value of 27.20°C. Design indoor temperatures of 23°C to 26°C recommended in MS1525:2007 [118] are highlighted. Accordingly, development of high performance insulation materials is essential to yield indoor temperatures within the minimum and maximum range recommended by MS1525:2007.

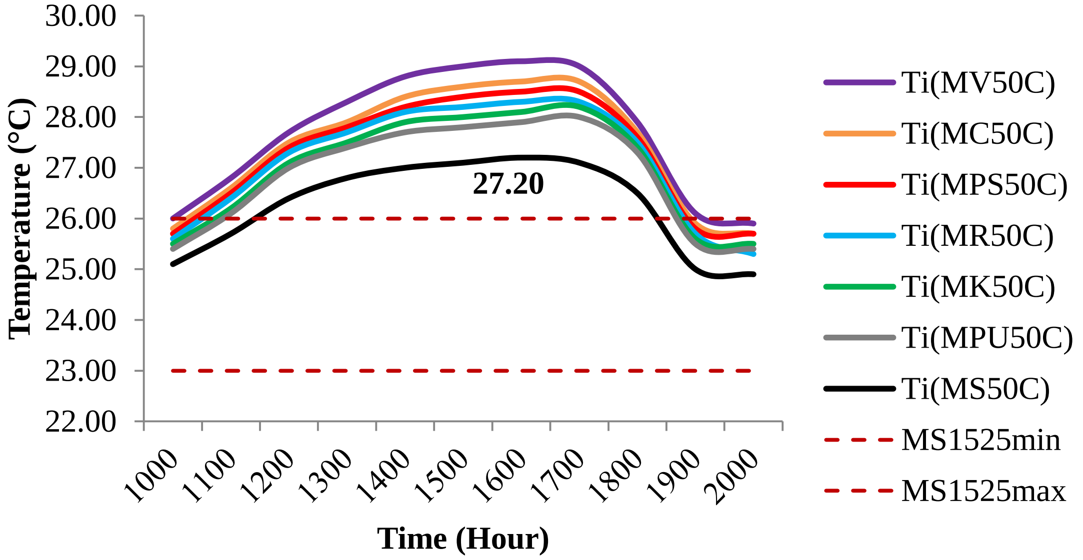


Figure 4.34: Comparison of all insulation materials placed above the ceiling

4.5 Cost-Benefit Analysis

This section presents the results of cost-benefit analysis calculations conducted to quantify cost and environmental impacts of thermal insulation in residential roofing system.

4.5.1 Cost Rate to Supply and Install Insulation

Table 4.4 presents the cost rates to supply and install insulation. Cost rates were determined with reference to priced quotations issued by several local and foreign manufacturers and contractors of insulation. Priced quotations used are attached in Appendix H. Detailed calculations of cost rates are attached in Appendix I.

Table 4.4: Cost rates to supply and install insulation

Item	Cost Rate
Supply of EPS	RM145.67/m^3
Supply of fibreglass	RM164.36/m^3
Supply of cellulose	RM158.92/m^3
Supply of rock wool	RM503.53/m^3
Supply of ENR	RM3490.50/m^3
Supply of kapok fibre	RM180.00/m^3
Labour for installation of insulation	RM10.76/m^2

4.5.2 Area Covered by Insulation

Calculations of the area covered by insulation for placement of insulation above the ceiling and beneath the roof tiles are presented in this section. Figure 4.35 shows the top view of the ceiling. Figure 4.36 and Figure 4.37 show the front and bottom views of the roof pitch.

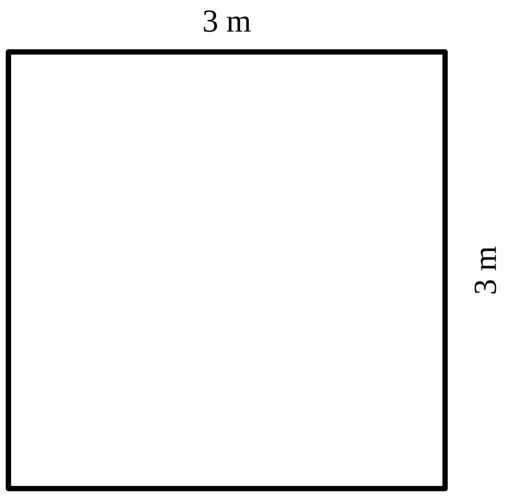


Figure 4.35: Top view of ceiling

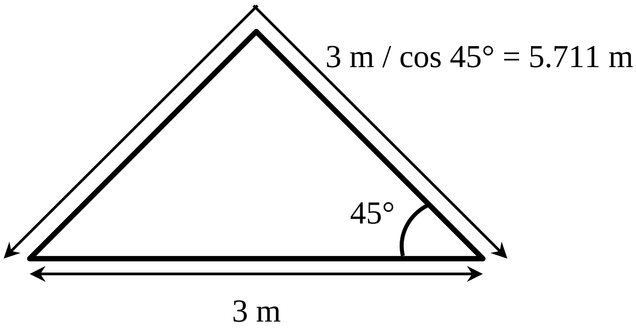


Figure 4.36: Front view of the roof pitch

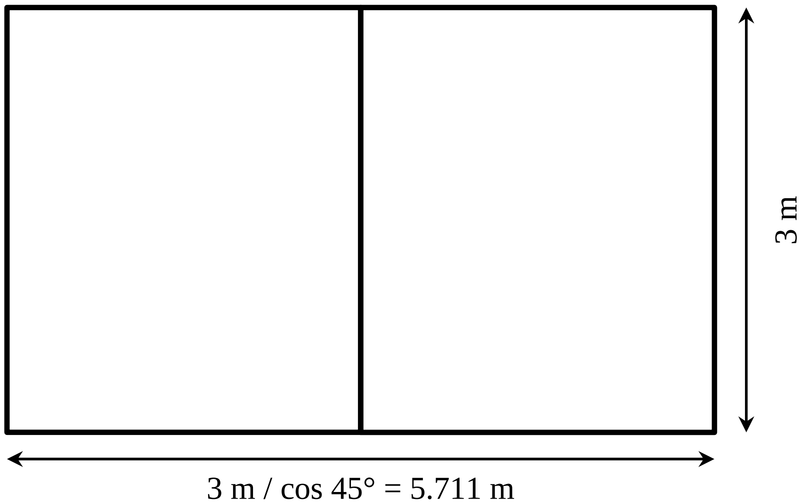


Figure 4.37: Bottom view of the roof pitch

Therefore, the areas covered by insulation placed above the ceiling and below the roof pitch can be calculated as follows:

$$A_{insulation-ceiling} = 3.00\ m\ \times 3.00\ m = 9.00\ m^2$$

$$A_{insulation-pitch} = \frac{3.00\ m}{\cos 45°} \times 3.00\ m = 17.13\ m^2$$

4.5.3 Cost Analysis

Table 4.5 and Table 4.6 present input variables used to calculate cost savings of insulation.

Table 4.5: Input variables used to calculate cost savings of insulation

Input Variable	Value
Supply cost rate of insulation	Refer to Section 4.5.1
Installation cost rate of insulation (RM/m^2)	10.76
Area covered by insulation	Refer to Section 4.5.2
Design outdoor temperature (°C)	35.80
Design indoor temperature (°C)	23.00
Average outdoor temperature (°C)	27.80
AC hours per day (hours/day)	6
AC days per year (days/year)	365
COP of AC	2.5
Lifetime period (years)	10
Inflation rate (%)	5
Discount rate (%)	5
Cost of electricity (RM/kWh)	0.334

Table 4.6: Input variables used to calculate cost savings of insulation

Input Variable	Value
k-Value (W/m-K)	
EPS	0.035
Fibreglass	0.035
Cellulose	0.042
Rock wool	0.034
ENR	0.037
Kapok fibre	0.034
Reinforced aerogel	0.013
Plaster ceiling	0.431
Air gap in attic	5.560
Clay tiles	18.828
Thickness (m)	
Plaster ceiling	0.05
Air gap in attic	0.10
Clay tiles	0.05

Figure 4.38 reveals the cost savings from kapok fibre at both pitch and ceiling placements. Placement of insulation above the ceiling results in higher cost savings than below the roof tiles, which is due to the lower area of insulation that results in lower insulation cost. However, several past researches reported on the preference of placement of insulation below the roof tiles as compared to above the ceiling for better thermal performance [36, 39, 105]. Even so, it is essential to consider that in Morris *et al.* (2011) [39] the insulation material and thickness used for each placement are varied. While, Halim *et al.* (2011) [105] reported that placement of insulation below roof tiles results in lower attic temperature and at the same time higher indoor temperature as compared to above the ceiling. Ong (2011) [36] reported that placement of insulation below roof tiles is preferred based on the roof, attic and ceiling temperatures, which does not take into consideration the indoor space.

Theoretically, the advantage of insulation placed below roof tiles as compared to above the ceiling is the retard of heat transfer at its first point entry, which does not allow the attic temperature to increase and heat up the ceiling. On the other hand, the disadvantage is its larger insulation area that requires higher insulation cost. Furthermore, the dimension of house models tested can be a key factor in determining whether placement of insulation above the ceiling or below roof tiles is preferred. The advantage of insulation placed below roof tiles could be more significant in house models with larger surface area of heat transfer through the roof.

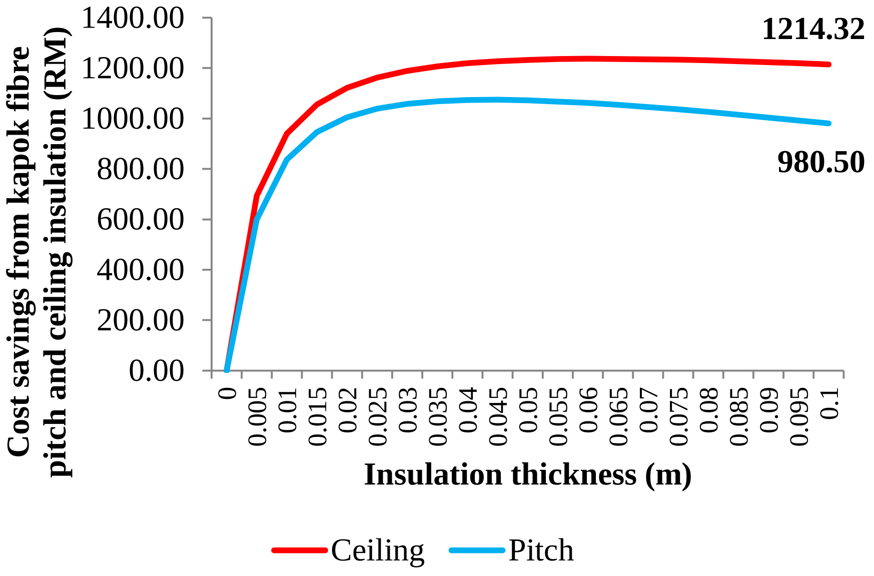


Figure 4.38: Cost savings from kapok fibre pitch and ceiling insulation

The relationship between insulation thickness and cost savings are plotted in Appendix J. The regression equations for each plot are identified. Based on the coefficients of each regression equation, the optimum thickness and maximum cost savings of each insulation material are determined.

Figure 4.39 and Figure 4.40 compares the optimum thicknesses and maximum cost savings of each insulation material. The optimum insulation thicknesses for ceiling insulation are higher than pitch insulation. This is due to the lower insulation cost of ceiling insulation as compared to pitch insulation that has a smaller insulation area above the ceiling as compared to roof pitch. Even though the thermal performance for pitch insulation is better, but in this case, the insulation cost has a higher weightage on the cost savings, which is expected to be due to the small size of the house model that has a small heat transfer area at the roof as compared to bigger house models.

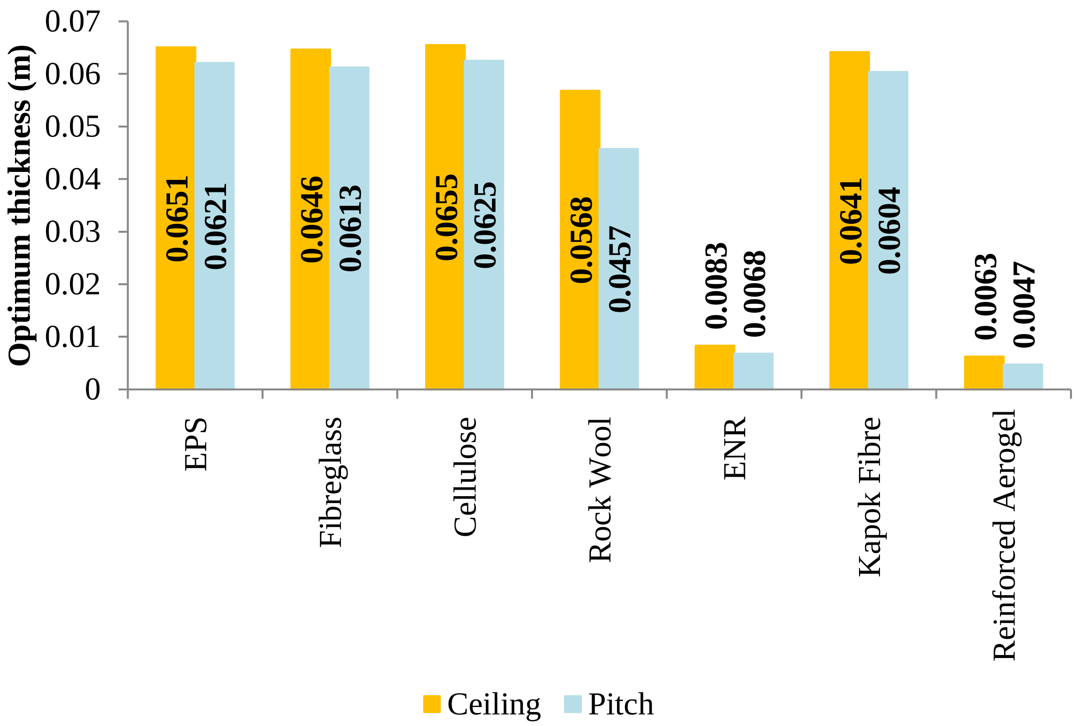


Figure 4.39: Optimum thickness of insulation

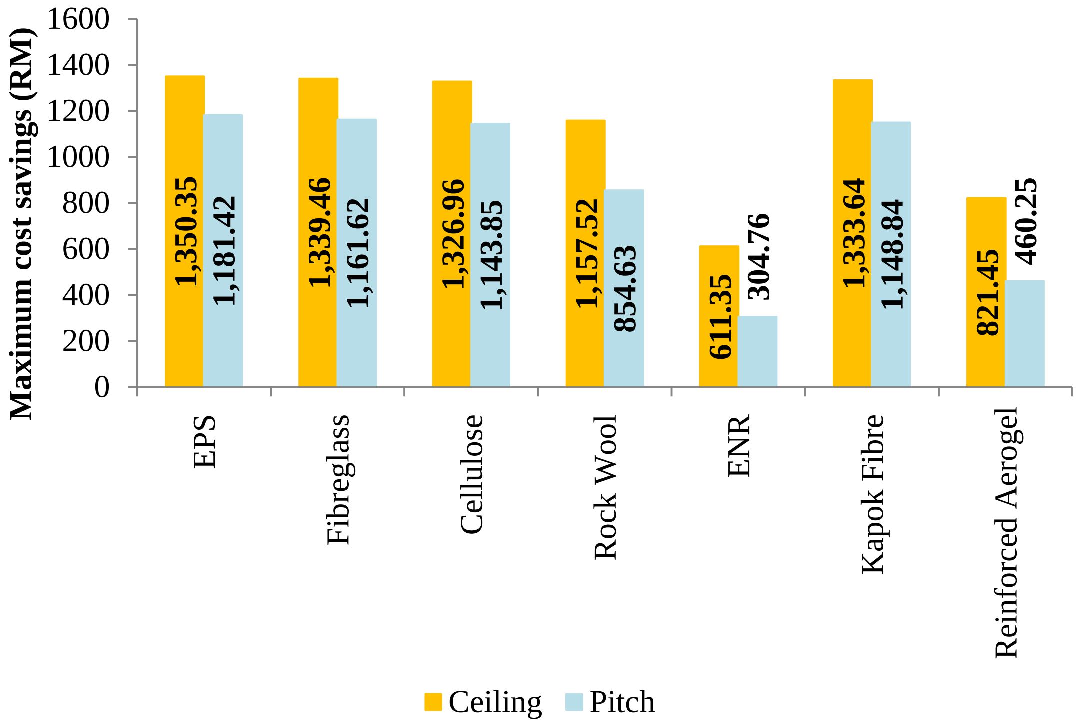


Figure 4.40: Maximum cost savings of insulation

The traditional insulation materials more or less have similar optimum thicknesses that are between 0.04 m to 0.07 m, with cellulose ceiling insulation possessing the highest optimum thickness at 0.0655 m and rock wool pitch insulation possessing the lowest optimum thickness at 0.0457 m. The alternative insulation material kapok fibre also has optimum thicknesses that are similar to traditional insulation materials, which are 0.0641 m and 0.0604 m for ceiling and pitch insulations respectively. Therefore, kapok fibre is a viable insulation material that can replace the traditional insulation materials, considering that kapok fibre is a raw organic material that is more environmentally-friendly than most of the traditional insulation materials. Similarly, cellulose is also a raw organic material.

Reinforced aerogel possess the lowest optimum thickness with 0.0063 m and 0.0047 m for ceiling and pitch insulations respectively. This is partly due to its higher cost rate when compared to the other insulation materials, but at the same time due to its superior thermal performance. Reinforced aerogel can be a common high performance insulation material in the future provided that researches on its manufacturing process are conducted in order to seek for cheaper alternative manufacturing process. Breakthroughs in the development of reinforced aerogel and increase in the market supply can further reduce its cost and improves it cost feasibility as a building insulation material.

The trend for maximum cost savings is similar to optimum insulation thickness. The maximum cost savings for the traditional insulation materials and kapok fibre are in between RM1100 and RM1400. EPS ceiling insulation possess the highest maximum cost savings at RM1350.35. ENR possess the lowest maximum cost savings at RM611.35 and RM304.76 for ceiling and pitch insulations respectively. Furthermore, the maximum cost savings for reinforced aerogel are RM821.45 and RM460.25 for ceiling and pitch insulations respectively. As mentioned earlier, with further development on the manufacturing process of reinforced aerogel and expansion of its market supply, its supply cost rate is expected to further reduce and its cost feasibility as a building insulation material is expected to increase.

4.5.4 Payback Period Analysis

The investment return of each insulation material studied with respect to their service periods are attached in Appendix K. The service period at zero investment return or the interception at the x-axis is the payback period.

Figure 4.41 highlight the payback period for each insulation material and placement. EPS ceiling insulation has the shortest payback period at because of its low supply cost rate, which is due to its high market supply rate in various industries, not only as building insulation. The payback periods for ENR and reinforced aerogel are longer than the other insulation materials. The payback periods of all insulation materials studied range in between a year to 7 years. This information is essential in convincing house owners to implement insulation. The short payback period for all insulation materials studied justifies the feasibility in purchasing and installing insulation materials in houses not only for its economic benefits, but also for other benefits such as thermal comfort, acoustic comfort and environmental impact.

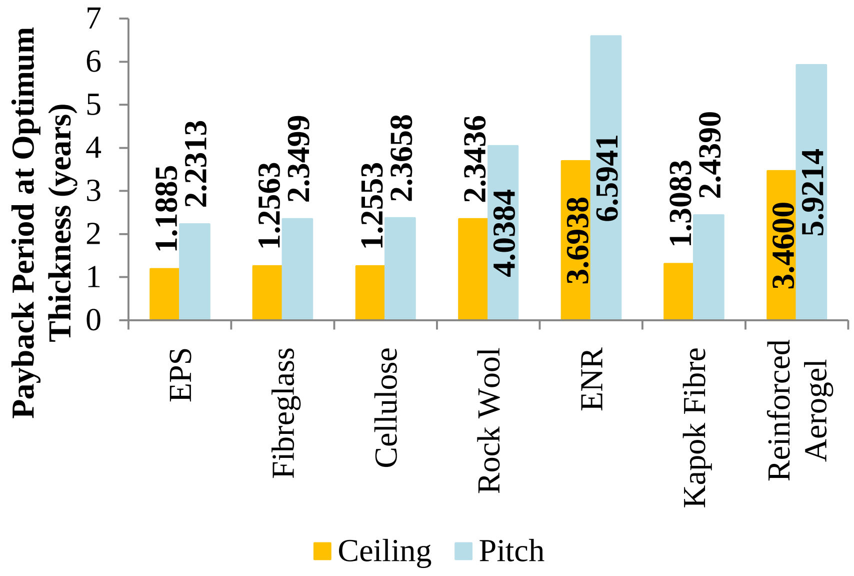


Figure 4.41: Payback period of insulation at optimum thickness

4.5.5 Electricity Consumption Projection

Figure 4.42 reveals the AC electricity consumption reduction per house from three (3) selected insulation materials placed at roof pitch, which are kapok fibre, ENR and reinforced aerogel. The electricity consumption reduction from kapok fibre pitch insulation at 0.1 m thickness is 2646.39 kWh. While, the electricity consumption reductions from ENR and reinforced aerogel pitch insulations at 0.01 m thickness are 1839.35 kWh and 2351.59 kWh respectively. Even though the electricity consumption reduction due to kapok fibre is higher than both ENR and reinforced aerogel, it is important to consider that the values obtained for ENR and reinforced aerogel are at a thickness that is 10 times lower as compared to kapok fibre. Furthermore, when comparing ENR with reinforced aerogel, reinforced aerogel provides a better performance with a higher electricity consumption reduction, which highlights the potential of reinforced aerogel as a promising future insulation material, provided the cost rate is reduced as the market supply for reinforced aerogel expands and more breakthroughs are developed. Detailed projection of AC electricity consumption reduction is attached in Appendix L.

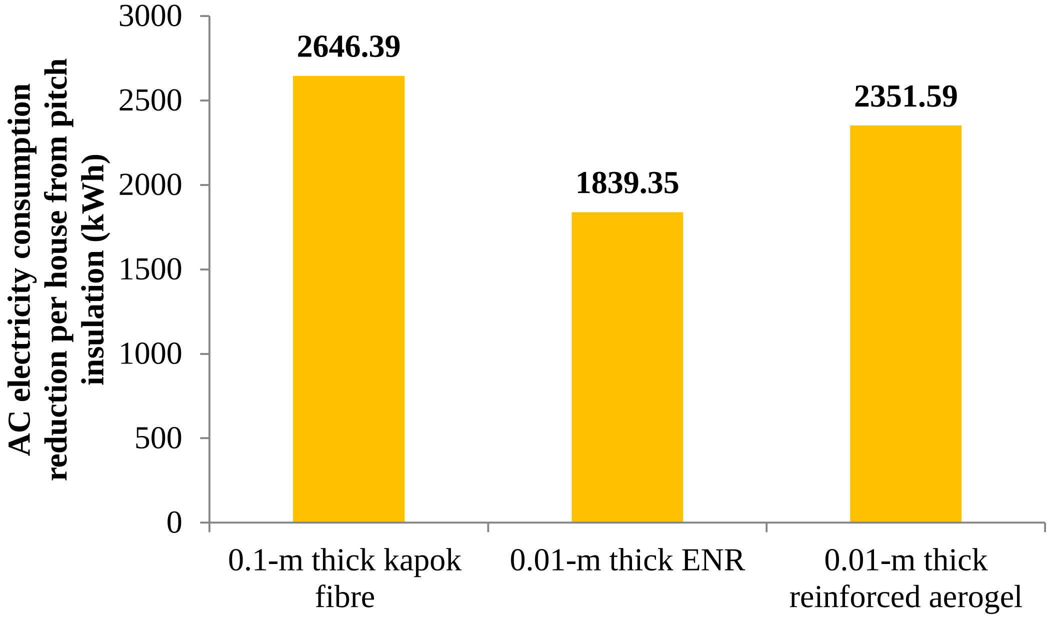


Figure 4.42: AC electricity consumption reduction per house from pitch insulation

4.5.6 CO_2 Emission Projection

Figure 4.43 presents the CO_2 emission reduction per house with three (3) selected insulations, which are kapok fibre, ENR and reinforced aerogel pitch insulations. CO_2 emission reduction for 0.1-m thick kapok fibre pitch insulation is 1720.15 kg CO_2 per house. While, CO_2 emission reductions for 0.01-m thick ENR and reinforced aerogel pitch insulations are 1195.58 kg CO_2 and 1528.53 kg CO_2 per house respectively. The trend for CO_2 emission reduction is the same with AC electricity consumption reduction. Furthermore, if insulation is implemented all over Malaysia, for instance, 500,000 houses, the total CO_2 emission reduction can be projected to be 860075000 kg CO_2, 597790000 kg CO_2 and 764265000 kg CO_2 for 0.1-m thick kapok fibre, 0.01-m thick ENR and 0.01-m thick reinforced aerogel pitch insulations respectively, which are significant amounts that can contribute massively in reducing the impact of global warming. CO_2 emission reductions due to insulation were also reported [84, 106, 108] to be in the range of 35%-77%. Detailed projection of CO_2 emission reduction is attached in Appendix M.

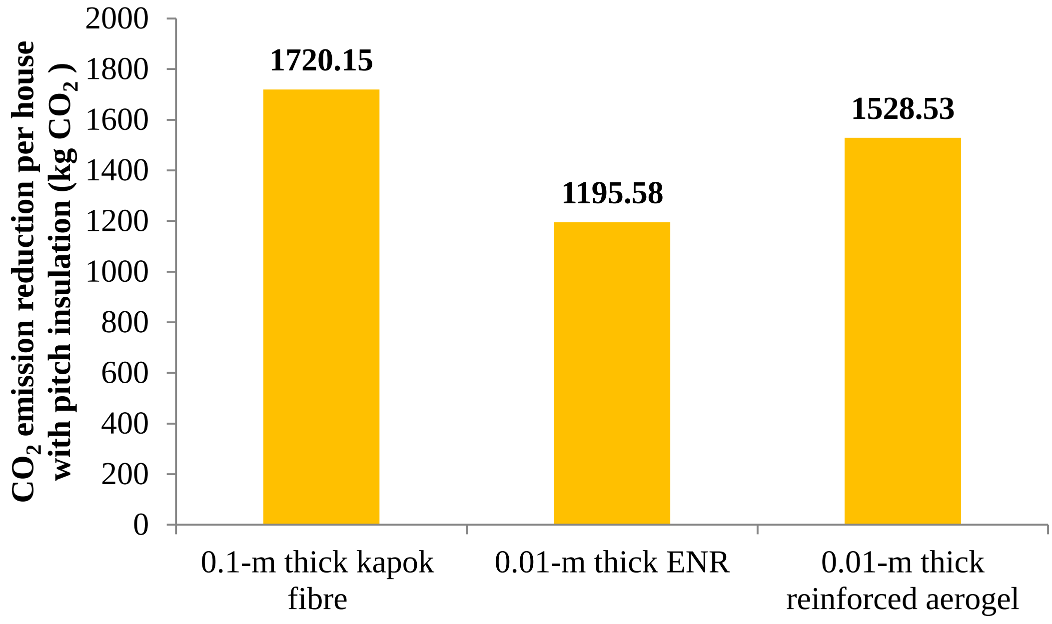


Figure 4.43: CO_2 emission reduction per house with pitch insulation

4.5.7 Environmental Impact Projection

The impact of the CO_2 emission reduction due to building insulation on the environmental is quantified in units of cars removed from the road and new trees planted as presented in Figure 4.44. Implementation of 0.1-m thick kapok fibre pitch insulation results in environmental impacts that are equivalent to planting 10.81 new trees and removing 5.49 cars from the road per house. To add to that, 0.01-m thick ENR pitch insulation results in environmental impacts that are equivalent to planting 7.51 new trees and removing 3.82 cars from the road per house. Furthermore, 0.01-m thick reinforced aerogel pitch insulation results in environmental impacts that are equivalent to planting 9.60 new trees and removing 4.88 cars from the road per house. If the calculation is extended to consider the implementation of insulation in 500,000 houses all over Malaysia, the number of trees and cars are 5405000 trees and 2745000 cars, 3755000 trees and 1910000 cars and 4800000 trees and 2440000 cars for kapok fibre, ENR and reinforced aerogel pitch insulations respectively. Therefore, the positive impact of implementing building insulation on the environmental is very huge and must be seriously taken into consideration in the construction of new buildings and retrofitting of existing buildings. Detailed projection of environmental impact is attached in Appendix N.

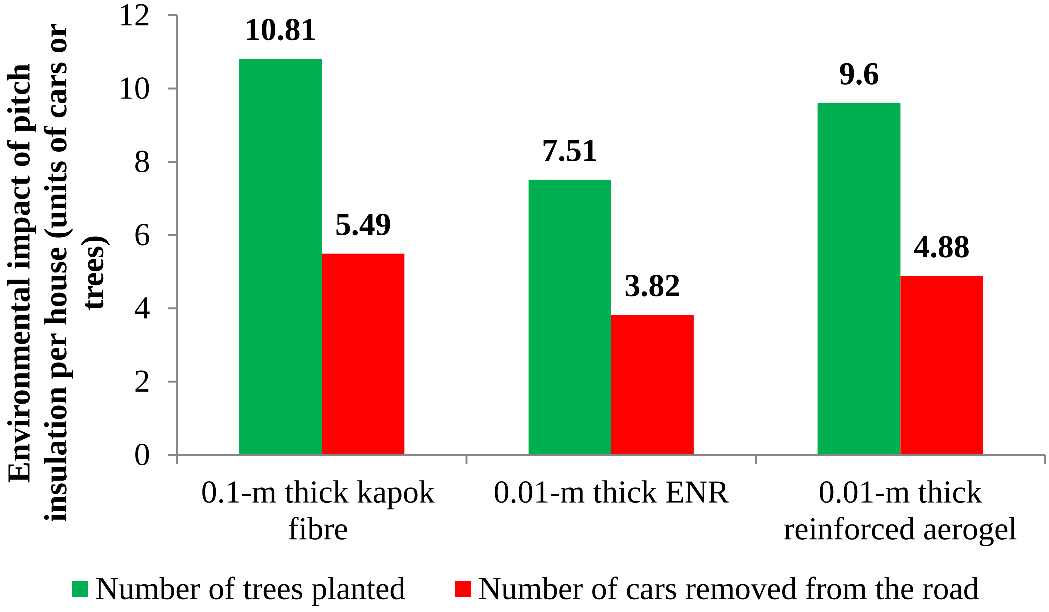


Figure 4.44: Environmental impact of pitch insulation per house

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter is commenced with a review on the objectives of the research. Then, it explains the conclusions drawn for each objective based on the results obtained. Next, the main conclusion is stated. Lastly, based on lessons learned from the research, recommendations are made for improvement of future related research works.

5.2 Review of Research Aim and Objectives

The aim of this research is to optimize thermal insulation in residential roofing system in hot-humid climate for maximum reduction in cost and CO_2 emission. This aim is supported by the following objectives:

1. To determine levels of awareness and preparedness and barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia
2. To validate the effectiveness of thermal insulation in roof in hot-humid climate
3. To evaluate the indoor temperature profiles of thermal insulation of varying material, thickness and placement in energy-efficient residential roofing system
4. To project the cost and CO_2 emission of residential building for optimization of thermal insulation in roof

5.3 Conclusion for Objective 1

The first objective is to determine the levels of awareness, preparedness and barriers among house owners, developers and professionals on the implementation of building insulation in Malaysia. Questionnaire survey and online interview were conducted to achieve the objectives. Based on the results obtained, it can be concluded that the level of awareness on building insulation is low. In addition, the level of preparedness among developers is also low because of the lack of appreciation towards the long-term benefits of housing insulation and excessive focus on the additional capital investment that comes with installing insulation. Barriers of the implementation of housing insulation are identified and listed as follows:

- No legal requirement
- Low electricity tariff
- Trend of installing room AC
- Additional cost

5.4 Conclusion for Objective 2

The second objective is to validate the effectiveness of thermal insulation in roof in hot-humid climate. A house model experiment is employed to address the objective. Results validated that thermal insulation in roof results in a significant decrease in the indoor temperature in relation to the outdoor temperature. The highest outdoor-indoor temperature difference achieved is 8.40°C, which is obtained by 100-mm kapok fibre insulation at 1000 hours.

5.5 Conclusion for Objective 3

The third objective is to evaluate the indoor temperature profiles of thermal insulation of varying material, thickness and placement in energy-efficient residential roofing system. Simulation results show that 50-mm thick reinforced silica aerogel insulation placed beneath roof tiles performed best, obtaining the lowest indoor temperature of 27.20°C at peak outdoor temperature at 1600 hours.

5.6 Conclusion for Objective 4

This fourth objective is to project the cost and CO_2 emission of residential building for optimization of thermal insulation in roof. The maximum electricity consumption reduction obtained is 2646.39 kWh, which is obtained by kapok fibre ceiling insulation. Furthermore, the maximum CO_2 emission reduction obtained is 1720.15 kg CO_2, which is equivalent to removing 5.49 cars from the road or planting 10.81 new trees. Furthermore, the smallest optimum insulation thickness obtained is 0.0047 m, which is obtained by reinforced aerogel pitch insulation, while the largest optimum insulation thickness obtained is 0.0655 m, which is obtained by cellulose ceiling insulation.

5.7 Main Conclusion

The research aim is to optimize thermal insulation in residential roofing system in hot-humid climate for maximum reduction in cost and CO_2 emission. Optimization of thermal insulation in residential roofing system is achieved by determining the combination of material, thickness and placement of thermal insulation in residential roofing system that can lead to the highest cost savings and positive environmental impact. The optimum thermal insulation obtained in the research is 0.0641-m thick kapok fibre ceiling insulation.

5.8 Recommendation

Based on lessons learned from conducting this research, several recommendations are made to enhance the relevance and quality of results of future related research.

Field study can generate better results and more relevant findings by utilizing house models with more complex conditions such as irregular building geometry, presence of occupants, arrangement of furniture and utilization of appliances. Data points can be increased by measuring temperatures not only for outdoor and indoor air, but also above and below roof tiles, insulation layers and ceiling. This enhanced method enables researchers to explore the heat transfer through the roof in more depth.

The understanding of the effect of insulation placement on the overall thermal performance of the roof must be further investigated. This research highlighted that pitch insulation provides better thermal performance, but at the expense of higher insulation cost due to larger insulation area at roof pitch as compared to the ceiling. A research method that investigates the performance of ceiling in comparison with pitch insulation at varying roof sizes is recommended to develop new knowledge in this area.

The potential of NIMs is highlighted in this research. The researcher recommends future research which explores the effectiveness and cost feasibility NIMs. An NIM like silica aerogel possesses thermal conductivity that is extremely lower than traditional insulation materials. However, due to its brittleness, its viability as a building insulation material must be improved by providing reinforcement. Reinforcement of silica aerogels is a field of research with interesting possibilities. Other than the brittleness, the other barrier of NIMs is its supply cost rate. This can be reduced by developing alternative manufacturing methods that are more cost-effective. Further innovation in this area is expected to lead to increase in market supply of NIMs and thus, is expected to reduce its supply cost rate further.

Other than exploring the possibilities of high performance insulation such as NIMs, the possibilities of raw and natural or waste materials that are more environmentally-friendly such as kapok fibre can be explored too. This approach not only benefits the house owners economically, but also the environment.

The quantification of the environmental impact of insulation has been investigated by previous researchers by considering the effect of AC electricity consumption reduction on CO_2 emission. The present research extends this area by projecting the equivalent number of cars that can be removed from the road and the number of new trees that can be planted those results in the same reduction in CO_2 emission. However, there is a lack of research that puts into consideration the environmental-friendliness of insulation prior to its installation, such as the CO_2 emission that results from its manufacturing process. Quantification of this factor can provide a more accurate comparison of insulation materials.

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APPENDIX A: LIST OF PUBLICATIONS

BOOK SECTIONS

1. **Farhan, S. A**., Khamidi, M. F., Murni, M. H., Nuruddin, M. F., Idrus, A. and Al Yacouby, A. M. (2012). Effect of silica fume and MIRHA on thermal conductivity of cement paste. In: High Performance Structures and Materials VI. WIT Transactions on the Built Environment, 124. WIT Press, Great Britain, pp. 331-339. ISBN 978-1-84564-596-0.

2. Al Yacouby, A. M., Khamidi, M. F., Teo, Y. W., Nuruddin, M. F., **Farhan, S. A.**, Sulaiman, S. A. and Razali, A. E. (2012). Housing developers and home owners' awareness on implementation of building insulation in Malaysia. In: Management of Natural Resources, Sustainable Development and Ecological Hazards III. Ravage of the Planet VI (2011), 3. WIT Press, Great Britain, pp. 219-230. ISBN 978-1-84564-532-8.

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1. **Farhan S. A.**, Khamidi M. F., Ziela D. F., Al Yacouby A. M., Idrus A., Nuruddin M. F. and Razali A. E. (2012). Performance of reflective insulation in gable roofs: small-scale experimental investigation. In: 2012 International Conference on Civil, Offshore & Environmental Engineering, 12-14 June 2012, Kuala Lumpur, Malaysia.

2. **Farhan, S. A.**, Khamidi, M. F., Al Yacouby, A. M., Idrus, A. and Nuruddin, M. F. (2012). Critical review of published research on building insulation: focus on building components and climate. In: 2012 IEEE Business, Engineering and Industrial Applications Colloquium, 7-8 April 2012, Kuala Lumpur, Malaysia.

3. Al Yacouby, A. M., Khamidi M. F., Nuruddin M. F., **Farhan S. A.** and Razali A. E. (2012). Experimental study on the effects of roof colors on thermal performance of housing in Malaysia. In: 2012 International Conference on

Civil, Offshore & Environmental Engineering, 12-14 June 2012, Kuala Lumpur, Malaysia.

4. Al Yacouby, A. M., Khamidi, M. F., Nuruddin, M. F., **Farhan, S. A.** and Razali, A. E. (2011). Study on roof tile's colors in Malaysia for development of new anti-warming roof tiles with higher solar reflectance index (SRI). In: National Postgraduate Conference 2011, 19-20 September 2011, Universiti Teknologi PETRONAS, Perak, Malaysia.

5. Al Yacouby, A. M., Khamidi, M. F., Nuruddin, M. F., **Farhan, S. A.**, Idrus, A. and Razali, A. E. (2011). A review on thermal performance of roofing materials in Malaysia. In: International Building & Infrastructure Technology Conference 2011, 7-8 June 2011, Penang, Malaysia.

APPENDIX B: SAMPLE QUESTIONNAIRE (SET 1)

Survey on Preference of Housing Insulation

1. Age:

   a) Below 24   b) 25 - 34   c) 35 - 44   d) 45 and above

2. Gender: M / F

3. Race: M / C / I / Others

4. Occupation: ___________________

5. Are you planning to buy houses in 3 years' time?

   ☐ Yes   ☐ No

6. What is your house budget?

   a) Below RM100,000
   b) RM100,000 – RM200,000
   c) RM200,000 – RM300,000
   d) RM300,000 – RM400,000
   e) Above RM400,000

7. Do you know what 'insulation' is?

   ☐ Yes   ☐ No

If your answer is 'No', please proceed to question 10.

8. How do you judge your understanding about housing insulation?

   a) Low   b) Medium   c) High

9. From where or how do you know this term?

a) Newspaper
b) Website
c) Television show
d) Radio
e) Friends and family
f) Exhibition
g) Others, please state : ___________________

The insulation layer absorbs sound and heat, hence it is commonly used as sound barrier and to produce cooler indoor environment in hot climate country. With cooler indoor temperature, less energy is used and this leads to greener environment. Besides that, insulation is a great fire retardant as it can resist up to 800 degree Celsius.

10. Will you consider installing housing insulation after reading the above paragraph?

☐ Yes ☐ No

11. How much will you spend on installing housing insulation?

a) Below RM1.00 per square feet
b) RM1.00 – RM2.00 per square feet
c) RM2.00 – RM3.00 per square feet
d) RM3.00 – RM4.00 per square feet
e) Above RM4.00 per square feet

APPENDIX C: SAMPLE QUESTIONNAIRE (SET 2)

Survey Questionnaire

Part 1 - Company Profile

Name:
Email:
Position:
Company Name:
Company Address:
Company Telephone Number:
Company Fax Number:
Company's Grade:

Part 2 - Survey on Completed Projects

1. How many residential projects have your company completed in the last 20 years?
a. 5
b. 6 – 10
c. 11 – 15
d. > 15

2. How many of the residential projects completed implement insulation?
a. 0
b. 1 - 5
c. 6 - 10
d. 11 - 15
e. > 15
** If your answer is 'a', please proceed to Part 3, otherwise, please continue on Question 3.*

3. What is/are the preferred insulation method/s and what is/are the reason/s?

a. Blanket type, ____
____

b. Loose-fill insulation, ____
____

c. Rigid or semi-rigid boards, ____
____

d. Spray-foam insulation, ____
____

4. What are the insulation materials used and why is it being chosen?

a. Glass wool, ____

b. Stone wool, ____

c. Fibre wool, ____

d. Others: Please state: ____

Part 3 - Opinion Survey

5. Which do you think is/are the benefit/s of insulation?

(You can choose more than one)

a. Sound barrier

b. Fire retardant

c. Cooler indoor temperature

d. Energy efficiency

e. Cost saving

f. Health concern

g. None

h. Others: Please state: ____

6. What do you think about the knowledge/understanding level towards insulation usage by architects, engineers, clients and government (approving) authorities?

a. Low

b. Medium

c. High

7. What do you think about the acceptance level towards insulation usage by architects, engineers, clients and government (approving) authorities?

a. Low

b. Medium

c. High

8. Do you think there are enough insulation manufacturers in Malaysia?

a. Yes

b. No

c. Not sure

9. If given a choice, will you consider using insulation in future construction projects? If no, why?

a. Yes

b. No, ____

10. If there is a request from the architect, will you consider using insulation in particular projects?

a. Yes

b. No

c. Depends on cost. Please state the price range acceptable for insulation per square feet. RM __________ / square feet

11. If there is a demand on good quality insulation from clients/potential house buyers, will you consider using insulation in whole projects?

a. Yes

b. No

12. What is the price range acceptable / reasonable for you to adopt housing insulation?

a. < RM1.00 per square feet

b. RM1.00 – RM2.00 per square feet

c. RM2.00 – RM3.00 per square feet

d. RM3.00 – RM4.00 per square feet

e. RM4.00 – RM5.00 per square feet

f. None of the above, house buyers should pay for themselves.

13. Would you adopt insulation after knowing the benefits of it, even though there is no law stated that it is compulsory? If no, why?

a. Yes

b. No, ____

14. Have you ever thought of / would you consider using insulation as the gimmick in promoting your project? Are there any particular reasons for the choice?

a. Yes, ____

b. No, ____

Part 4 - Comments and Suggestions

15. What do you think on making insulation usage in construction compulsory?

____

____

____

____

____

16. Any suggestions to promote insulation in the Malaysian construction industry?

____

____

____

____

17. What do you think about the government subsidizing on the insulation industry?

APPENDIX D: DETAILS OF PROFESSIONALS WHO PARTICIPATED IN ONLINE INTERVIEW SURVEY

1. Amna A Emir
    - Architect, CEO of NEUformation Group of Companies
    - Honorary Secretary General of the Malaysian Structural Steel Association

2. Ir. Wong Yee Foong
    - Engineer, BES Perunding
    - GBI Facilitator

3. Husam Haron
    - Architect, Associate EAG Consulting Sdn. Bhd.
    - GBI Facilitator

4. Ar. Lee Chor Wah
    - Architect
    - President of PAM Council 2008 - 2009
    - GBI Facilitator

5. Ir. Matthew Lim Guang Ming
    - GBI Facilitator

6. Tang Chee Khoay
    - Director and Engineer, IEN Consultants
    - GBI Facilitator

7. Lam Kok Liang
    - Architect, BEPAKITEK
    - GBI Facilitator

8. HASA Green Technologies Sdn. Bhd.

9. Philip Lew

- Midvalley City Gardens Sdn. Bhd.
- GBI Facilitator

10. Vekneswaran Arasappan

- Faber Group Berhad
- GBI Facilitator

11. Ar. Menaha Ramanath

- Pakatan Reka Arkitek Sdn. Bhd.
- GBI Facilitator

12. Faizul bin Haji Ideris

- Manager, Norms, Standards and External Relations, RockWool Malaysia Sdn. Bhd.
- GBI Facilitator

13. Chin Foong Lin

- Architect, Associate M. Kiandee Architect
- GBI Facilitator

14. Ralph Dixon

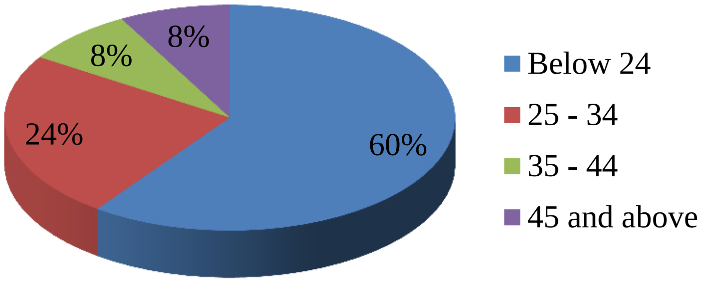
- Director of Environmental Investments, YTL Corp Berhad
- CEO / Director, YTL-SV Carbon Sdn. Bhd.
- Trustee, Malaysian AIDS Foundation

15. James Ding

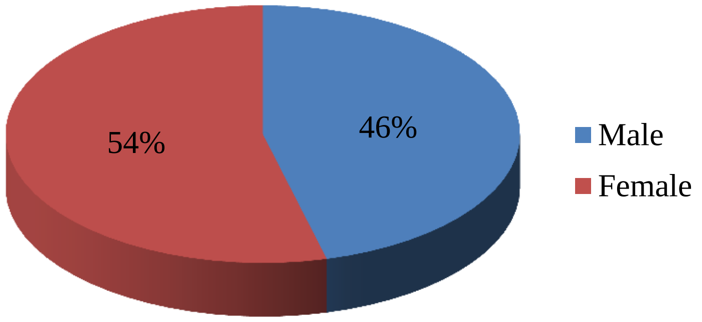
- Regional Representative, Thermoshield AUS PTY. LTD.

APPENDIX E: RESULTS FROM QUESTIONNAIRE FOR HOUSE OWNERS

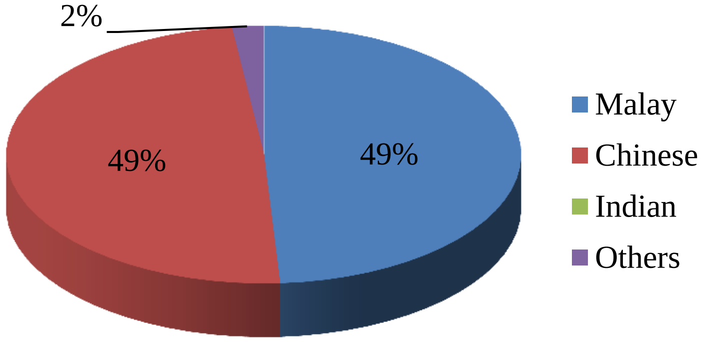
1. Feedback for Question 1: Percentages of respondents based on age



2. Feedback for Question 2: Percentages of respondents based on gender



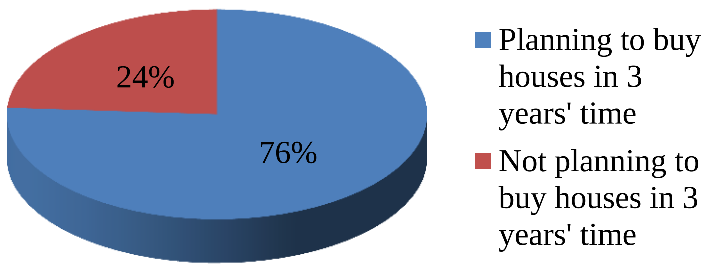
3. Feedback for Question 3: Percentages of respondents based on race



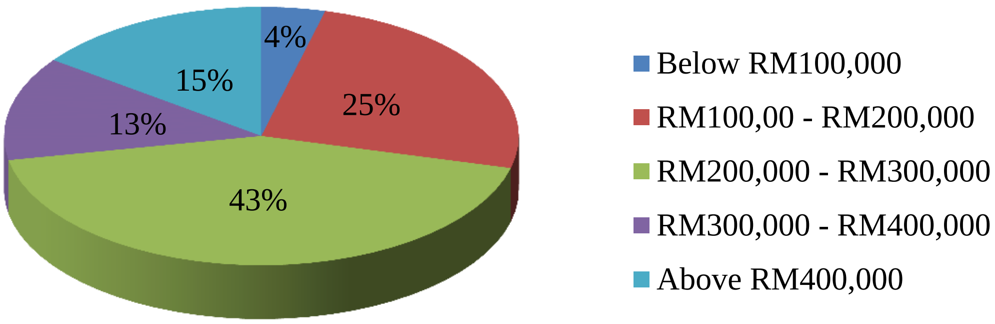
4. Feedback for Question 4: Percentages of respondents based on occupation

Occupations of respondents vary widely.

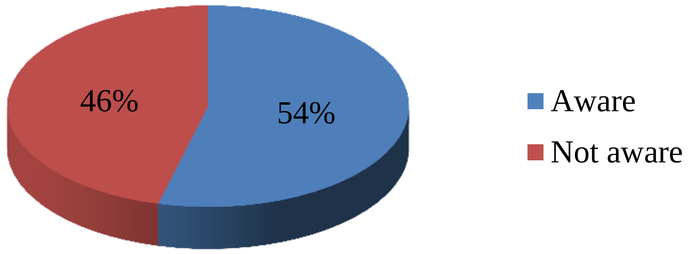
5. Feedback for Question 5: Percentages of respondents planning to buy houses in 3 years' time



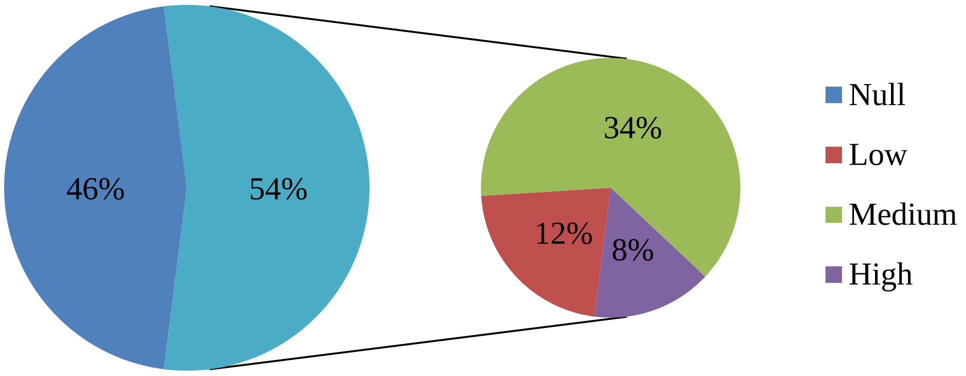
6. Feedback for Question 6: Percentages of respondents based on house budgets



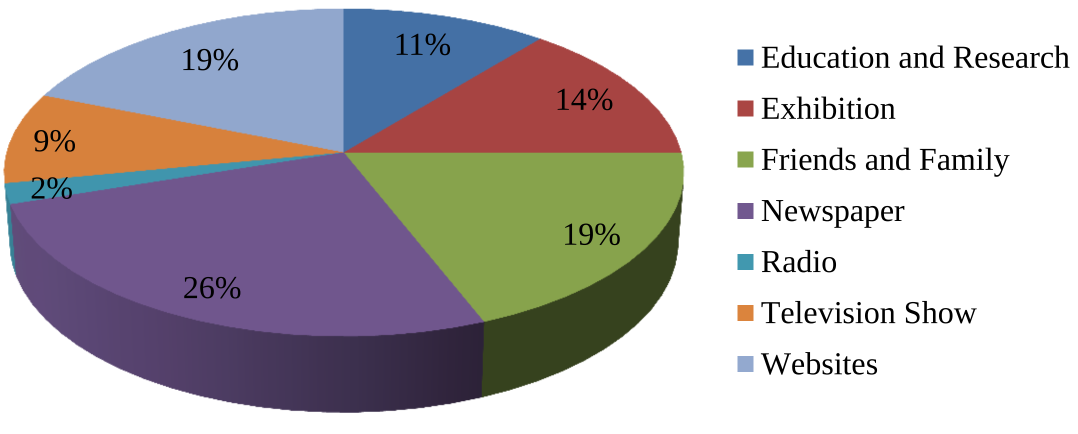
7. Feedback for Question 7: Percentages of respondents based on awareness on insulation



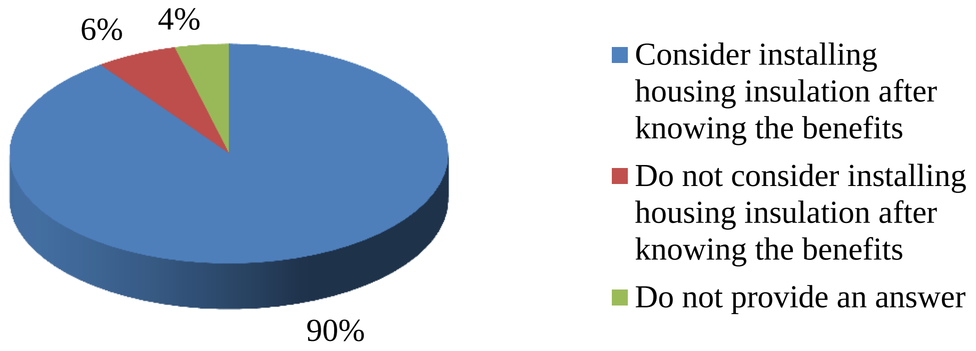
8. Feedback for Question 8: Percentages of respondents based on level of understanding on insulation



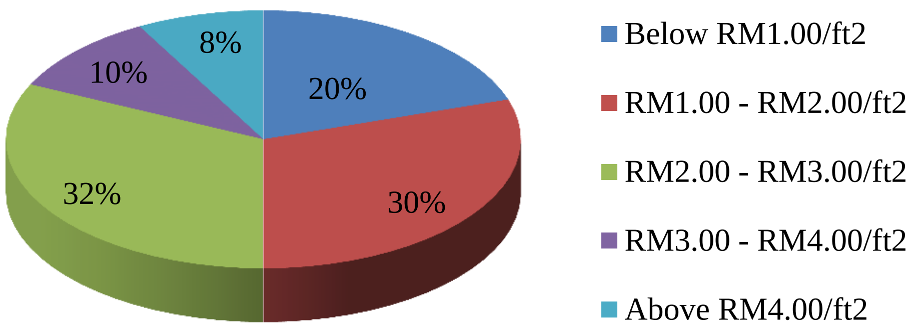
9. Feedback for Question 9: Percentages of respondents who know about insulation based on source of knowledge



10. Feedback for Question 10: Percentages of respondents based on acceptance level on housing insulation after knowing the benefits



11. Feedback for Question 11: Percentages of respondents based on the amount of money they are willing to spend to install housing insulation



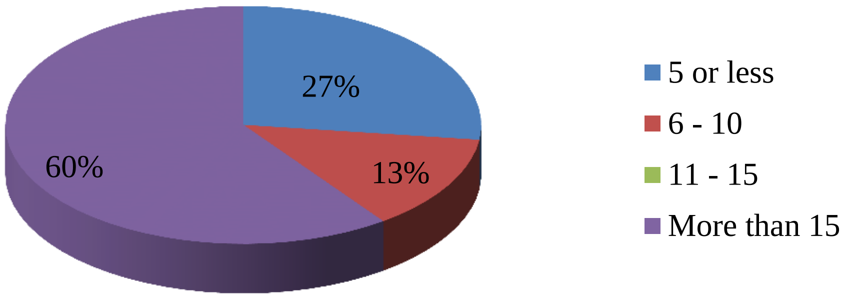
APPENDIX F: RESULTS FROM QUESTIONNAIRE FOR DEVELOPERS

1. Feedback for Part 1: Company Profile

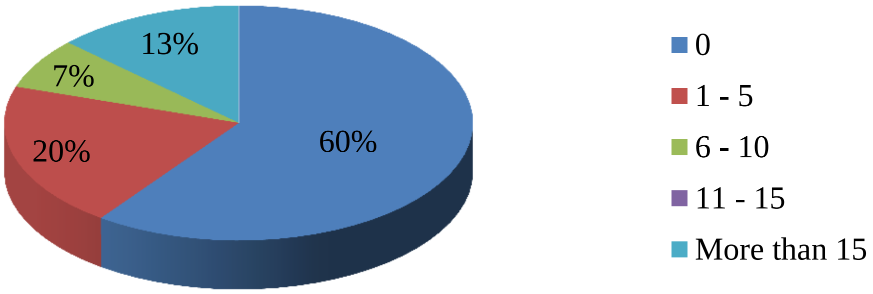
Respondents were mostly project managers or project directors of their company.

2. Feedback for Part 2: Survey on Completed Projects

2.1. Feedback for Question 1: Percentages of respondents based on the amount of residential projects completed in the last 20 years



2.2. Feedback for Question 2: Percentages of respondents based on the amount of residential projects completed in the last 20 years with insulation



2.3. Feedback for Question 3: Preference of insulation methods

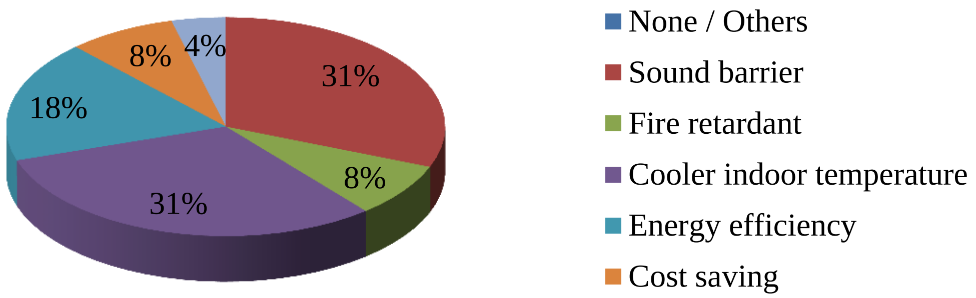
The most preferred insulation methods are blanket and loose-fill types. Preference towards particular insulation methods is due to ease of installation, economic feasibility and request of the architect.

2.4. Feedback for Question 4: Preference of insulation materials

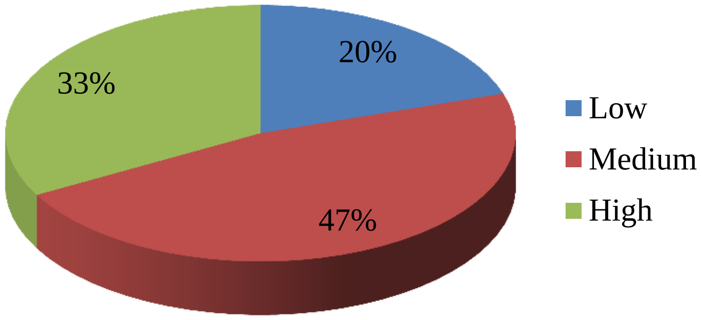
According to respondents, typical insulation materials used are mineral wools and radiant barriers. Preference towards particular insulation materials is due to economic feasibility and insulation effectiveness.

3. Feedback for Part 3: Opinion Survey

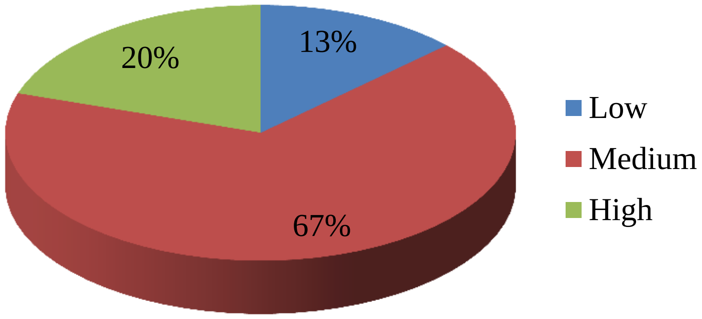
3.1. Feedback for Question 5: Percentages of respondents based on perceived benefits of insulation



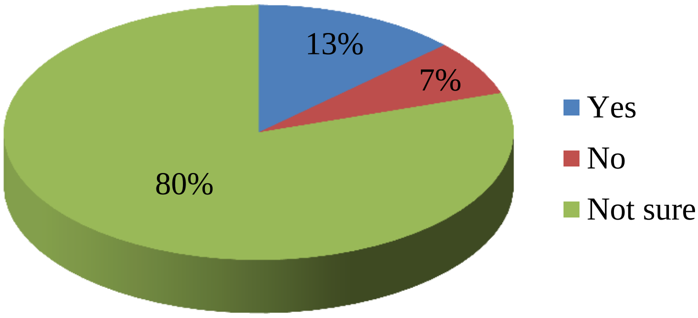
3.2. Feedback for Question 6: Percentages of respondents based on perception on the level of knowledge/understanding towards usage of insulation by architects, engineers, clients and government/approving authorities



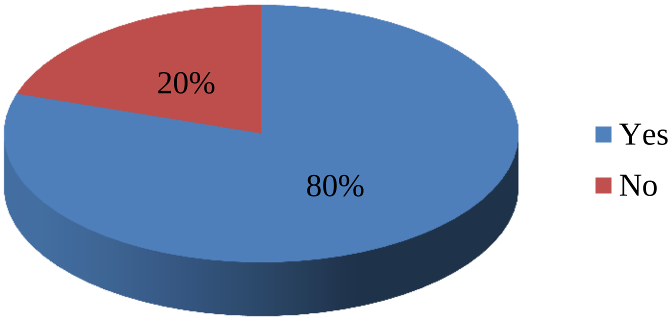
3.3. Feedback for Question 7: Percentages of respondents based on perception on the level of acceptance towards usage of insulation by architects, engineers, clients and government/approving authorities



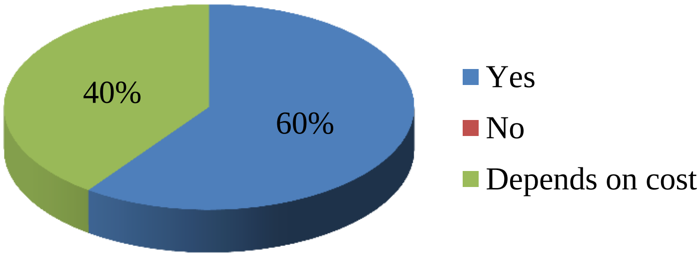
3.4. Feedback for Question 8: Percentages of respondents based on perception on the sufficiency of insulation manufacturers in Malaysia



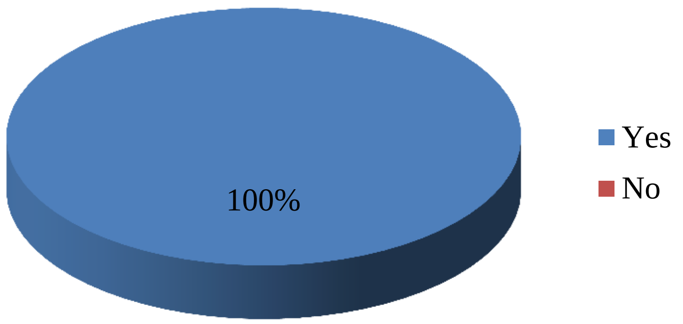
3.5. Feedback for Question 9: Percentages of respondents based on willingness to consider using insulation in future construction projects



3.6. Feedback for Question 10: Percentages of respondents based on willingness to consider using insulation in particular projects if there is a request from the architect



3.7. Feedback for Question 11: Percentages of respondents based on willingness to consider using insulation in whole projects if there is demand on good quality insulation from client/potential house buyers



3.8. Feedback for Question 12: Percentages of respondents based on price range acceptable / reasonable to adopt housing insulation

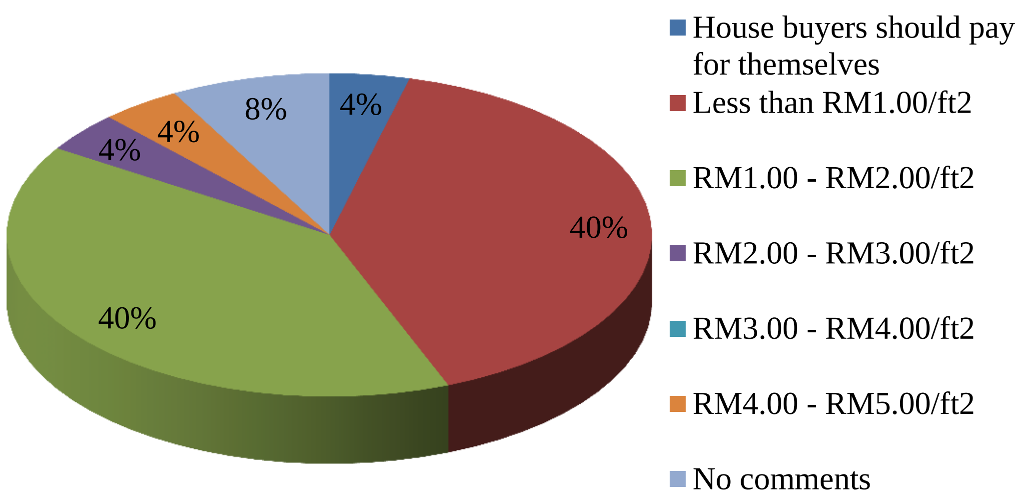
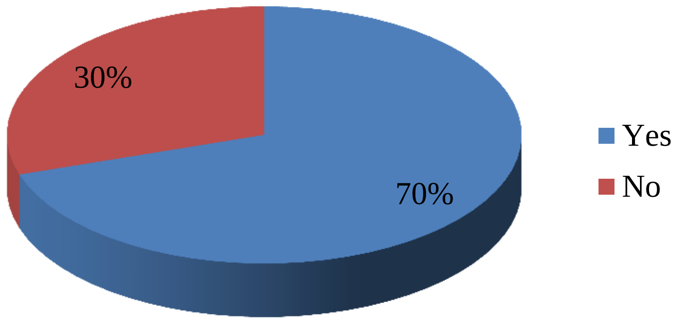
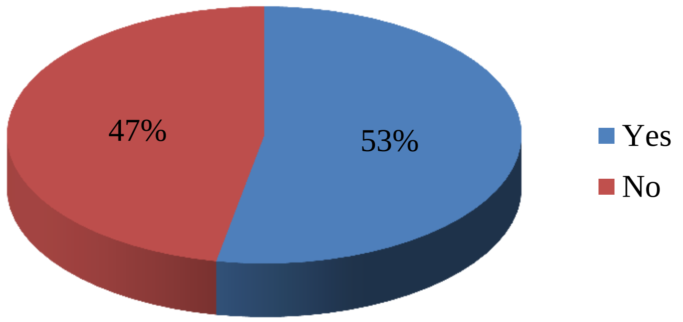


Figure 4.20: Percentages of respondents based on price range acceptable / reasonable to adopt housing insulation

3.8. Feedback for Question 13: Percentages of respondents based on willingness to adopt insulation after knowing the benefits even without legal requirement



3.9. Feedback for Question 14: Percentages of respondents based on willingness to consider using insulation as a gimmick in promoting projects



APPENDIX G: MONTHLY AVERAGE AND MAXIMUM TEMPERATURES FOR KUALA LUMPUR

Month	**Temperature (°C)**	
	Average	*Maximum*
January	26.80	33.00
February	27.00	33.00
March	27.40	34.00
April	27.50	34.00
May	27.60	34.00
June	27.80	34.20
July	27.30	35.80
August	27.00	32.70
September	27.10	33.90
October	26.70	33.70
November	26.70	32.60
December	26.40	33.00

APPENDIX H: PRICED QUOTATIONS OF INSULATION

1. EPS

PULAI PACKAGING INDUSTRIES SDN BHD (115073-W)
No.6, SOLOK RISHAH 3, KWS PERINDUSTRIAN SILIBIN
30100 IPOH, PERAK DARUL RIDZUAN.
Tel : 05-5261152, 5264443 Fax : 05-5272291
Email add : pulaipkg@streamyx.com

FAX MESSAGE

TO : Mr Syed Farhan (017-7060946) DATE : 10-4-2013

ATTN : REF : PPI/131

FAX : FROM : MS CHIN

Re : Quotation

We are pleased to quote you as follows :-

Item	Description	Price (RM)
01	4' x 8' x 1" EPS	11.00 per pc

Terms : Cash.
Remarks : Price subject to change without prior notice.

Thanks & Regards,

MSCHIN

2. FIBREGLASS

POLY GLASS FIBRE™ Insulation

Attn : Syed Ahmad Farhan

Email : syfarisk@gmail.com

Ref : MKTG/4046/Q
Date : 08/04/2013
Page : 1 of 1

Dear Sir,

Re: Quotation

Thanks for your enquiry hereby we append our best price for your perusal.

ECOWOOL Glasswool Blanket

Item	Code	Thickness (mm)	Width (m)	Length (m)	Ex-Factory Price Price/roll
1	EBWL 1.35	50	1.22	15	RM 103.00
2	EWBL 1.45	50	1.22	12	RM 124.00

BROWNIE Slab

Item	Code	Thickness (mm)	Width (m)	Length (m)	Ex-Factory Price Price/piece
1	BROWNIE 1.50	50	0.6	1.2	RM 7.60

Remark: 6pcs per pack

Terms & Conditions:

1) The above quoted prices are ex-factory prices.
2) Payment Term: **Cash before delivery**
3) Validity of offer: 08/05/2013
4) Validity of delivery: 08/06/2013
5) Transportation cost to Ipoh for ECOWOOL Blanket RM 4.00/roll (minimum delivery is 63 rolls)
   Transportation cost to Ipoh for BROWNIE Slab RM 5.40/pack (minimum 45 packs)
6) The receipt of Purchase Order constitutes the acceptance of our Terms and Conditions of Sales.
   A copy of our Terms and Conditions of Sales is available upon request.

Thanks and Regards,

I-Lein, Lim
Assistant Manager - Marketing

PGF Insulation Sdn. Bhd. (228905-M)
No. 2449, Lorong Perusahaan Sepuluh, Kawasan Perusahaan Perai, 13600 Perai, Penang, Malaysia.
Tel: +604-3908460
Fax: +604-3996197
E-mail: mail@polyglass.com.my
www.polyglass.com.my

3. CELLULOSE

TCL RESOURCES SDN BHD

Date : 11/4/13 Appendix 'A'

QUOTATION FOR SUPPLY OR SUPPLY AND INSTALL CELLULOSE INSULATION FOR HOME THERMAL INSULATION

Item	Description	Unit	Quantity	Rate	Amount
	HOME THERMAL INSULATION WITH CELLULOSE INSULATION				
1.	Preliminaries / Mobilisation and demobilisation of "Krendle" Fibre Moving Equipment	Sum			
2.	Supply and install 4" thick Incide PC Cellulose Insulation on top of existing ceiling (1st Floor Only)	FS		$3.50	
3.	Allow for making upstand support using galvanised zinc sheet beside downlights and seal gaps at ceiling	No		$10.00	
	Remarks : a. Mobilisation cost depends on location of property b. Unit rate for supply and install is indicative rate and subject to total areas involved				
	SUPPLY OF CELLULOSE INSULATION				
1.	Supply of cellulose insulation (11 kg / Bag)	Bag		$100.00	
2.	Supply of loosen cellulose insulation (5.5 Kg / Bag)	Bag		$75.00	
	Remarks : a. Cellulose need to be loosen before installation. b. Installation requires fiber moving machine eitherwise the cellulose need to be loosened if installation were by labour c. Coverage per bag base on 4" thick is approximately 50FS (Installation using machine)				

4. ROCK WOOL

Home Insulation - CoolBatts

From: "Majumec Bina" <majumecbina@yahoo.com>

To: "Farhan Iskandar" <syfarisk@yahoo.com>

5 Files (6037KB)

Cool Batt 1 Cool Batt 2 Cool Batt 3 Cool Batt 4 Cool Batt 5

Dear Farhan,

We attach herewith some catalogue for your information.

Coolbatt size: 1 roll = 2ft x 8ft, thickness: 2", Density: 40kg/m3, selling price: RM2.40/sqft (supply only), ie.1 roll = 16sq/ft x 2.40= RM38.40.

For an area of 150 sqm or around 500 sqft you need about 31 rolls of coolbatts.
31 rolls x 38.40 = RM1190.40.

Regards

Ong LS
Majumec Bina Sdn Bhd
No.31-2 Jalan Cempaka SD 12/2, Bandar Sri Damansara, 52200 Kuala Lumpur.
Tel: 03 - 6273 1229. Fax: 03 - 6272 9929. Email:majumecbina@yahoo.com

5. ENR

quotation

From: "Jared" <jaredwoo@insulflex.com.my>
To: "Farhan Iskandar" <syfarisk@yahoo.com>
Cc: "June Lee" <junelee@insulflex.com.my>, "mazna" <mazna@insulflex.com.my>

Dear Mr Iskandar,

Thank you for your interest in our product.

Insulflex flat sheet foam comes in 4 ft x 3 ft from 3 mm thickness to 38 mm tk. We recommend you to use 2 pieces of 25 mm (1" tk) joint together to form 50 mm (2" tk).

Insulflex closed cell sheet

Size : 1" tk x 4 ft x 3 ft
Price Per Piece : RM98.84
Quantity Per Carton : 10 Pcs
Price Per Carton : RM989.40

Insulflex Adhesive
Price Per 800 ML : RM18.50
Quantity Per Carton : 24 Tin
Price Per Carton : RM444.00

Term and Conditions:-

1. Payment Term : By cash before delivery

2.. Delivery : Own collection . Transport fee shall be charged for any delivery arrangement requested.

3. Price Validity : 30 days from date hereof.

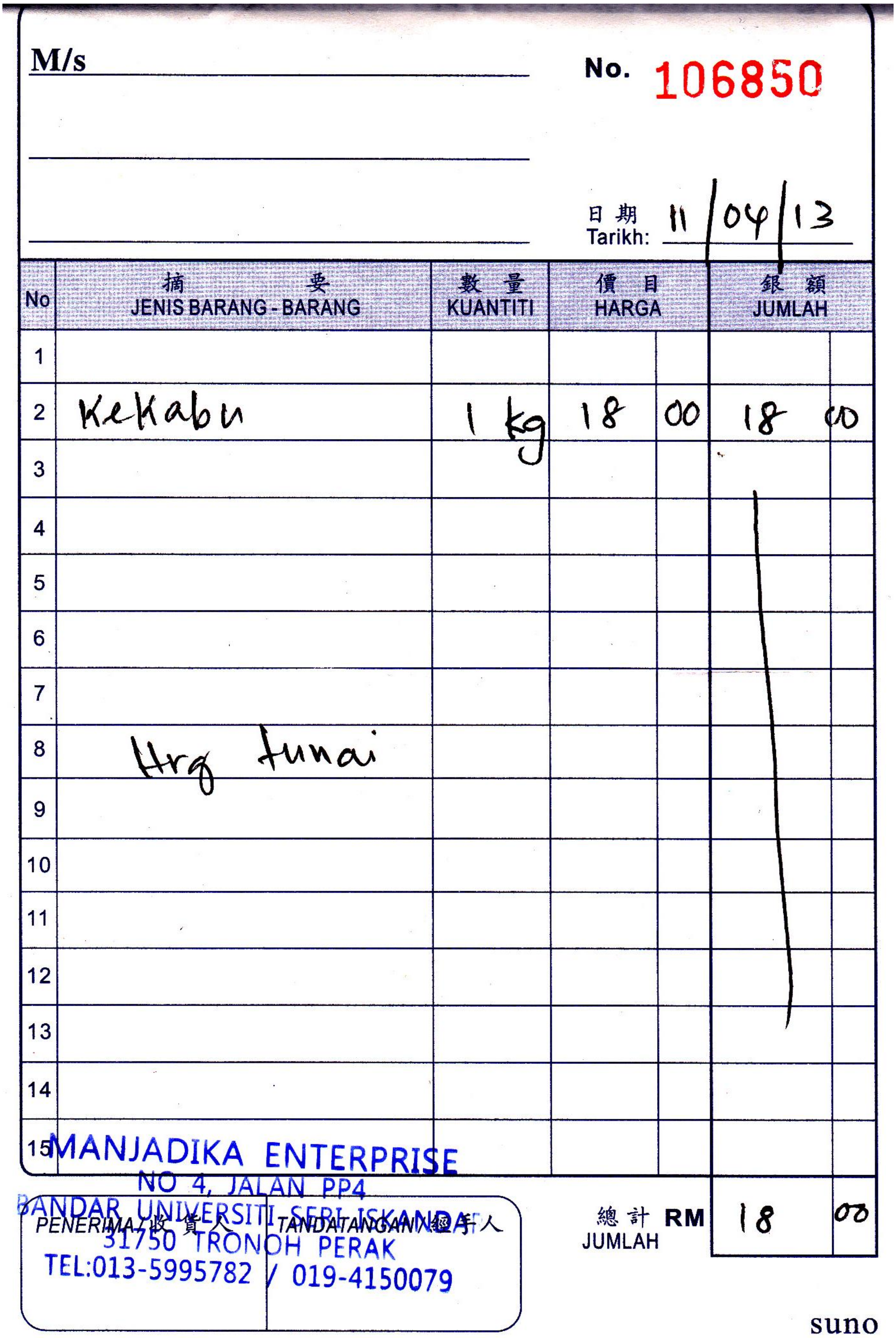
We trust that our offer are reasonable to you and we look forward to you favorable response.

Thank you

Jared

Size : 1" tk x 4 ft x 3 ft
Price Per Piece : RM98.84

6. KAPOK FIBRE



M/s

No. 106850

日期 Tarikh: 11/04/13

No	摘要 JENIS BARANG - BARANG	數量 KUANTITI	價目 HARGA		銀額 JUMLAH	
1						
2	Kekabu	1 kg	18	00	18	00
3						
4						
5						
6						
7						
8	Hrg tunai					
9						
10						
11						
12						
13						
14						
15						
			總計 JUMLAH RM		18	00

MANJADIKA ENTERPRISE
NO 4, JALAN PP4
BANDAR UNIVERSITI SERI ISKANDAR
31750 TRONOH PERAK
TEL:013-5995782 / 019-4150079

PENERIMA/收貨人 TANDATANGAN/經手人

suno

APPENDIX I: CALCULATION OF COST RATES TO SUPPLY AND INSTALL INSULATION

1. Cost Rate to Supply Expanded Polystyrene

The price of a piece of EPS with dimension of 8-ft length by 4-ft width by 1-in thickness is RM11.00. Therefore, cost rate to supply EPS can be calculated as follows:

$$C_{supply-EPS} = RM11.00 \div \left(8\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(4\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(1\,in \times \frac{0.02540\,m}{1\,in}\right) = RM145.67/m^3$$

2. Cost Rate to Supply Fibreglass

The price of a roll of fibreglass of type EBWL 1.35 with dimension of 15-m length by 1.22-m width by 50-mm thickness is RM103.00. Therefore, cost rate to supply fibreglass of type EBWL 1.35 can be calculated as follows:

$$C_{supply-fibreglass} = RM103.00 \div 15\,m \div 1.22\,m \div \left(50\,mm \times \frac{1\,m}{1000\,mm}\right) = RM112.57/m^3$$

The price of a roll of fibreglass of type EBWL 1.45 with dimension of 12-m length by 1.22-m width by 50-mm thickness is RM124.00. Therefore, cost rate to supply fibreglass of type EBWL 1.45 can be calculated as follows:

$$C_{supply-fibreglass} = RM124.00 \div 12\,m \div 1.22\,m \div \left(50\,mm \times \frac{1\,m}{1000\,mm}\right) = RM169.40/m^3$$

The price of a piece of fibreglass of type BROWNIE 1.50 with dimension of 1.2-m length by 0.6-m width by 50-mm thickness is RM7.60. Therefore, cost rate to supply fibreglass of type BROWNIE 1.50 can be calculated as follows:

$$C_{supply-fibreglass} = RM7.60 \div 1.2\ m \div 0.6\ m \div \left(50\ mm \times \frac{1\ m}{1000\ mm}\right)$$
$$= RM211.11/m^3$$

The cost rate to supply fibreglass can be estimated by taking the average cost rate of EBWL 1.35, EBWL 1.45 and BROWNIE 1.50

$$C_{supply-fibreglass} = \frac{RM112.57/m^3 + RM169.40/m^3 + RM211.11/m^3}{3}$$
$$= RM164.36/m^3$$

3. Cost Rate to Supply Cellulose

The price of a bag of loosened cellulose that can cover an area of 50 ft^2 at 4-in thickness is RM75.00. Therefore, cost rate to supply cellulose can be calculated as follows:

$$C_{supply-cellulose} = RM75.00 \div \left(50\ ft^2 \times \frac{0.09290\ m^2}{1\ ft^2}\right) \div \left(4\ in \times \frac{0.02540\ m}{1\ in}\right)$$
$$= RM158.92/m^3$$

4. Cost Rate to Supply Rock Wool

The price of a roll of rock wool with dimension of 8-ft length by 2-ft width by 2-in thickness is RM38.40. Therefore, cost rate to supply rock wool can be calculated as follows:

$$C_{supply-rock\,wool} = RM38.40 \div \left(8\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(2\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(2\,in \times \frac{0.02540\,m}{1\,in}\right) = RM503.53/m^3$$

5. Cost Rate to Supply Elastomeric Nitrile Rubber

The price of a sheet of ENR with dimension of 4-ft length by 3-ft width by 1-in thickness is RM98.84. Therefore, cost rate to supply ENR can be calculated as follows:

$$C_{supply-rubber} = RM98.84 \div \left(4\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(3\,ft \times \frac{0.3048\,m}{1\,ft}\right) \div \left(1\,in \times \frac{0.02540\,m}{1\,in}\right) = RM3490.50/m^3$$

6. Cost Rate to Supply Kapok Fibre

The price of 1 kg of kapok is RM18.00. In [70], samples of kapok with apparent bulk densities of 6.66 kg/m^3, 13.73 kg/m^3 and 16.66 kg/m^3 were used. With reference to this study, for this calculation, the density of kapok is assumed to be 10 kg/m^3 to simplify calculation. Therefore, cost rate to supply kapok can be estimated as follows:

$$C_{supply-kapok\,fibre} = \frac{RM18.00}{1\,kg} \times \frac{10\,kg}{1\,m^3} = RM180.00/m^3$$

7. Cost Rate to Supply Reinforced Aerogel

The price of a reinforced aerogel product called Spaceloft® by Aspen Aerogels, Inc. from Northborough, MA, US is \$4000/m^3 as in November 2008 [62]. However, the price of aerogel is expected to reduce by 80% - 90% in the near future due to breakthroughs of ongoing researches on alternative manufacturing processes of aerogel [119-121]. Taking the potential reduction in the price of aerogel into consideration, the assumed cost rate of reinforced aerogel used for calculation is reduced by 50% as follows:

$$C_{supply-reinforced\ aerogel} = \frac{\$4000}{1\ m^3} \times \frac{RM3}{\$1} \times \frac{1}{2} = RM6000/m^3$$

8. Cost Rate to Install Insulation

The cost rate to install insulation depends on the area and method of installation and not on the type of insulation material installed. Therefore, only one insulation material, which is cellulose, is chosen to determine the cost rate to install insulation. The cost of supplying and installing 4-in thick cellulose insulation is RM3.50/ft^2. Therefore, the cost rate of supplying and installing cellulose insulation is as follows:

$$C_{supplyandinstall-cellulose} = \left(\frac{RM3.50}{1\ ft^2} \times \frac{1\ ft^2}{0.09290\ m^2}\right) = RM37.67/m^2$$

The cost rate to supply cellulose insulation as calculated in Section 4.5.1.3 is RM158.92/m^3. Therefore, the cost rate of installing cellulose insulation is as follows:

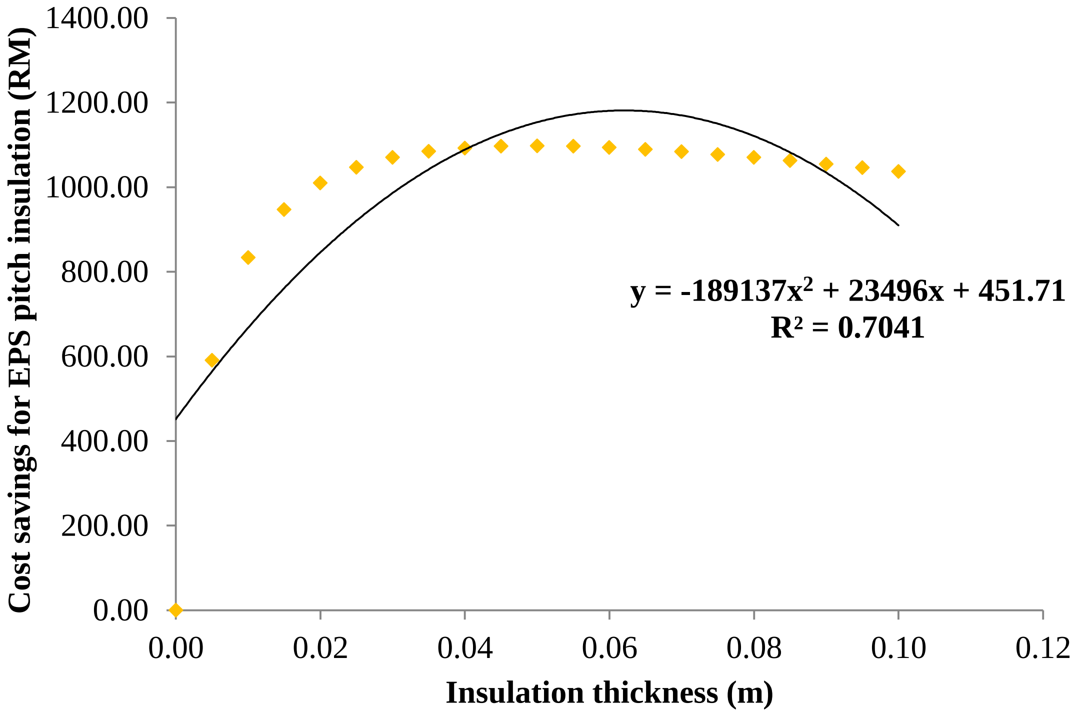
$$C_{install-cellulose} = RM37.67/m^2 - \left(\frac{\text{RM158.92}}{1\ \text{m}^3} \times 4\ in \times \frac{0.02540\ m}{1\ in}\right)$$
$$= \text{RM21.52/m}^2$$

The installation of cellulose insulation involves the use of a fibre moving machine because cellulose insulation is supplied in the form of loose fills. For insulation that is in the form of blankets, the installation process is simpler and hence, cheaper. The cost rate to supply insulation can be estimated by assuming that the cost to install insulation that is supplied in the form of blankets is 50% cheaper than the cost to install insulation that is supplied in the form of loose fills, as follows:

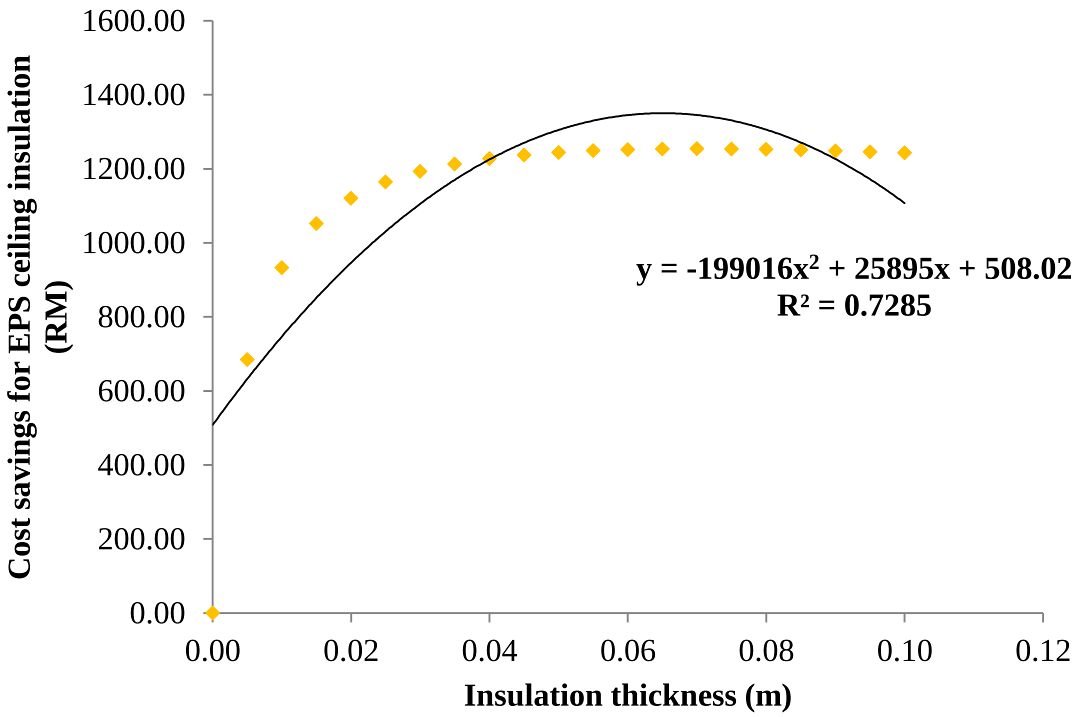
$$C_{install} = \frac{\text{RM21.52/m}^2}{2} = RM10.76/m^2$$

APPENDIX J: COST SAVINGS OF INSULATION

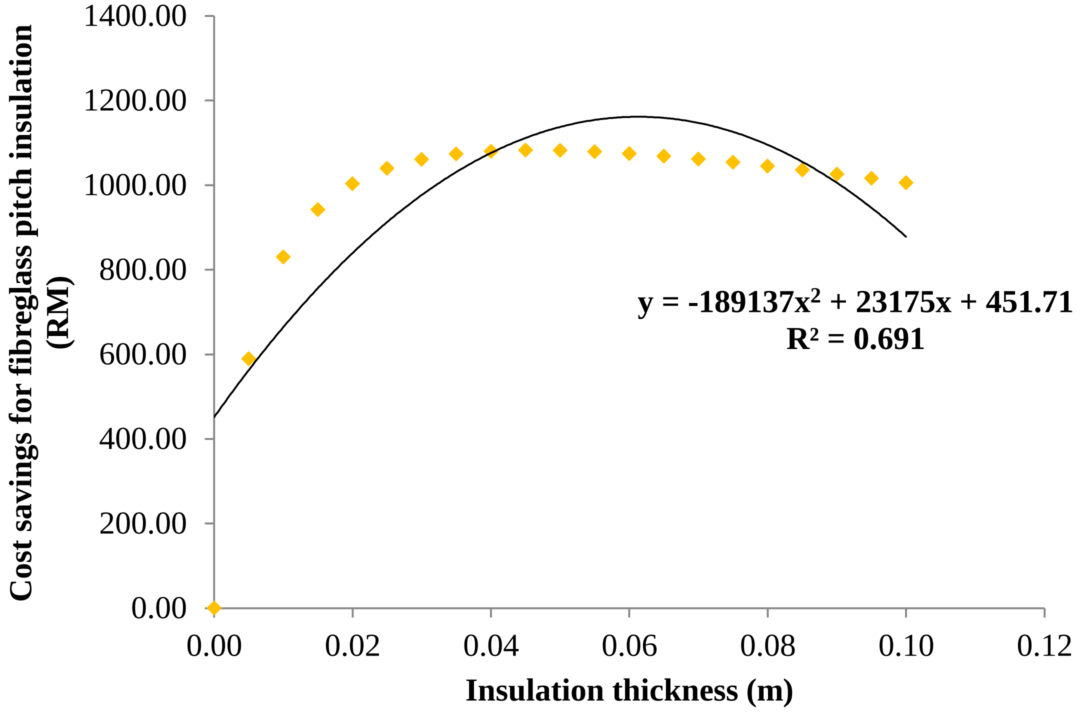
1. Cost savings for EPS pitch insulation



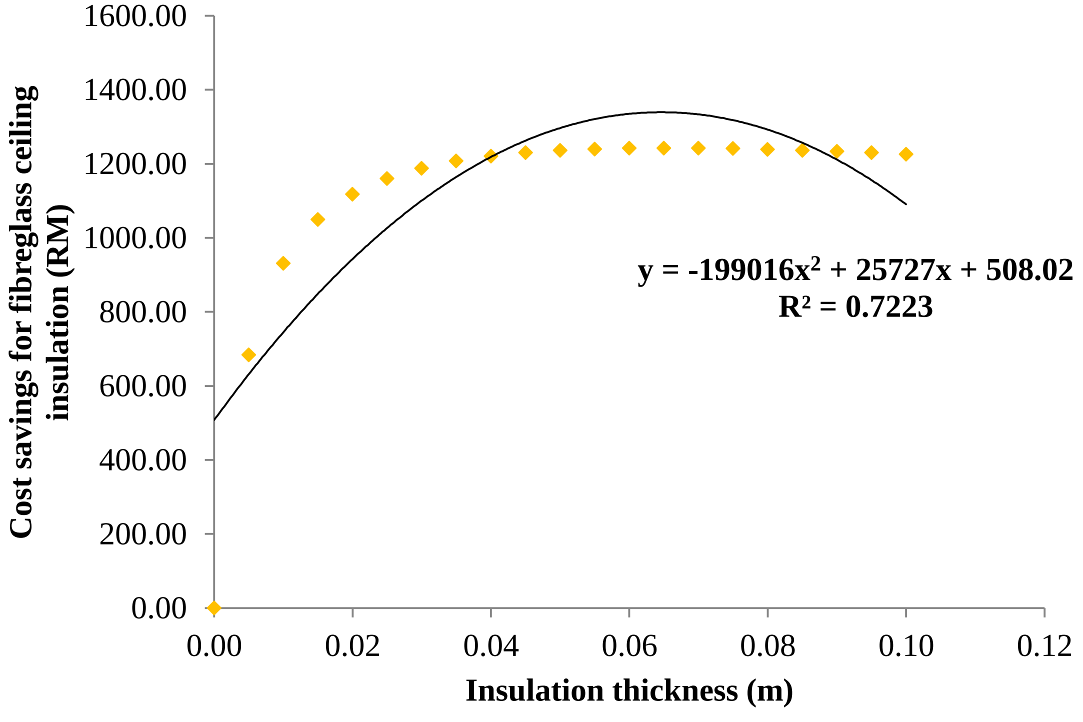
2. Cost savings for EPS ceiling insulation



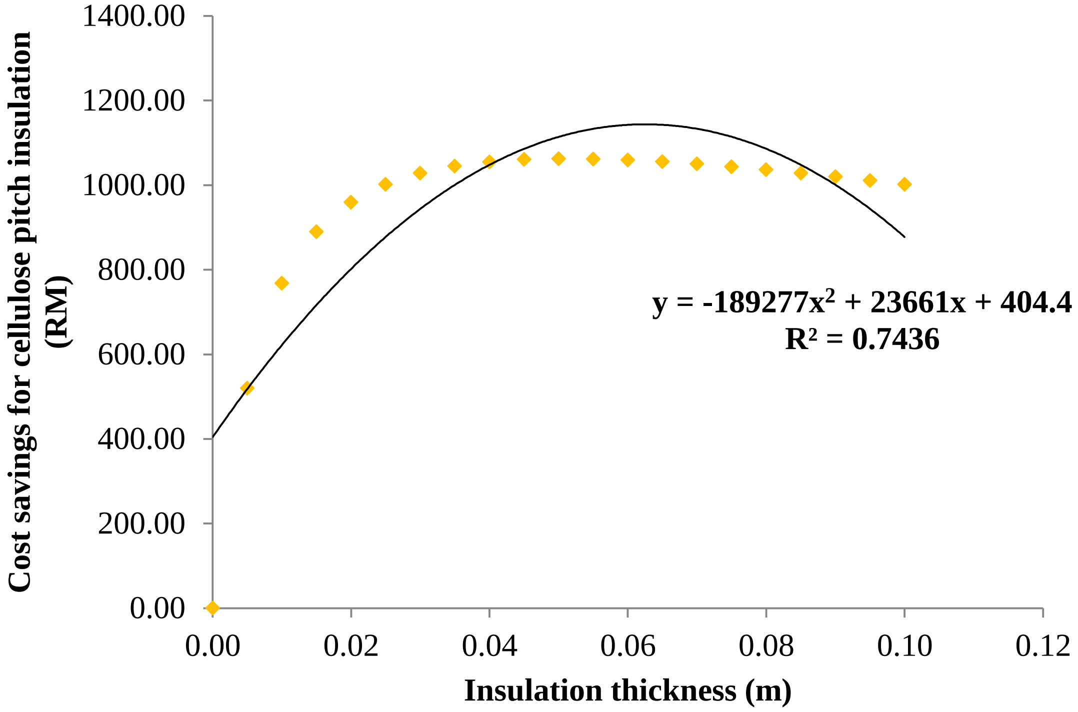
3. Cost savings for fibreglass pitch insulation



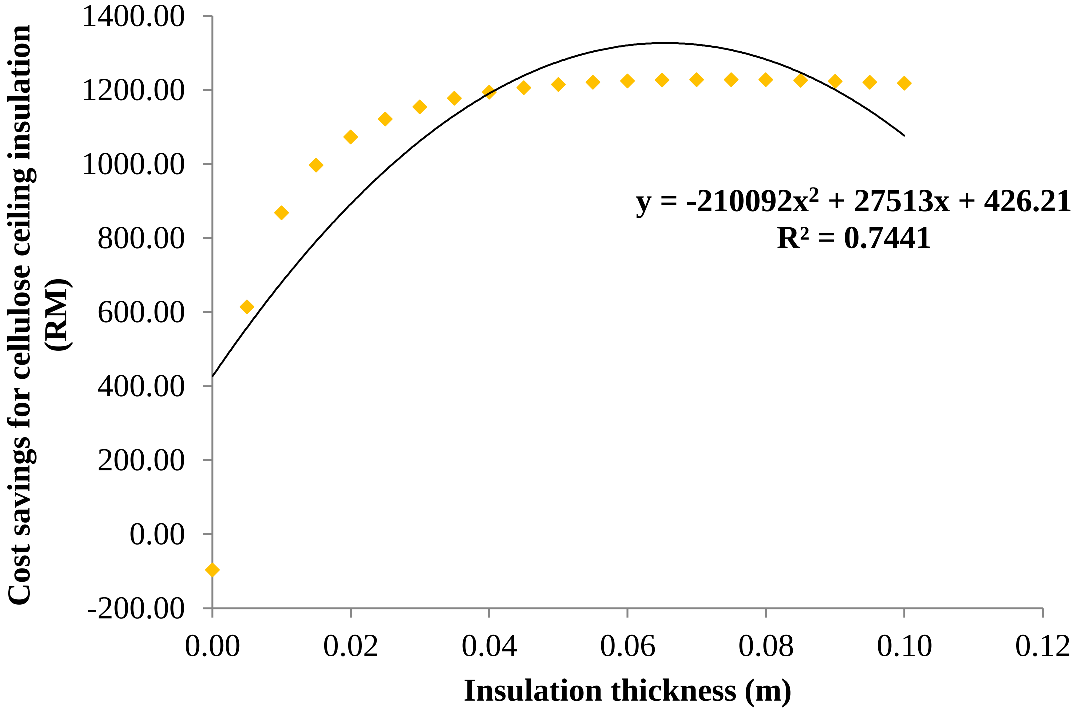
4. Cost savings for fibreglass ceiling insulation



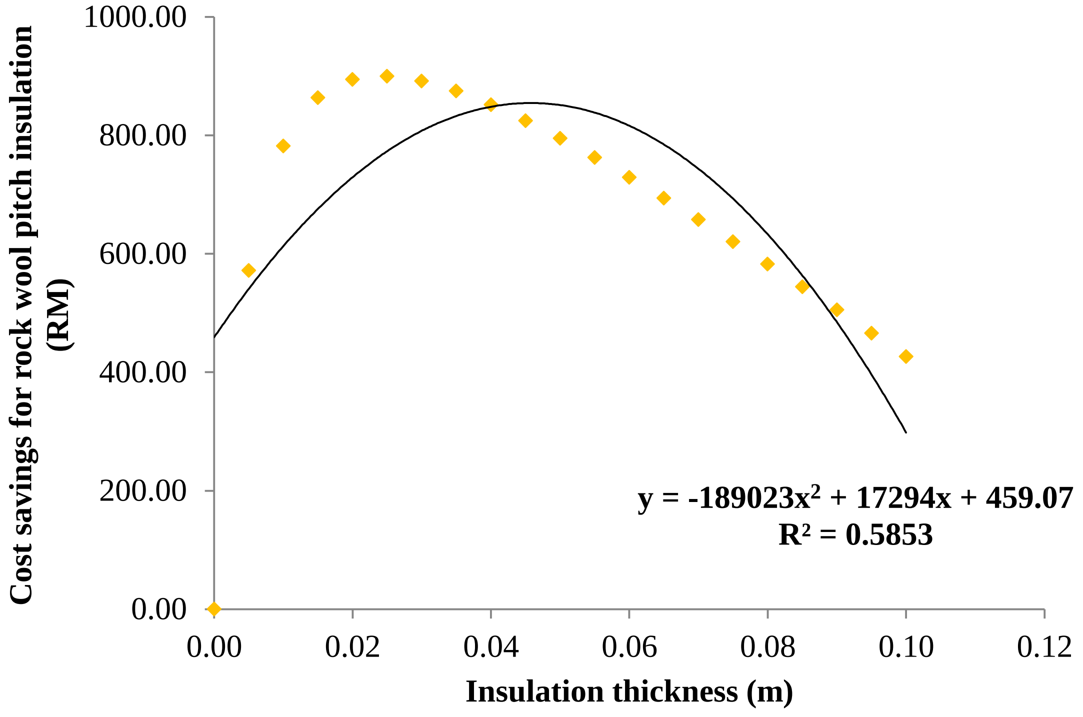
5. Cost savings for cellulose pitch insulation



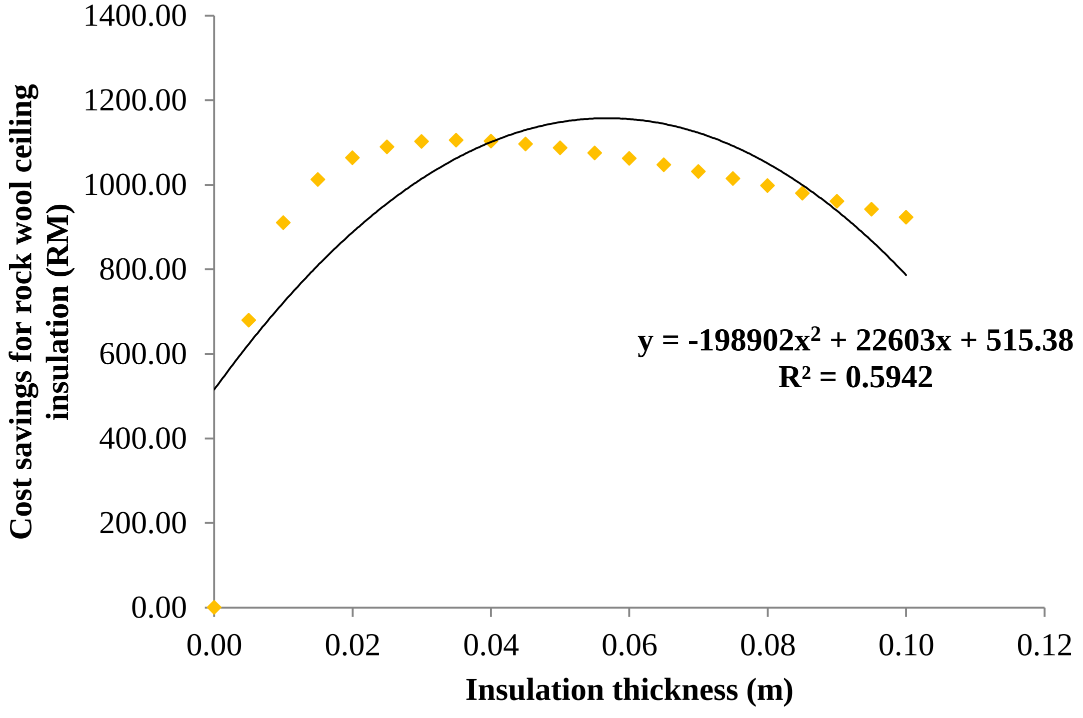
6. Cost savings for cellulose ceiling insulation



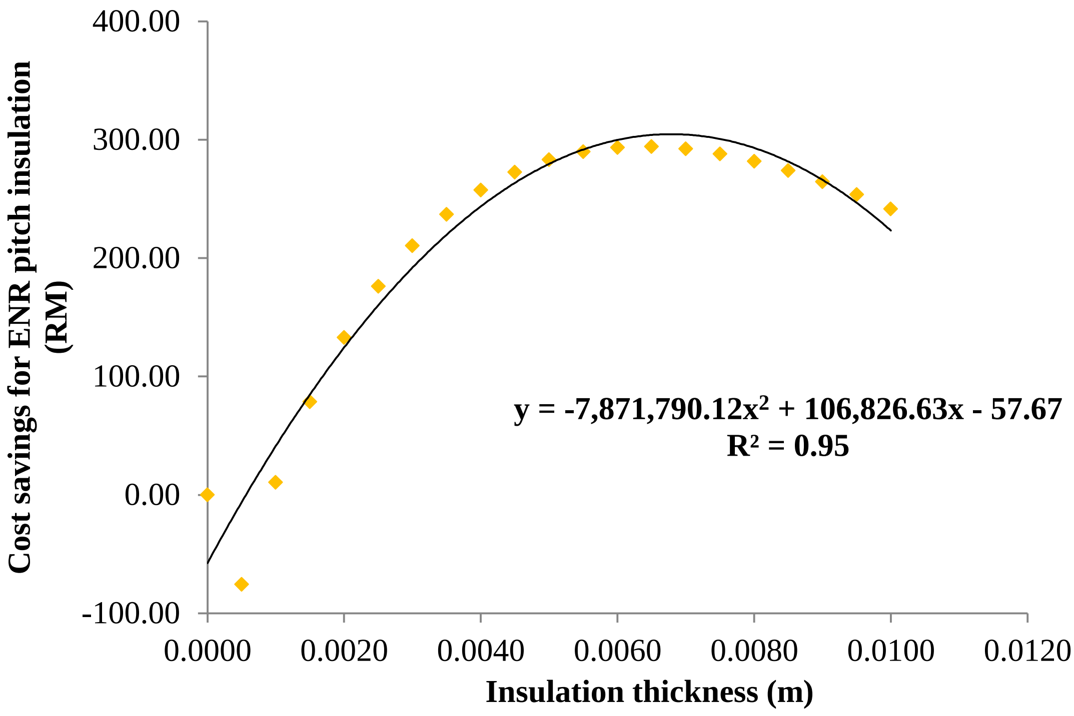
7. Cost savings for rockwool pitch insulation



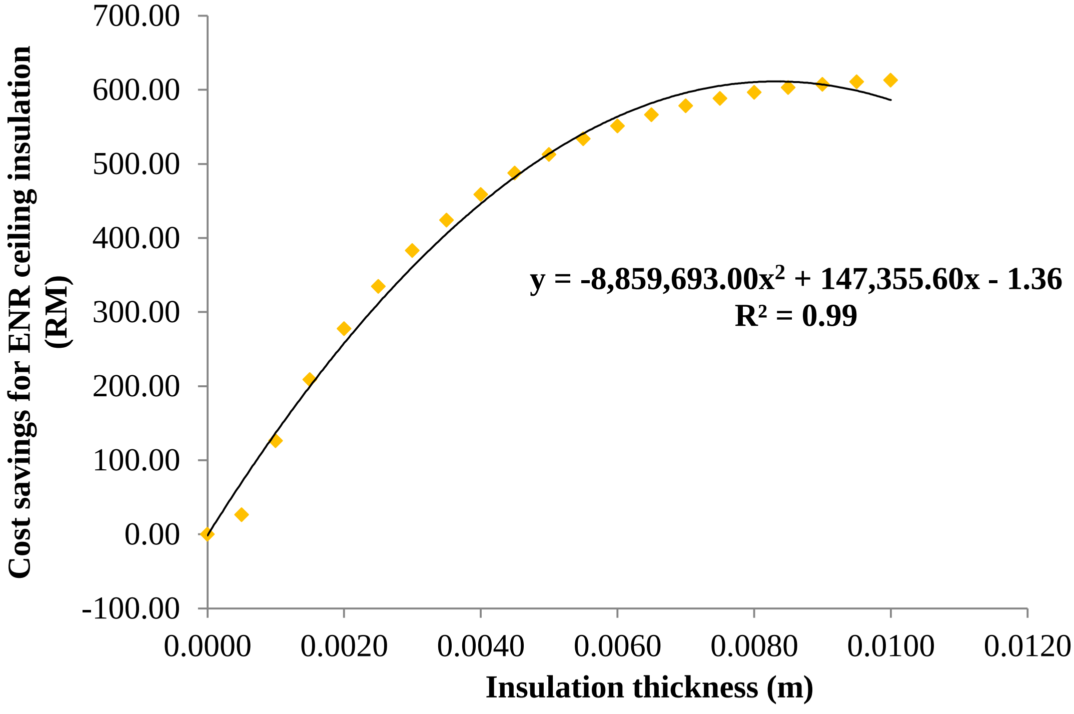
8. Cost savings for rockwool ceiling insulation



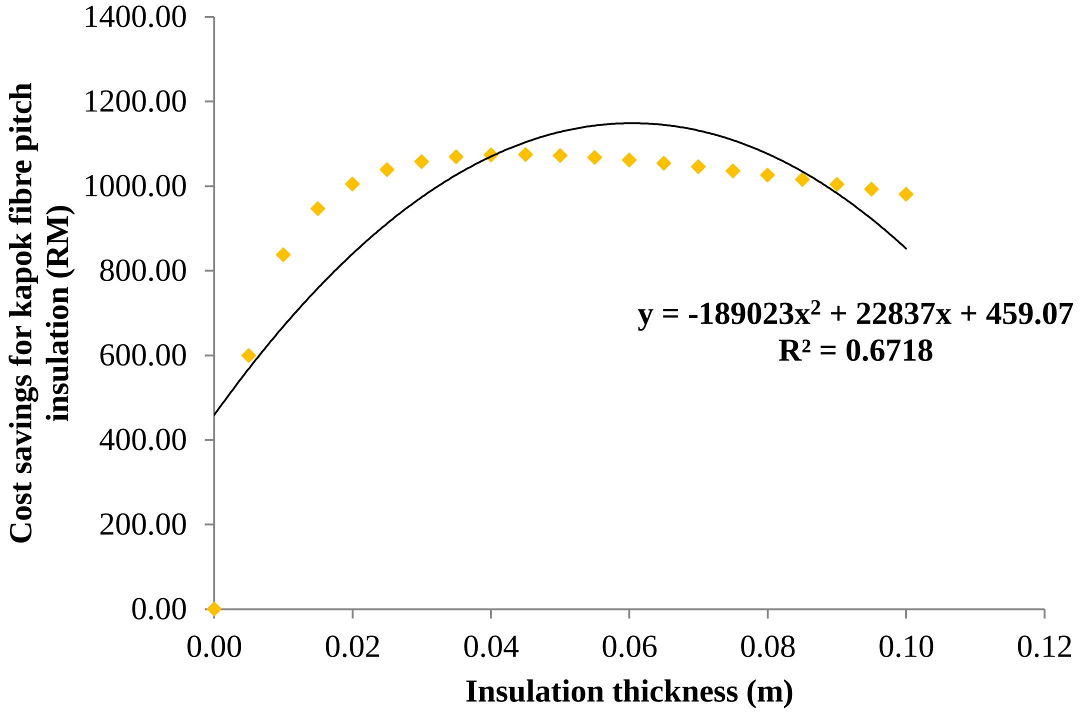
9. Cost savings for ENR pitch insulation



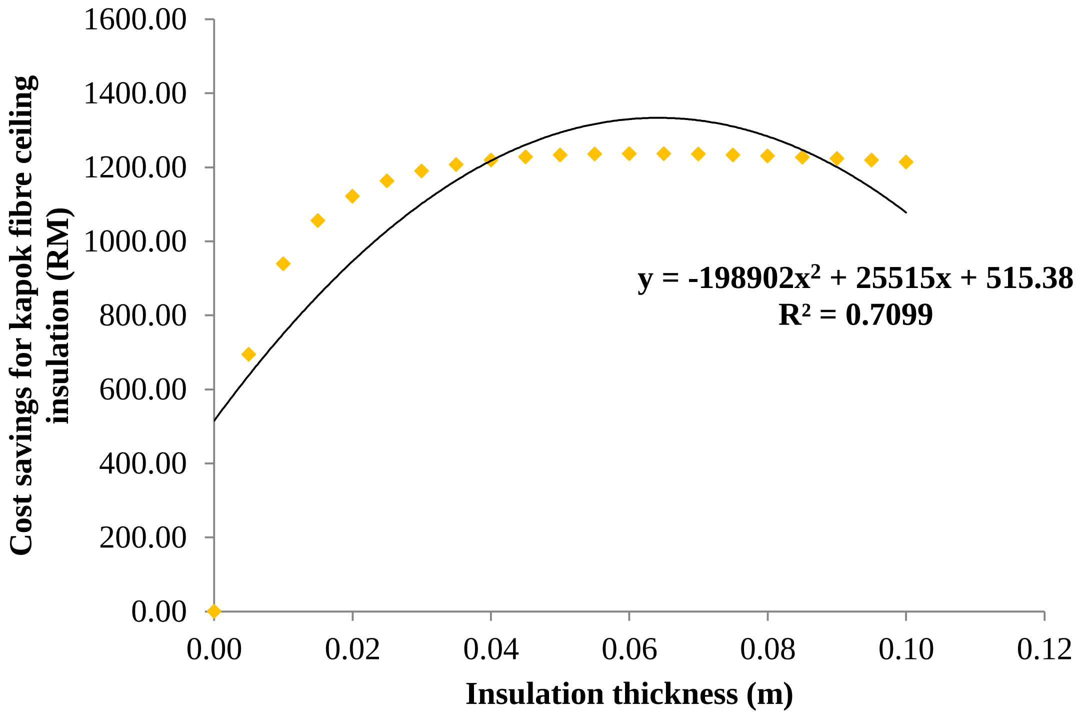
10. Cost savings for ENR ceiling insulation



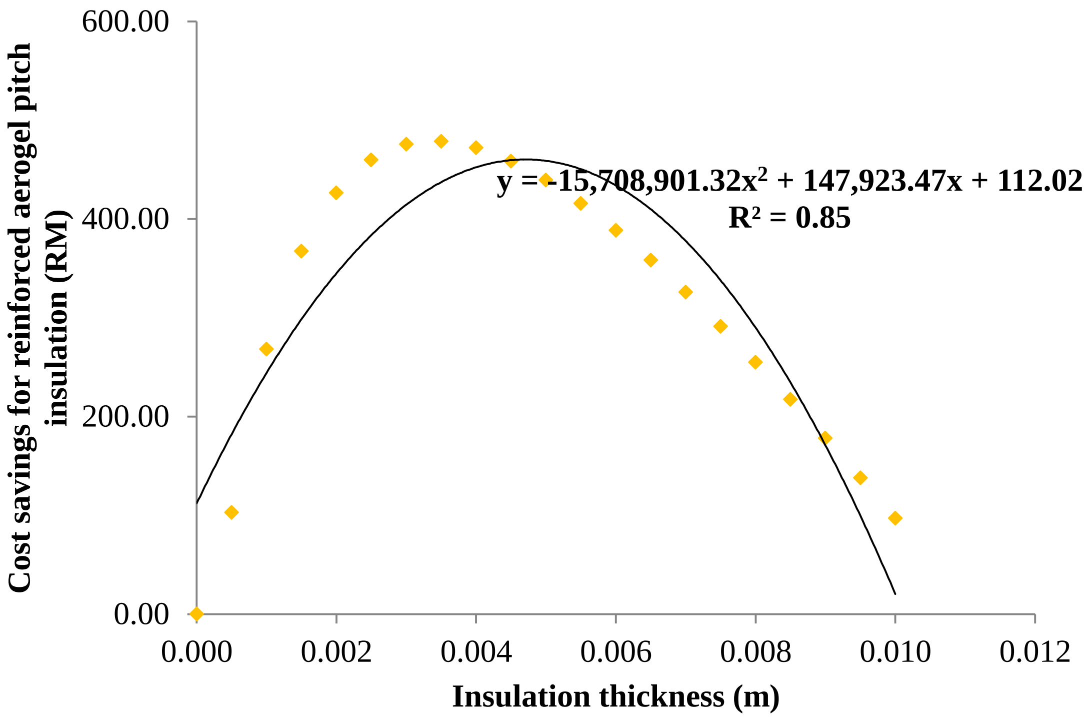
11. Cost savings for kapok fibre pitch insulation



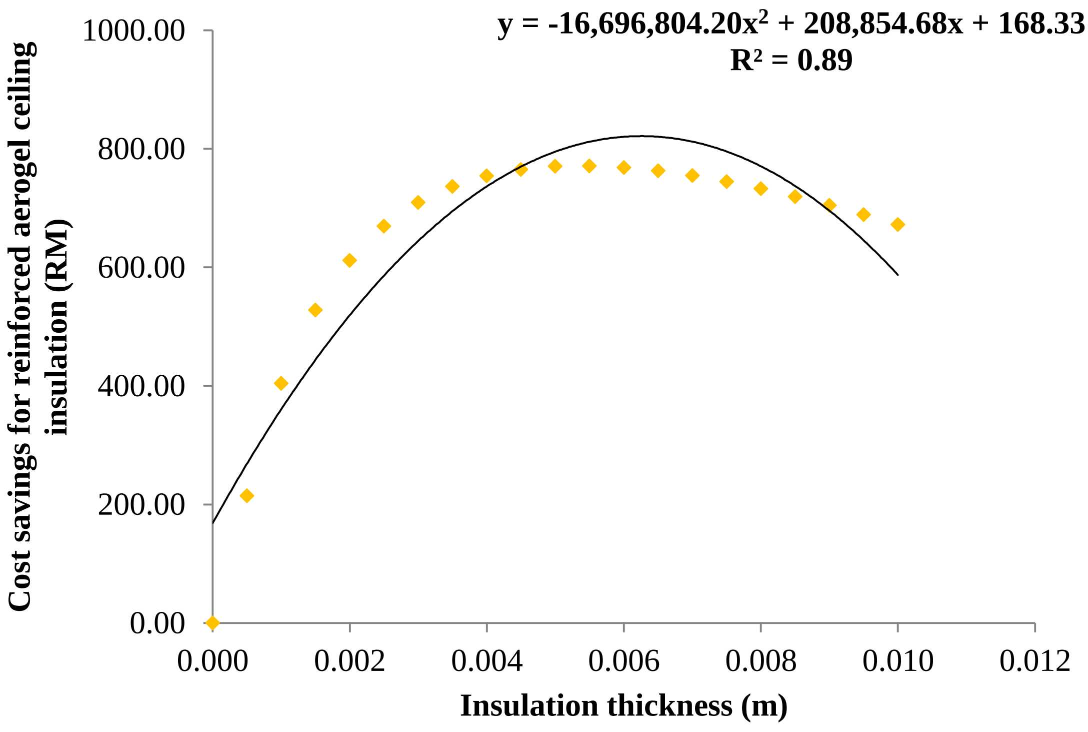
12. Cost savings for kapok fibre ceiling insulation



13. Cost savings for reinforced aerogel pitch insulation

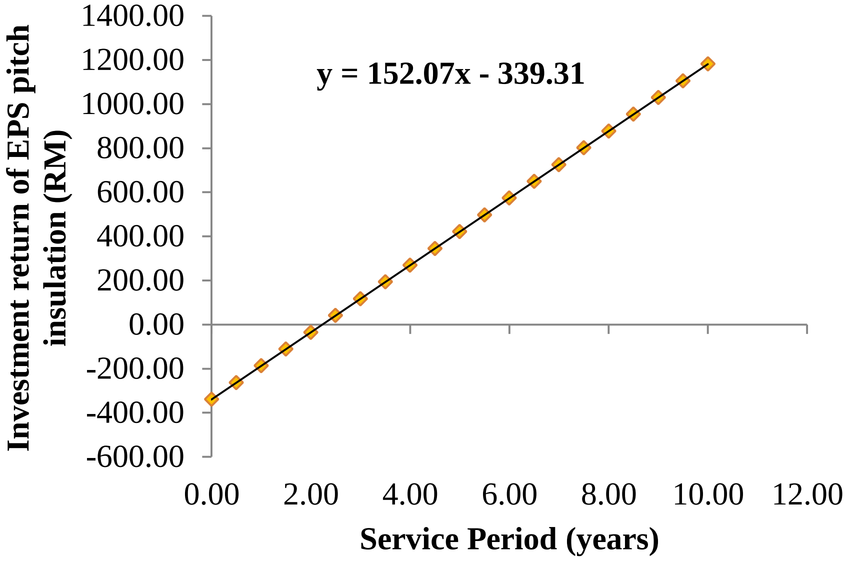


14. Cost savings for reinforced aerogel ceiling insulation

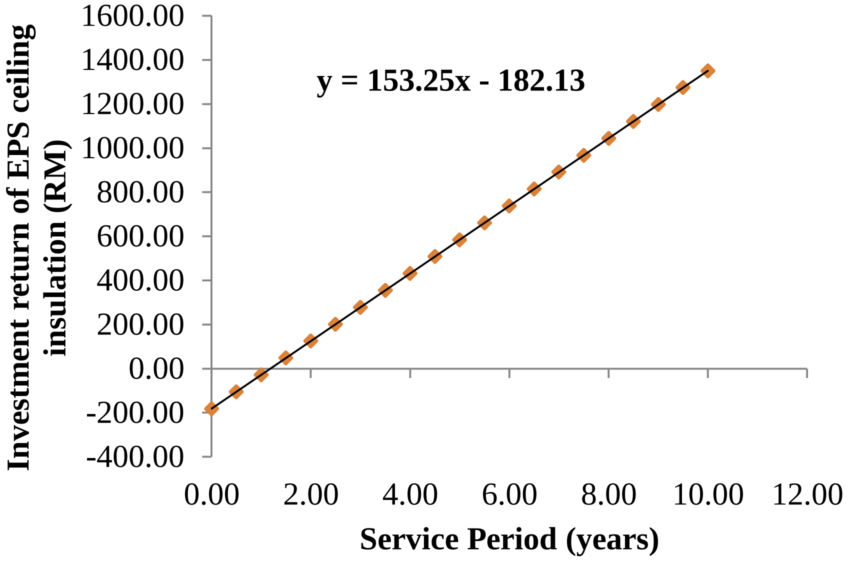


APPENDIX K: INVESTMENT RETURN OF INSULATION

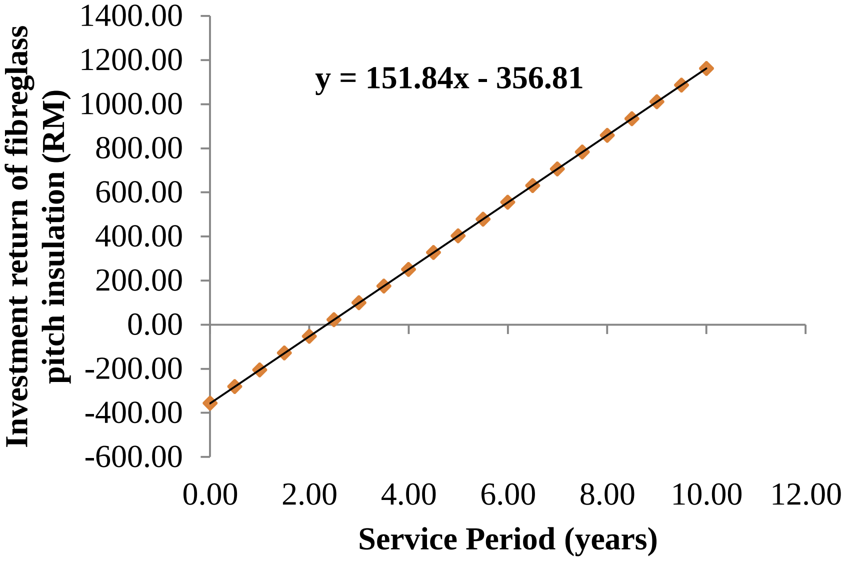
1. Investment return of EPS pitch insulation



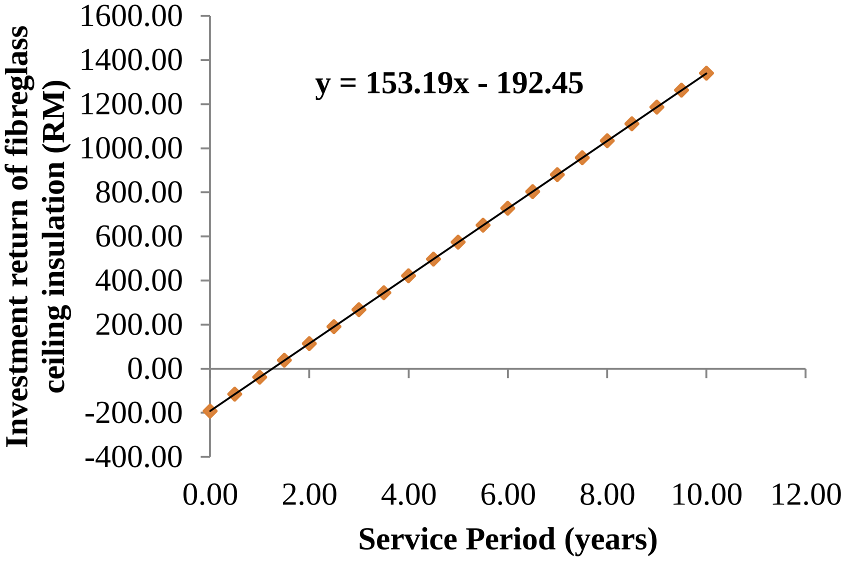
2. Investment return of EPS ceiling insulation



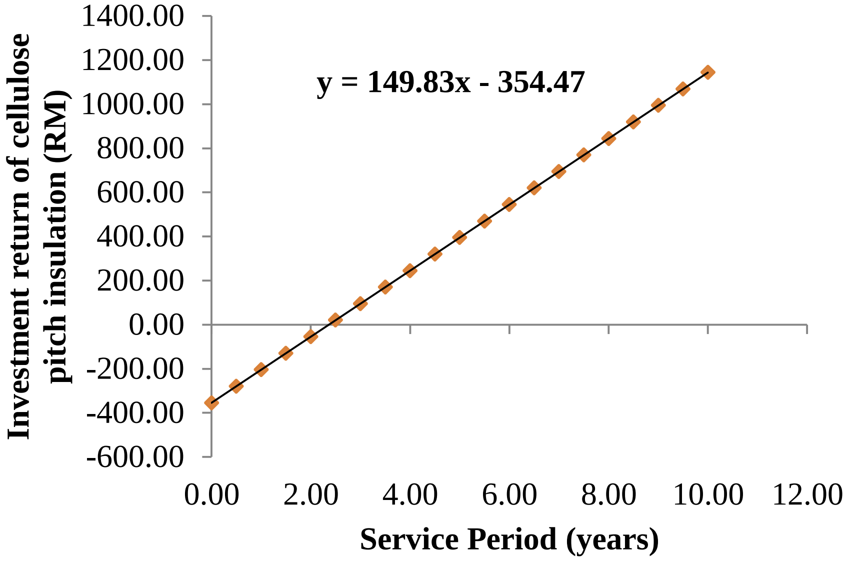
3. Investment return of fibreglass pitch insulation



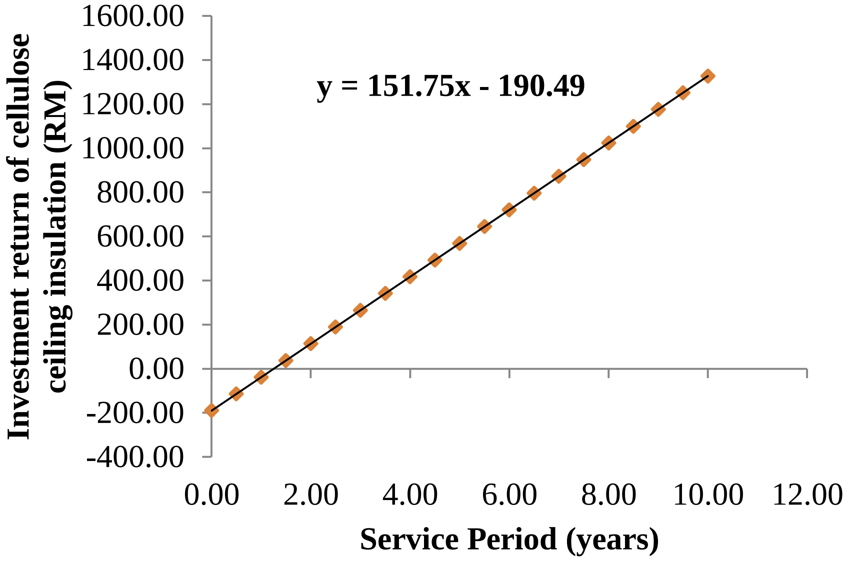
4. Investment return of fibreglass ceiling insulation



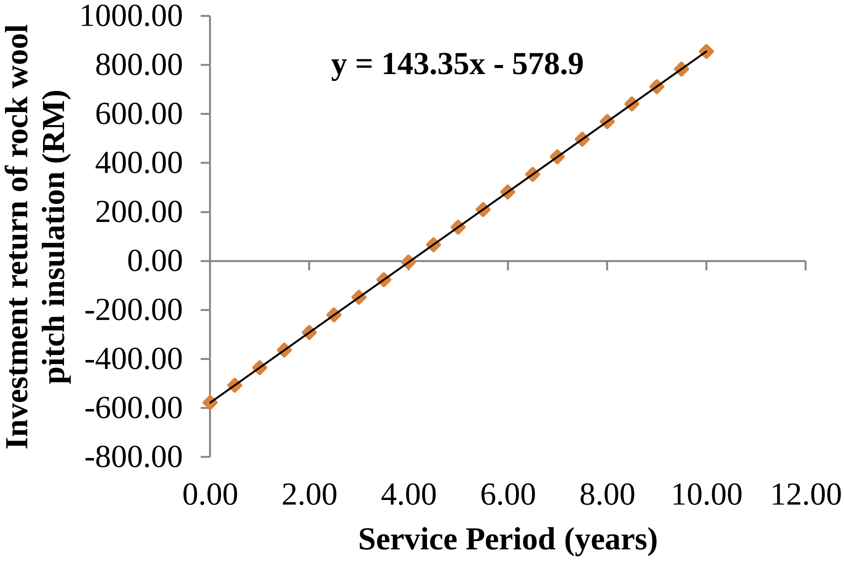
5. **Investment return of cellulose pitch insulation**



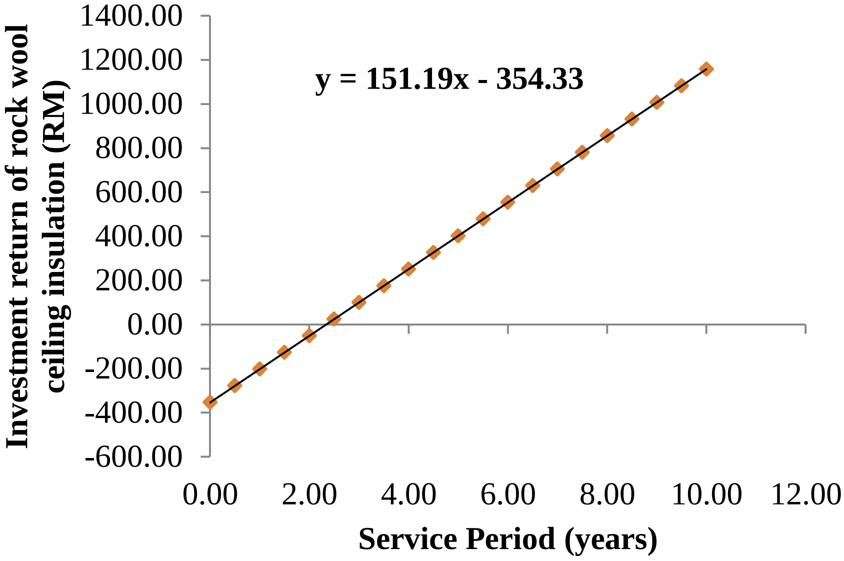
6. **Investment return of cellulose ceiling insulation**



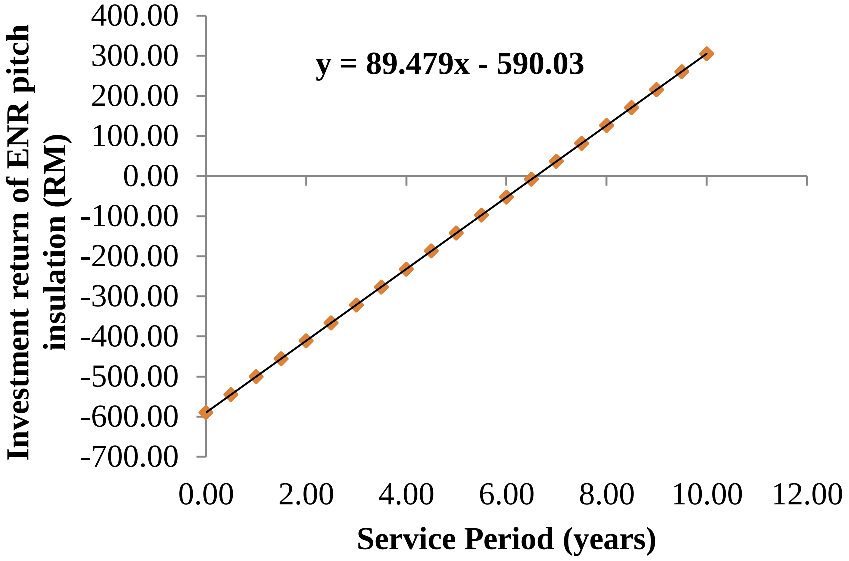
7. **Investment return of rock wool pitch insulation**



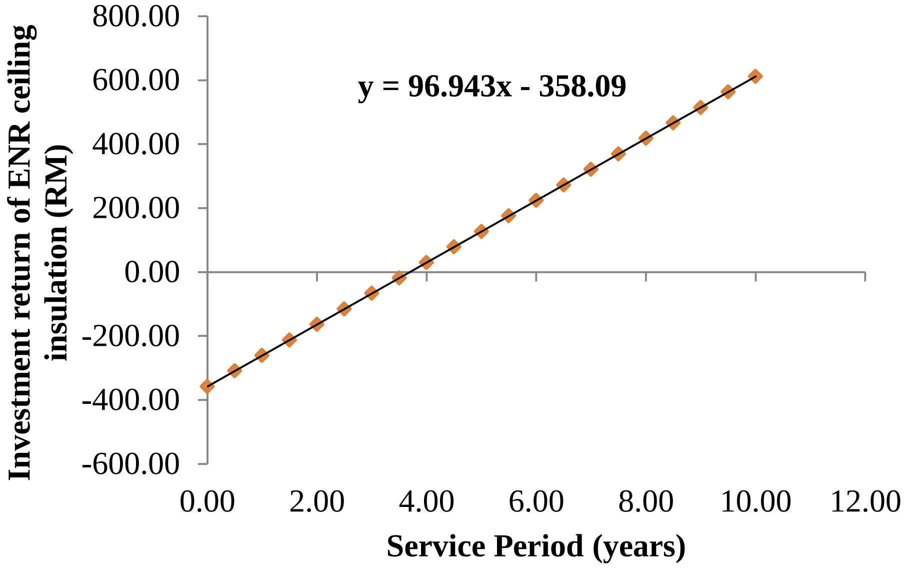
8. **Investment return of rock wool ceiling insulation**



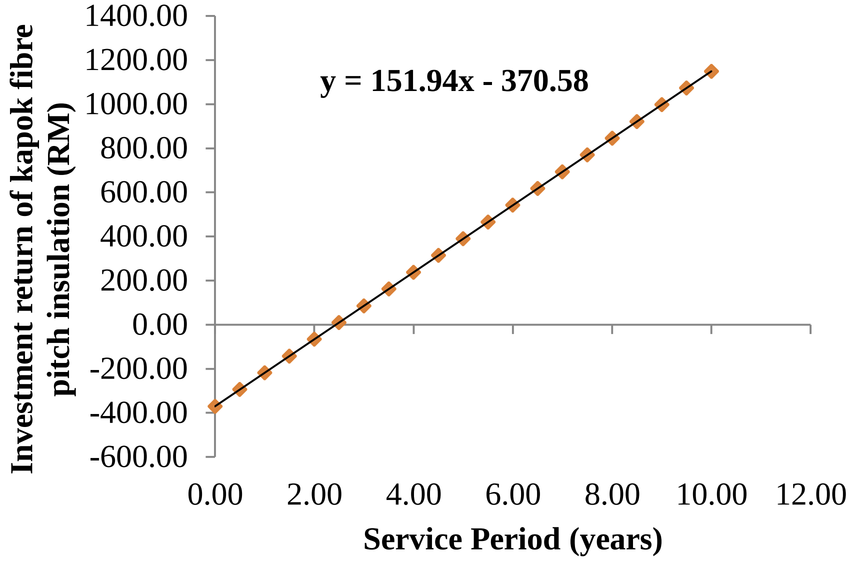
9. **Investment return of ENR pitch insulation**



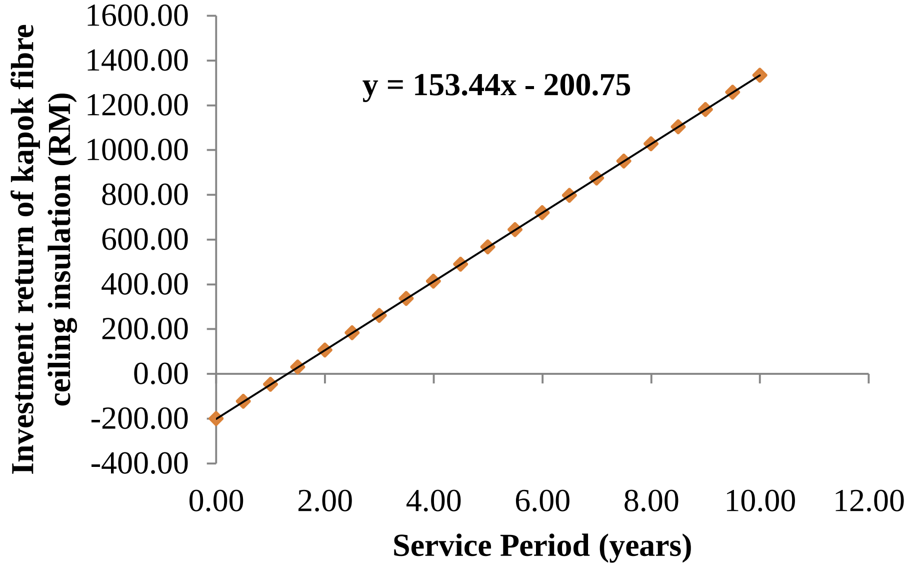
10. **Investment return of ENR ceiling insulation**



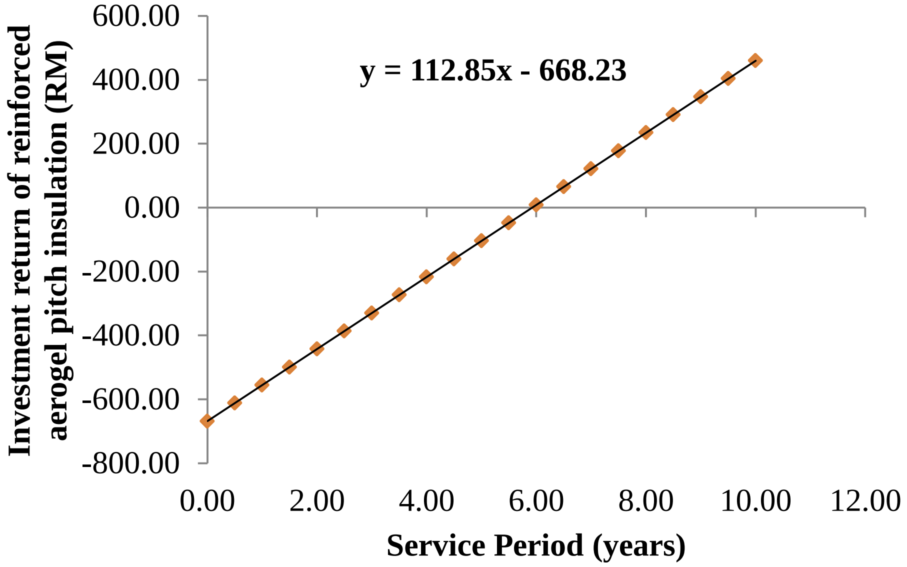
11. Investment return of kapok fibre pitch insulation



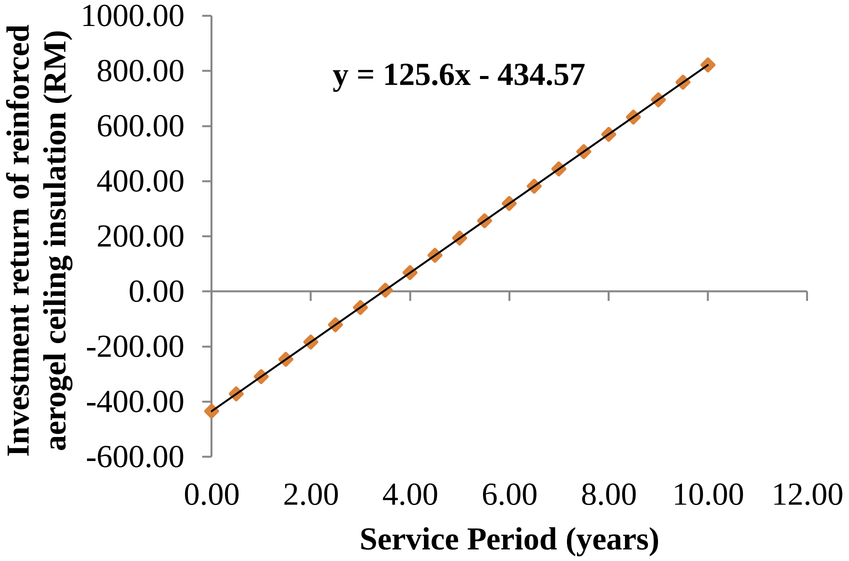
12. Investment return of kapok fibre ceiling insulation



13. Investment return of reinforced aerogel pitch insulation

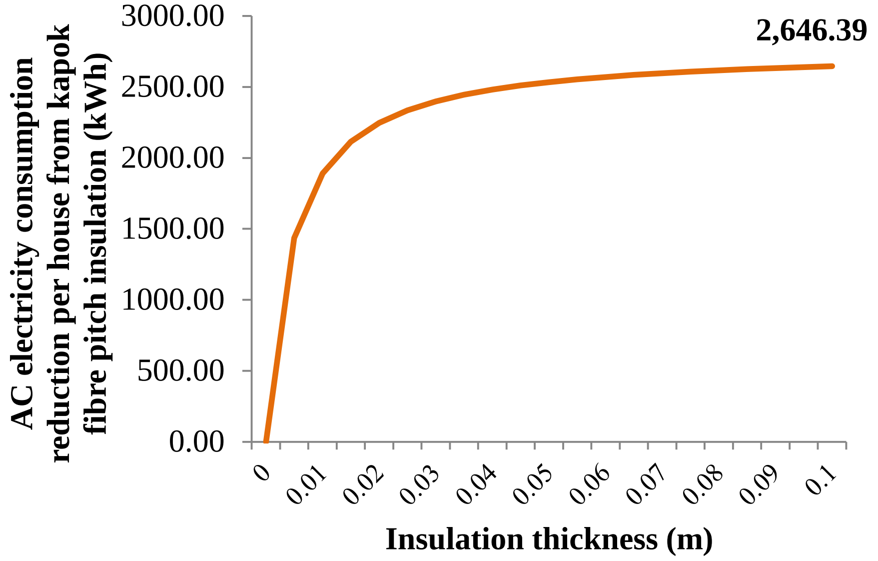


14. Investment return of reinforced aerogel ceiling insulation

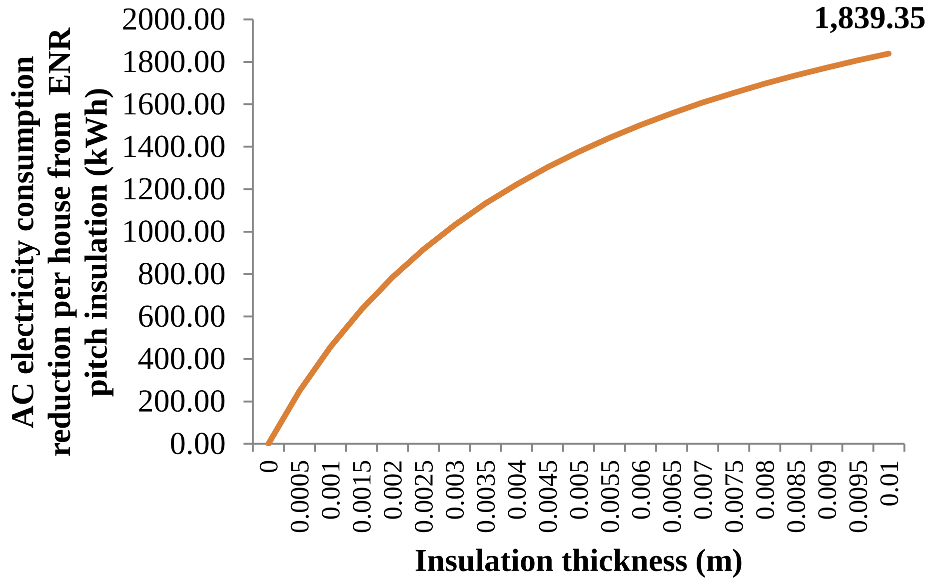


APPENDIX L: ELECTRICITY CONSUMPTION REDUCTION PER HOUSE FROM INSULATION

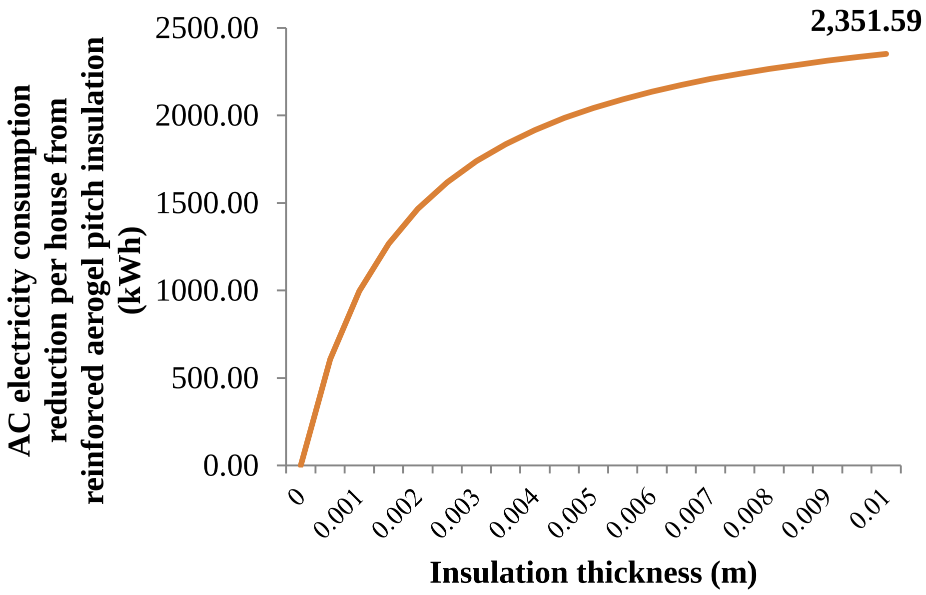
1. AC electricity consumption reduction per house from kapok fibre pitch insulation



2. AC electricity consumption reduction per house from ENR pitch insulation

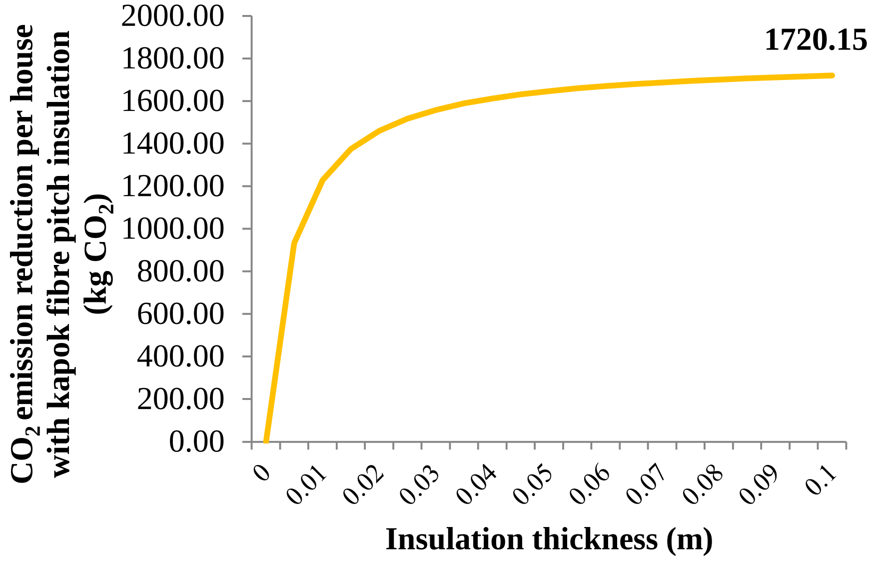


3. AC electricity consumption reduction per house from reinforced aerogel pitch insulation

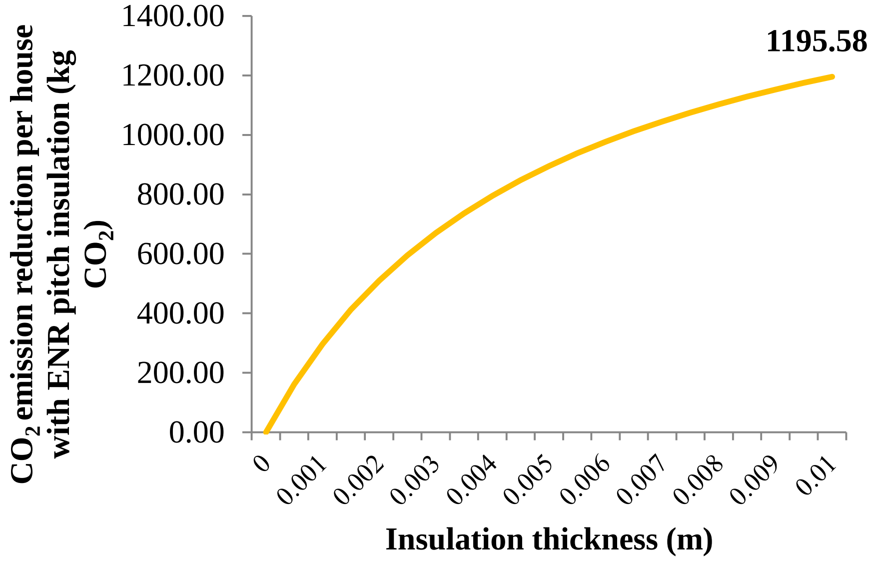


APPENDIX M: CO_2 EMISSION REDUCTION PER HOUSE FROM INSULATION

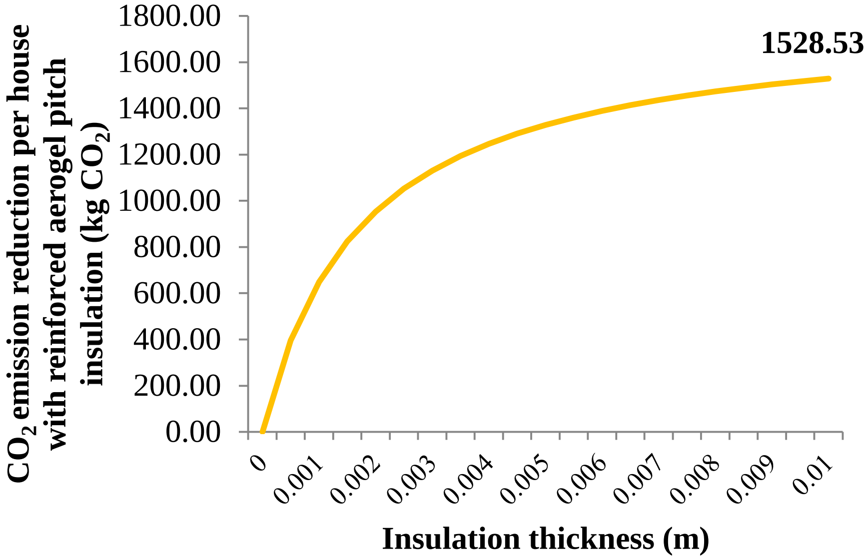
1. CO_2 emission reduction per house from kapok fibre pitch insulation



2. CO_2 emission reduction per house from ENR pitch insulation

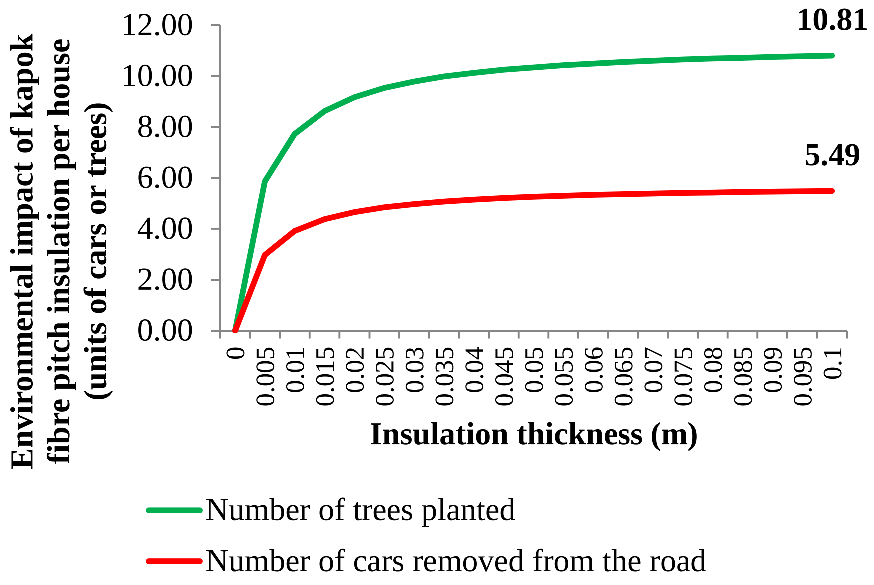


3. CO_2 emission reduction per house from reinforced aerogel pitch insulation

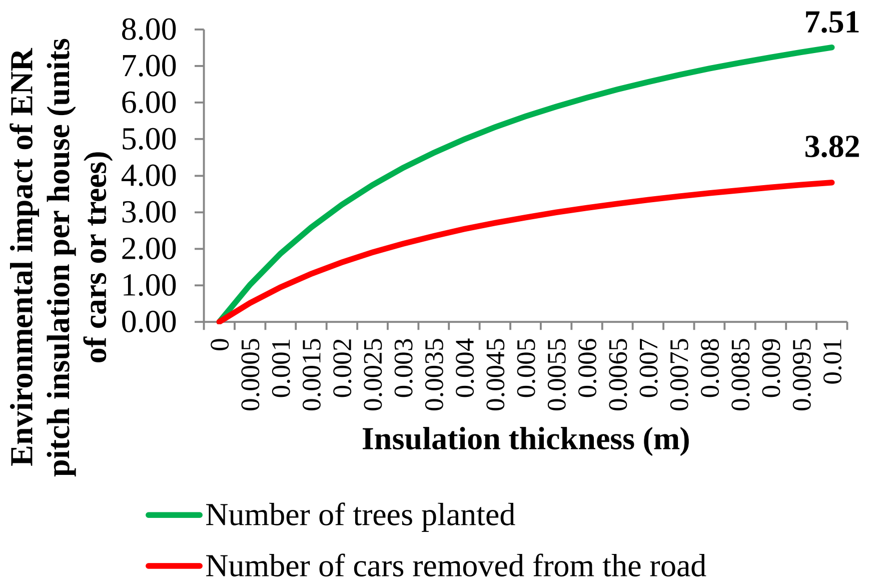


APPENDIX N: ENVIRONMENTAL IMPACT OF INSULATION PER HOUSE

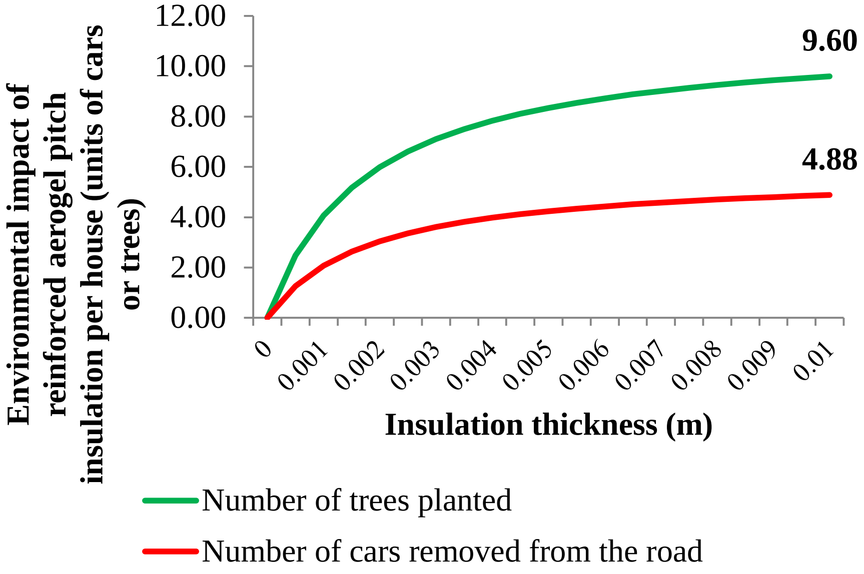
1. Environmental impact of kapok fibre pitch insulation per house



2. Environmental impact of ENR pitch insulation per house



3. Environmental impact of reinforced aerogel pitch insulation per house



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Race	:	Malay
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Foundation (Engineering)	Universiti Teknologi PETRONAS	2005
Sijil Pelajaran Malaysia (SPM)	Maktab Sultan Abu Bakar (English College)	2004
Penilaian Menengah Rendah (PMR)	Maktab Sultan Abu Bakar (English College)	2002

Employment History :

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Graduate Assistant	Universiti Teknologi PETRONAS	2010 - 2012
Site Engineer	E Charis Ingenieur (M) Sdn. Bhd.	2008