A COMPARISON STUDY ON THE EFFECTIVENESS OF A RESIDENTIAL CLAY ROOF TILE AND INDUSTRIAL METAL DECK ROOF IN MALAYSIA TO DRAIN RAINWATER

MUHAMMAD AFIF SHAFI BIN MOHD FADZLI

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Disahkan oleh:

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Bandar Country Homes
48000 Rawang, Selangor

Cop Rasmi:
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Jurutera Pengajar
Jabatan Teknologi Kejuruteraan Mekanikal
Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan
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DEDICATION

To my beloved father, Mohd Fadzli Bin Mohd Hassan, your unwavering support, encouragement, and sacrifices have been my driving force. Your belief in me has given me the strength to pursue my dreams. Thank you for always being there for me.

To my dear mother, Norsiah Binti Abd Halim, your love, patience, and guidance have been my constant inspiration. Your unwavering faith in my abilities has fuelled my determination. Thank you for instilling in me the values of perseverance and hard work.

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ABSTRACT

This study aims to assess the drainage efficacy and rainwater quality of two commonly used roofing materials in Malaysia, specifically residential clay roof tiles and industrial metal deck roofs. The goals are to offer insights into the relative effectiveness of different systems in draining rainwater and to contribute to the study of how they behave aerodynamically in different wind situations. Comprehensive investigation, encompassing pH, salinity, conductivity, total dissolved solid (TDS), and mineral content, reveals that clay roof tiles consistently indicate better rainwater quality in comparison to metal deck roofs. The clay tiles have a larger mineral content due to their composition, while metal deck roofs include increased quantities of heavy metals including zinc, iron, and aluminum, which could have environmental consequences. The validation investigation confirms that the realizable k-ε turbulence model is dependable for modeling horizontal homogenous velocity profiles, hence improving the precision of aerodynamic simulations that are vital for assessing wind-induced behavior. An in-depth analysis of wind pressure coefficients on roof surfaces reveals fascinating patterns. Surfaces that are at a right angle to the direction of the wind suffer higher pressure coefficients than surfaces that are parallel to the wind. Specifically, joint surfaces that are perpendicular to the wind experience reduced wind pressure across the whole surface of the roof. These discoveries are crucial for architects and engineers as they provide vital insights into the aerodynamic characteristics of roofs and assist in designing structures that can resist various wind conditions. The study on wind-induced suction on pyramidal roofs of different slopes demonstrates that the angle at which the wind approaches is a crucial feature that determines the pressure coefficients across the entire surface area. The 10° roof slope exhibits the most pronounced negative pressure coefficient, highlighting the importance of slope angle in the construction of wind-resistant roofs. To summarize, this study provides a comprehensive view of the drainage effectiveness, water quality, and aerodynamic characteristics of clay roof tiles used in residential buildings and metal deck roofs used in industrial buildings in Malaysia. The results contribute to the promotion of sustainable construction practices by offering empirical data and verified simulation models, highlighting the significance of careful material selection and design considerations for roofs in tropical climates. This research is at the forefront of developments in roofing technologies and practices because to its integration of environmental sustainability, structural resilience, and aerodynamic insights. The presented findings provide a comprehensive framework for making informed decisions in architectural and engineering practices, which is crucial as the construction industry places more importance on environmentally friendly and resilient solutions. These findings also serve as a foundation for future innovations in roofing materials and designs.

ABSTRAK

Kajian ini bertujuan untuk menilai keberkesanan saliran dan kualiti air hujan bagi dua bahan bumbung yang biasa digunakan di Malaysia, iaitu genting tanah liat untuk kediaman dan bumbung logam dek industri. Tujuannya adalah untuk memberikan wawasan tentang keberkesanan relatif sistem yang berbeza dalam menyalurkan air hujan dan untuk menyumbang kepada kajian tentang bagaimana mereka berkelakuan secara aerodinamik dalam pelbagai situasi angin. Kajian menyeluruh, merangkumi pH, saliniti, kekonduksian, pepejal terlarut sepenuhnya (TDS), dan kandungan mineral, menunjukkan bahawa genting tanah liat secara konsisten menunjukkan kualiti air hujan yang lebih baik berbanding dengan bumbung logam dek. Genting tanah liat mempunyai kandungan mineral yang lebih besar disebabkan oleh komposisinya, manakala bumbung logam dek mengandungi lebih banyak logam berat termasuk zink, besi, dan aluminum, yang boleh mempunyai konsekuensi alam sekitar. Kajian pengesahan mengesahkan bahawa model kekacauan k-ε yang dapat direalisasikan adalah boleh dipercayai untuk memodelkan profil halaju homogen mendatar, dengan demikian meningkatkan ketepatan simulasi aerodinamik yang penting untuk menilai kelakuan yang dipengaruhi angin. Analisis mendalam mengenai pekali tekanan angin pada permukaan bumbung mendedahkan corak yang menarik. Permukaan yang bersudut tepat dengan arah angin mengalami pekali tekanan yang lebih tinggi berbanding permukaan yang selari dengan angin. Secara khusus, permukaan bersama yang bersudut tegak lurus dengan arah angin mengalami penurunan tekanan angin di seluruh permukaan bumbung. Penemuan ini penting untuk arkitek dan jurutera kerana memberikan pandangan penting tentang ciri-ciri aerodinamik bumbung dan membantu dalam merancang struktur yang boleh menahan pelbagai keadaan angin. Kajian mengenai sedutan angin pada bumbung piramid dengan pelbagai kemiringan menunjukkan bahawa sudut serangan angin adalah ciri penting yang menentukan pekali tekanan di seluruh permukaan. Sudut bumbung 10° menunjukkan pekali tekanan negatif yang paling ketara, menonjolkan kepentingan sudut kemiringan dalam pembinaan bumbung yang tahan angin. Untuk merangkum, kajian ini memberikan pandangan menyeluruh tentang keberkesanan saliran, kualiti air, dan ciri-ciri aerodinamik genting tanah liat yang digunakan dalam bangunan kediaman dan bumbung logam dek yang digunakan dalam bangunan industri di Malaysia. Hasilnya menyumbang kepada promosi amalan pembinaan mampan dengan menyediakan data empirik dan model simulasi yang disahkan, menyoroti kepentingan pemilihan bahan yang berhati-hati dan pertimbangan reka bentuk untuk bumbung di iklim tropika. Kajian ini berada di barisan hadapan perkembangan dalam teknologi dan amalan bumbung kerana ia mengintegrasikan kelestarian alam sekitar, ketahanan struktur, dan pandangan aerodinamik. Hasil yang dikemukakan menyediakan kerangka kerja menyeluruh untuk membuat keputusan yang berpengetahuan dalam amalan senibina dan kejuruteraan, yang penting ketika industri pembinaan memberi lebih banyak penekanan kepada penyelesaian yang mesra alam dan tahan lama. Penemuan ini juga berfungsi sebagai landasan untuk inovasi masa depan dalam bahan dan reka bentuk bumbung.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C	-	Celcius
SUDS	-	Sustainable Urban Drainage Systems
RHA	-	Rice husk ash
CS	-	Ceramic sludge
pH	-	A scale used to specify the acidity or basicity of an aqueous solution.
mg/l	-	Miligrams per liter
TS	-	Total concentration of suspended solids
µm	-	Micrometer
$mJ\ m^{-2}$	-	Milijoule per square meter
g/m^2a	-	Gram per square meters area
SiO_2	-	Silicon dioxide
Al_2O_3	-	Aluminum oxide
Fe_2O_3	-	Iron (III) oxide
CaO	-	Calcium oxide
MgO	-	Magnesium oxide
SO_3	-	Sulphur trioxide
K_2O	-	Potassium oxide
Na_2O	-	Sodium oxide
LOI	-	Loss on Ignition
Ti	-	Titanium
Zn	-	Zinc
Cu	-	Copper
CFD	-	Computational Fluid Dynamics
TDS	-	Total Dissolved Solid
Cp	-	Pressure coefficient
UV	-	Ultraviolet

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CHAPTER 1

INTRODUCTION

1.1 Background

Due to the country's tropical climate and high levels of precipitation, rainwater discharge is a crucial aspect of urban planning and infrastructure development in Malaysia. Malaysia experiences heavy precipitation throughout the year, especially during the monsoon seasons, which poses significant challenges for regulating rainwater runoff (Tan, 2018). Effective precipitation drainage systems are crucial for addressing this issue, and the choice of roofing materials is crucial in this regard.

Clay roof tiles have long been a popular option for residential roofing in Malaysia. These tiles are renowned for their resilience, visual appeal, and thermal insulation properties. Clay roof tiles typically have a curved or corrugated shape, which aids in the efficient drainage of rainfall. The tiles are arranged in overlapping patterns to create a series of gradients that direct water to the gutters and downspouts. The porous nature of clay roof tiles permits some water absorption, which can aid in reducing surface discharge (De Silva, 2018).

In contrast, industrial metal deck roofs are commonly utilised in Malaysian commercial and industrial structures. According to (Raebel et al., 2020), these roofs comprise of lightweight, durable, and simple-to-install metal panels. Typically, flat, or slightly sloped, metal deck roofs provide a smooth surface for rainfall runoff. Typically, the panels are constructed with ridges or grooves to facilitate water movement and direct it to gutters. Metal roofs' impermeable character minimises water absorption, resulting in effective rainwater drainage.

Several factors come into play when comparing the rainwater drainage efficacy of residential clay roof tiles and industrial metal deck roofs. These elements include the pitch, contour, surface texture, and material properties of the roof (Friedler et al., 2017). The roof slope affects the speed and direction of water flow, with steeper slopes fostering faster drainage. Curved or flat, the shape of the roof effects the accumulation and movement of water. Surface texture, such as the corrugations of clay tiles or the ridge of metal panels, helps direct water to drainage locations.

Additionally, the material properties of clay roof tiles and metal deck roofs influence rainwater drainage. The porous nature of clay tiles allows for some water absorption, which can aid in reducing discharge. Nevertheless, excessive water absorption can result in roof leaks and water damage, highlighting the significance of appropriate maintenance. Metal deck roofs, being impermeable, ensure effective discharge of precipitation. However, their inability to absorb water can lead to increased surface discharge, which could overwhelm the drainage system (Akinwande et al., 2021).

Both residential clay roof tiles and industrial metal deck roofs necessitate routine inspection and cleansing to ensure unimpeded water flow. The accumulation of leaves, detritus, and moss on roof surfaces and in gutters can impede drainage. For optimal rainwater drainage performance, proper maintenance procedures, such as gutter cleansing and debris removal, are essential.

While both residential clay roof tiles and industrial metal deck roofs have advantages in terms of rainwater discharge, each has unique considerations. Clay roof tiles have aesthetic appeal, thermal insulation properties, and some capacity for water absorption. Nevertheless, they may necessitate more maintenance and have limitations when it comes to managing heavy rainfall. Metal deck roofs, on the other hand, excel at efficient precipitation drainage, but they may result in increased surface runoff. To ensure effective rainwater drainage in Malaysia, the selection of roofing materials should consider cost, aesthetics, maintenance requirements, and the local rainfall patterns and climatic conditions. Problem Statement

1.2 Problem Statement

In Malaysia, a country with a tropical climate and copious precipitation, the efficient management of rainwater discharge is of the utmost importance. Effective rainwater drainage systems are necessary to prevent flooding, waterlogging, and infrastructure damage considering the increasing frequency and intensity of rainstorms. The selection of roofing materials has a significant impact on the efficiency of these drainage systems. While residential clay roof tiles and industrial metal deck roofs are commonly used in Malaysia, there is a significant knowledge gap regarding the efficacy of each material in draining rainwater.

Despite their prevalence, comparative research on the drainage efficacy of residential clay roof tiles and industrial metal deck roofs is limited. To inform sustainable urban planning, infrastructure design, and building construction practises, the efficacy of these roofing materials in managing rainwater runoff must be examined critically. In order to optimise rainwater management, architects, engineers, and policymakers must make informed judgements regarding roof material selection based on their comparative performance (Mao et al., 2021).

In Malaysia, the dearth of a comprehensive comparative study hinders the ability to evaluate the benefits and drawbacks of residential clay roof tiles and industrial metal deck roofs. The effectiveness of rainwater drainage can be substantially influenced by roof shape, surface texture, slope, and material properties. There is a risk of ineffective rainwater management strategies in the absence of a comprehensive investigation, resulting in increased vulnerability to flooding, property damage, and compromised structural integrity.

Therefore, it is necessary to conduct a comparative evaluation and analysis of the efficacy of residential clay roof tiles and industrial metal deck roofs at draining rainwater. This study seeks to close the existing knowledge gap by evaluating their effectiveness in managing rainwater runoff under varying rainfall intensities and durations. The study will provide valuable insights into the comparative drainage efficacy, water absorption characteristics, and surface runoff patterns of these roofing materials by conducting detailed measurements and analyses. The findings of this research will not only aid in the comprehension of rainwater drainage performance, but also provide practical guidance for the selection of roofing materials in various regions of Malaysia. This research will ultimately contribute to the development of more resilient and sustainable rainwater management strategies in Malaysia, thereby reducing the impact of urban flooding and promoting the efficient use of this valuable resource.

1.3 Research Objectives

The objectives of this research are as follows:

a) To evaluate the drainage efficiency of both residential clay roof tiles and industrial metal deck roofs in Malaysia.

b) To compare the effectiveness of residential clay roof tiles and industrial metal deck roofs in terms of rainwater drainage.

1.4 Scope of Research

The scope of research are as follows:

a) The research will focus on comparing the rainwater drainage performance of residential clay roof tiles and industrial metal deck roofs in the Malaysian context.

b) The study will have a specific focus on the Malaysian context, taking into account the country's unique climate, rainfall patterns, and building practices.

c) The research will consider factors such as roof shape, surface texture, slope, and material properties that can influence rainwater drainage performance.

d) The study will evaluate the effectiveness of these roofing materials in managing rainwater runoff under varying rainfall intensities and durations.

e) Measurements and analysis will be conducted to assess the drainage efficiency, water absorption characteristics, and surface runoff patterns of both roofing materials.

f) Limitations and challenges associated with the use of residential clay roof tiles and industrial metal deck roofs for rainwater drainage will be discussed.

g) Future solutions for the study may include the exploration of innovative designs, incorporation of advanced drainage systems, and implementation of sustainable practises to improve the overall rainwater drainage efficiency of both roofing types.

CHAPTER 2

LITERATURE REVIEW

2.1 Malaysian Climate

Malaysia has a tropical climate characterized by year-round high temperatures and excessive humidity. Due to its proximity to the equator, the country obtains a great deal of sunlight and experiences little temperature variation throughout the year. Malaysia has two distinct monsoon seasons: the Southwest Monsoon from May to September and the Northeast Monsoon from November to March. During the Southwest Monsoon, Peninsular Malaysia's western coast experiences intense rainfall and strong winds. During the Northeast Monsoon, rainfall is typically lighter, but low-lying areas may experience occasional inundation (Tang, 2019).

In addition to the monsoon seasons, Malaysia experiences a dry season from April to October, characterized by reduced precipitation and higher temperatures. Even during the arid season, rain and thunderstorms are possible on occasion. Year-round, the climate in Malaysia is mild and humid, with temperatures ranging from approximately 23°C to 32°C. Particularly in coastal regions, the excessive humidity can make the temperature feel hotter than it is. In some areas, the excessive humidity can also produce occasional fog and mist (Tang, 2019).

Nonetheless, the high temperatures and humidity can present some difficulties, especially for those who are not habituated to such conditions. When spending time outdoors in Malaysia, it is important to remain hydrated and take precautions to avoid heat exhaustion and dehydration.

2.2 Rainfall Patterns in Malaysia

Malaysia has a tropical rainforest climate, which means that it receives a lot of rain all year, especially along the coast and in the mountains. The amount of rainfall varies based on geography and time of year, although Malaysia normally gets heavy rainfall from November to February and May to August. The average annual rainfall in Malaysia is approximately 2500 millimeters, but some regions can receive up to 5000 millimeters. The east coast of Peninsular Malaysia, the territories of Sabah and Sarawak in East Malaysia, and the west coast of Peninsular Malaysia have a slightly drier climate (Pour et al., 2020).

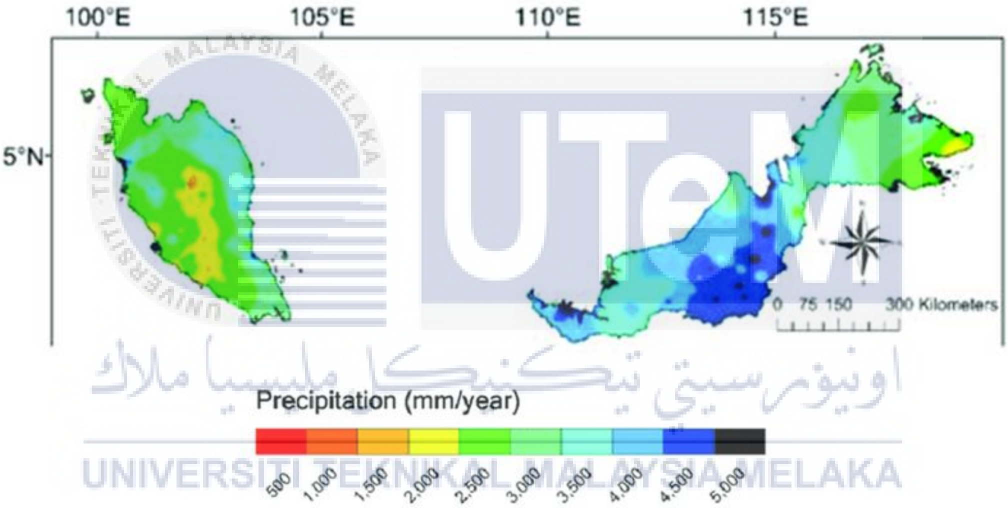

Figure 2.1 Annual rainfall intensity map over Malaysia (Tan et al., 2015)

In addition to excessive rainfall, Malaysia occasionally experiences flooding, especially in low-lying areas and regions with inadequate drainage. This can be caused by a combination of factors, such as excessive rainfall, poor urban planning, and deforestation.

Malaysia has instituted various measures to mitigate the effects of heavy rainfall and flooding, including the construction of drainage systems and dams, flood walls and levees, and zoning regulations to limit construction in flood-prone areas. However, these measures are not always effective, especially during times of exceptionally intense precipitation.

Overall, Malaysia's abundant rainfall can be both a benefit and a curse. While it is necessary for maintaining the country's verdant forests and agriculture, it can also cause flooding and other problems. Consequently, Malaysia must continue to invest in infrastructure and planning to mitigate the effects of excessive rainfall and flooding.

2.3 Climate Change and Its Impact on Rainfall

Climate change is a global phenomenon that refers to long-term shifts in weather patterns and climate caused primarily by the emission of greenhouse gases. As with many other nations, Malaysia is experiencing the effects of climate change, which have significant implications for precipitation patterns and water resources.

Malaysia's rainfall patterns have changed as a result of climate change. While the total annual precipitation may not alter significantly, the distribution of precipitation throughout the year does. There are changes in the timing, intensity, and duration of precipitation events across the nation. For example, there is evidence of more intense rainfall during monsoon seasons, resulting in heavier downpours and increased flash flood hazards. In contrast, protracted dry periods between rainfall events can result in water scarcity and drought conditions (Pour et al., 2020).

Increased frequency and intensity of extreme weather events is one of the most prominent impacts of climate change on rainfall in Malaysia. This includes more intense cyclones, episodes of heavy precipitation, and severe thunderstorms. These extreme weather events can cause localized flooding, landslides, and water supply system disruptions, affecting both urban and rural areas. Such occurrences present substantial challenges to the extant rainwater drainage infrastructure and emphasize the need for effective adaptation measures (Rahman, 2009).

Climate change also contributes to rising sea levels, which pose a serious hazard to Malaysia's coastal regions. Coastal flooding is more likely during intense rainfall events and storms in low-lying regions due to rising sea levels. Coastal cities such as Kuala Lumpur, Penang, and Malacca are especially susceptible to sea-level rise and associated inundation, which can exacerbate the effects of intense rainfall events and compromise existing drainage infrastructure (Loo et al., 2015).

Changing precipitation patterns due to climate change have implications for the management of water resources in Malaysia. While annual precipitation totals may remain relatively stable, the irregular distribution of precipitation and more intense rainfall events pose challenges for water storage, supply, and flood control. The development of reservoirs, efficient drainage systems, and precipitation harvesting techniques become essential for ensuring the long-term availability of water in urban and rural areas if water resources are not properly managed (Loo et al., 2015).

2.4 Importance of Rainwater Management

Rainwater management plays a crucial function in ensuring Malaysia's water security. As a tropical nation with abundant precipitation, Malaysia possesses significant water resource potential. However, the irregular distribution of precipitation throughout the year and the growing effects of climate change present obstacles to water availability. Effective rainwater management practices, such as storage, harvesting, and appropriate drainage, can assist in optimizing water resources, decreasing reliance on groundwater and surface water sources, and enhancing water security overall.

In order to reduce the risk of inundation in Malaysia, it is essential to manage rainwater properly. Intense rainfall, especially during monsoon seasons, can cause rapid flooding in both urban and rural areas. By instituting effective rainwater drainage systems, including well-designed and maintained drainage networks, retention ponds, and flood control infrastructure, it is possible to mitigate the effects of heavy rainfall. Proper management reduces flooding-related property damage, disruptions to daily life, and hazards to public safety (Getnet and MacAlister, 2012).

Rainwater management is crucial for Malaysia's sustainable urban development. Rapid urbanization and population growth place existing water resources and infrastructure under pressure. By implementing sustainable rainwater management practices such as rainwater catchment, green roofs, and permeable pavements, cities can reduce their reliance on centralized water supply systems and lessen the strain on freshwater resources. Additionally, sustainable runoff management can contribute to an improvement in urban microclimate, a reduction in the urban heat island effect, and an increase in urban biodiversity (Shaari, 2020).

In Malaysia, effective runoff management has numerous environmental benefits. By collecting and utilizing precipitation, the demand for freshwater from conventional sources can be decreased, thereby reducing the need for extensive dam construction and its associated environmental impacts. In addition, effective rainwater management can aid in the control of erosion, sedimentation, and pollution discharge, thereby protecting water bodies, rivers, and coastal ecosystems. It also contributes to the enhancement of water quality, as rainwater harvesting systems typically include filtration and treatment mechanisms.

2.5 Sustainable Urban Drainage System (SUDS)

Sustainable Urban Drainage Systems (SUDS) are innovative approaches to urban drainage that seek to manage stormwater runoff in an ecologically and sustainably responsible manner. In Malaysia, SUDS techniques are increasingly employed in response to urbanization, flooding, and water resource management challenges (Zhou, 2014).

Rainwater harvesting entails capturing and storing rainwater for a variety of applications, including irrigation, non-potable water supply, and groundwater recharge. Rainwater harvesting systems are being installed in residential, commercial, and institutional buildings in Malaysia. Typical components of these systems include roof collection, gutters, downspouts, filtration mechanisms, and storage containers. Rainwater collection reduces dependence on centralized water supply systems, conserves freshwater resources, and mitigates the effects of droughts (Zhou, 2014).

Green roofs and living walls are vegetation-based stormwater management systems that are incorporated into buildings and infrastructure. Especially in urban areas, green roofs and living walls are acquiring popularity in Malaysia. Green roofs involve the implementation of vegetated surfaces on rooftops that absorb and retain precipitation, reduce runoff, and enhance thermal insulation. Living walls, also known as vertical gardens, are vertical surfaces that are covered in vegetation and offer similar advantages. These systems improve biodiversity, air quality, and urban heat island effect (Vijayaraghavan, 2016).

Adoption of Sustainable Urban Drainage Systems (SUDS) in Malaysia contributes to addressing urbanization, flood management, water resource conservation, and environmental sustainability challenges. These innovative techniques provide multiple benefits, including a decrease in surface discharge, an improvement in water quality, an increase in groundwater recharge, an increase in biodiversity, and a more resilient urban infrastructure. Malaysia can create sustainable and habitable cities that are better equipped to manage the effects of urbanization and climate change by promoting the use of SUDS.

2.6 Role of Roofs in Rainwater Drainage

By serving as collection surfaces, roofs play a vital role in rainwater discharge. In Malaysia, where precipitation is abundant, roofs serve as the primary runoff collection area. The efficacy of rainwater collection is determined by the roof's design, material, and slope. Roofs with large surface areas and an appropriate slope collect rainfall and direct it to gutters and downspouts for further management.

Gutters and downspouts are integral roof components that efficiently channel rainfall. Typically installed along the roof's perimeter, gutters capture water running off the roof's surface. Connected to the gutters, downspouts direct roof-collected water to the ground or to rainwater harvesting systems. Effective rainwater drainage is ensured by gutters and downspouts that are designed and maintained correctly, preventing water from accumulating on roofs and causing structural damage (Baryła, 2019).

Roofs play a significant role in rainwater harvesting, a water conservation and management practice gaining popularity in Malaysia. According to (Baryła, 2019) the design and composition of roofs can affect the purity of rainwater collected. For rainwater catchment systems, smooth and non-toxic roofing materials, such as metal or clay tiles, are preferred to ensure water quality. Larger roof surfaces enable more significant rainwater harvesting potential.

Roofs also contribute to reducing surface discharge by directing precipitation into designated drainage pathways. It can mitigate the adverse effects of increased runoff in urban areas dominated by impervious surfaces and reducing the risk of flooding and soil erosion by collecting rainfall and channeling it through gutters and downspouts.

The selection of roofing materials can have a significant effect on the discharge of rainwater in Malaysia. Different roofing materials have properties that influence the flow and discharge of precipitation. For instance, cool roofs with high reflectivity and low heat absorption can reduce the temperature of collected precipitation and mitigate urban heat island effects. In addition, certain roofing materials, such as metal or tile, may permit better precipitation collection and runoff management than others, such as asphalt shingles (Berndtsson, 2010).

For adequate rainwater drainage in Malaysia, regular roof maintenance is required. Removing residue, leaves, and other obstructions from gutters and downspouts is essential to ensure unimpeded water flow. Inspecting for leaks, cracks, or damaged areas impeding rainwater discharge is also part of roof maintenance. Timely repairs and maintenance activities contribute to the durability and runoff management performance of roofs.

In Malaysia, roofs play a crucial role in the drainage of rainfall. They serve as collection surfaces, channel rainwater through gutters and downspouts, and contribute to rainwater harvesting and reducing surface discharge. The selection of suitable roofing materials and routine maintenance is essential for effective rainwater management, thereby enhancing the overall efficacy and sustainability of Malaysia's rainwater drainage system.

2.7 Characteristic of Residential Clay Roof Tile

Clay roof tiles in Malaysia have distinct qualities that make them a popular option among homeowners. These tiles are designed to withstand the challenging weather conditions pervasive in the country and are renowned for their resilience. Even in Malaysia's tropical climate, they help keep the interiors of buildings milder due to their superior thermal insulation properties.

Figure 2.2 Clay roof tile

Clay roof tiles have undeniable aesthetic value, providing a distinctive and traditional appearance that complements various architectural styles. In addition, their low maintenance needs, environmental friendliness, acoustic insulation, fire resistance, and long lifespan contribute to their desirability as a dependable roofing option for Malaysian homes (Utama et al., 2012). The table below depicts the detailed elaboration on the characteristics of residential clay roof tiles in Malaysia.

Table 2.1 Characteristic of clay roof tile

Characteristic	Explanation
Durability	Malaysian residential clay roof tiles are renowned for their durability. They are designed to withstand harsh weather conditions, including intense sunlight, heavy rain, and powerful winds because they are made from natural clay materials. Clay roof tiles resist crumbling, fading, and warping, providing residential buildings with long-lasting performance and protection.
Thermal Insulation	Clay roof panels provide exceptional thermal insulation. By reducing heat absorption, clay tiles in Malaysia's tropical climate, where temperatures can be high, keep the interiors of buildings more relaxed. The natural composition of clay, combined with the air openings between the tiles, creates a barrier that restricts heat transfer from the roof to the interior spaces below.
Aesthetic Appeal	There is widespread appreciation for the aesthetic allure of clay roof tiles. They offer a distinct and traditional appearance that complements a range of architectural styles, from conventional Malay homes to contemporary designs. Clay tiles are available in various forms, including flat, S-shaped, and barrel-shaped,

Characteristic	Explanation
	allowing design flexibility. They are available in multiple hues, including terracotta, red, brown, and grey, allowing householders to select a roof color that complements their tastes and the surrounding environment.
Low Maintenance	Roofing tiles made of clay require minimal maintenance. Their durability and resistance to deterioration reduce the frequency with which they must be repaired or replaced. Regular inspections, detritus removal, and moss or algae control are recommended to preserve their functionality and appearance. In addition, correct installation and adherence to the manufacturer's instructions contribute to the durability of clay roof tiles.
Environmental Sustainability	Clay roof panels are regarded as an environmentally responsible roofing material. They are made from abundant and replenishable natural clay. Clay is non-toxic and does not discharge any harmful chemicals into the environment. In addition, clay roof tiles can be recycled or repurposed after their useful life, thereby reducing waste and promoting sustainability.
Sound Insulation	Clay roof panels provide excellent sound insulation. They prevent external noises, such as rain or precipitation, from penetrating residential buildings. This results in a more peaceful and pleasant living environment for the occupants.
Fire Resistance	Clay roofing panels have exceptional resistance to fire. They provide a high measure of protection against fire hazards and are incombustible. In Malaysia, where wildfires and fire incidents can occur, clay roof tiles offer residential buildings an added level of security.
Longevity	Clay residential roof tiles in Malaysia have a long lifespan when properly installed and maintained. They can last for decades, providing homeowners with long-term protection and value.

2.8 Characteristic of Industrial Metal Deck Roof

Industrial metal deck roofs are a popular option for commercial and industrial buildings in Malaysia, as they possess various desirable qualities. These roofs are renowned for their resilience and resistance to the demanding conditions of industrial environments.

Figure 2.3 Metal deck roof

Metal deck roofs constructed from galvanized steel or aluminum offer exceptional strength, corrosion resistance, and durability. In Malaysia's tropical climate, they provide outstanding heat reflectivity, reducing cooling energy consumption.

Metal roofs are simple to install due to their lightweight, and their fire resistance is an important safety feature for industrial structures. With minimal maintenance requirements, industrial metal deck roofs provide a cost-effective and dependable roofing solution for various Malaysian applications. The table below depicts the detailed elaboration on the characteristics of industrial metal deck roofs in Malaysia.

Table 2.2 Characteristic of industrial metal deck roof

Characteristic	Explanation
Durability	Malaysian industrial metal deck roofing is renowned for its durability and resilience. They are constructed from high-quality materials, such as galvanized steel or aluminum, which provide superior structural strength and integrity. Metal roofs can withstand severe weather, such as heavy rainfall, powerful winds, and intense sunlight. They resist corrosion, rust, and deterioration, providing industrial structures with long-lasting performance and protection.

Characteristic	Explanation
Lightweight	The lightweight nature of industrial metal deck roofs is an important characteristic. Metal roofs, including concrete and clay tiles, are substantially lighter than other roofing materials. This property makes installation simpler and reduces the load on the building structure. It also allows for greater design flexibility and can facilitate construction process simplification.
Heat Reflectivity	In Malaysia's tropical climate, where temperatures can reach incredibly high levels, heat reflectivity is an essential quality of industrial metal deck roofs. Metal roofs are highly reflective, meaning they deflect much of the sun's heat from the building. This reduces the need for extensive air conditioning and lowers energy consumption by keeping interior spaces cooler.
Fire Resistance	The superior fire resistance of industrial metal deck roofs makes them a safe option for industrial buildings. Metal is incombustible and contributes nothing to the propagation of a fire. This feature provides additional protection against fire hazards, reducing the risk of damage and guaranteeing the safety of occupants and property.
Longevity	When installed and maintained correctly, metal deck roofs have a long lifespan. They are constructed to endure the test of time and can last for decades. Metal roofs are impervious to decay, insect infestations, and deterioration, ensuring their performance and structural integrity for an extended period. Regular inspections and maintenance, such as checking for loose fasteners and rectifying minor damage, can further increase their durability.
Versatility and Design Options	Industrial metal deck roofs offer a variety of design possibilities. Various profiles, including standing seam, corrugated panels, and interlocking systems, are available. This permits customization and adaptation to different architectural styles and project specifications. Metal roofs can be fabricated in various colors and finishes, allowing them to complement the building's design or corporate identity.

Characteristic	Explanation
Low Maintenance	Metal deck roofing requires less maintenance than other roofing materials. They are resistant to mold, decay, and insects, reducing the frequency with which repairs or replacements are needed. Routine inspections, detritus removal, and gutter clearing are sufficient to maintain their performance. Additionally, metal roofs are less susceptible to damage from intense rainfall and wind-borne debris.
Sustainability	The use of industrial metal deck roofs is environmentally responsible. They can be manufactured from recycled materials, such as steel or aluminum, reducing the demand for virgin materials. Additionally, metal roofs are 100 percent recyclable at the end of their useful life, minimizing waste and contributing to the circular economy.

CHAPTER 3

METHODOLOGY

3.1 Methodology Overview

The methodology for the comparative study employs a systematic approach to evaluate the efficacy of clay roof tiles and metal deck roofs in Malaysia in draining rainwater. The study begins with a well-defined research objective and a thorough review of the relevant literature to comprehend the existing knowledge and factors associated with rainwater discharge and roofing materials. Considerations such as experimental research, field observations, and computer simulations are made when determining the research methodology. Specific parameters for the efficacy of rainwater drainage are identified, and suitable study sites and samples are chosen. Numerous methods, including site visits, surveys, and laboratory testing, are utilized to collect data. Statistical analysis techniques are then applied to the collected data to compare the rainwater drainage efficacy of the two roofing materials. The results are interpreted, conclusions are derived, and recommendations are provided based on the research findings. The research methodology intends to offer a rigorous and evidence-based evaluation of the efficacy of clay roof tiles and metal deck roofs in Malaysia for rainwater drainage.

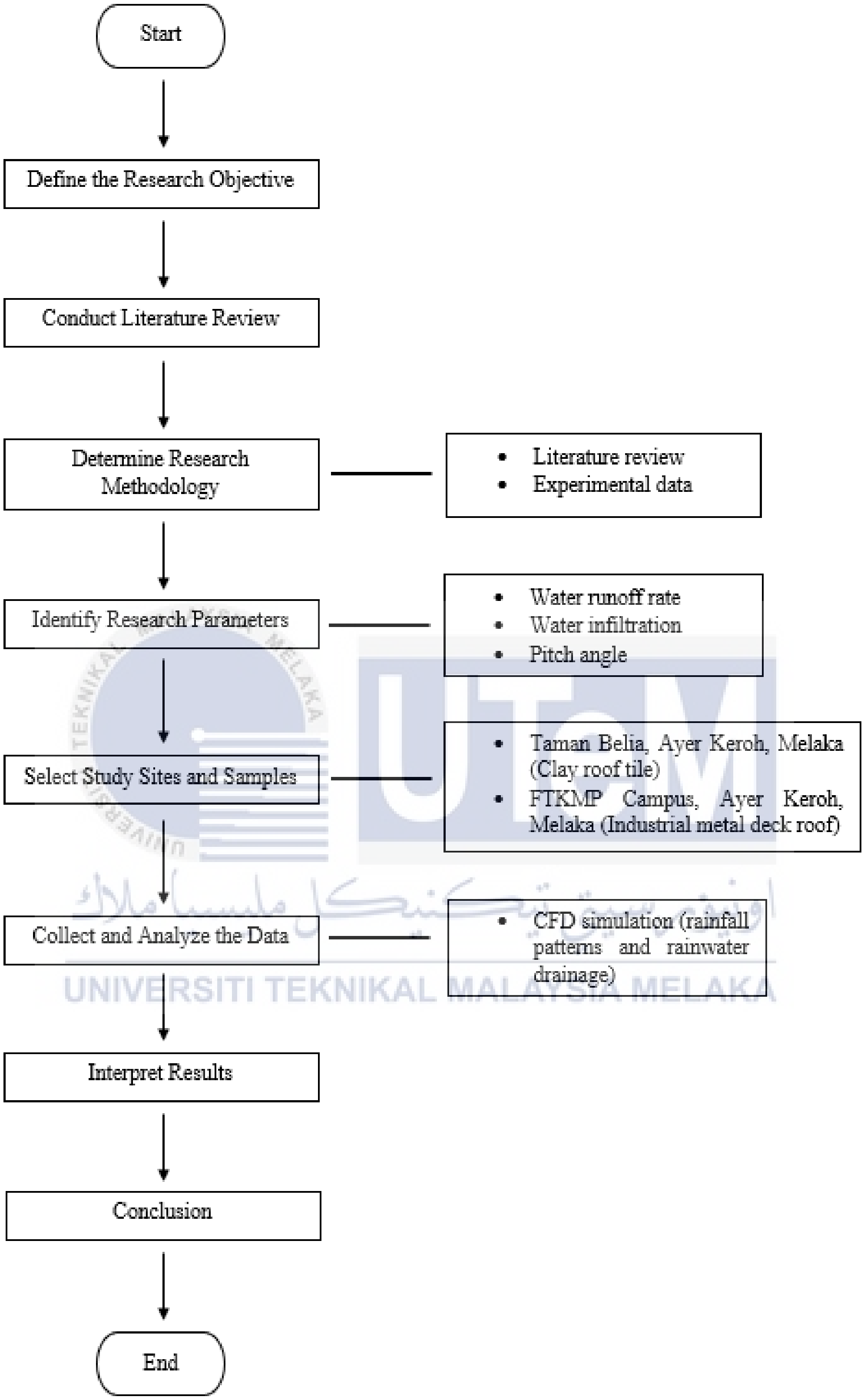

Figure 3.1 Flowchart of framework

3.2 Evaluation of Clay Roof Tile for Rainwater Drainage

In Malaysia, clay roof tiles for rainwater drainage are evaluated based on their efficacy in effectively channeling and managing roof rainwater runoff. Clay roof tiles have a specific absorption capacity for water. The water absorption characteristics can be evaluated to determine how well the tiles retain water during rainfall and how rapidly they release it afterward. Low water absorption is desirable to prevent excessive weight gain, reduce the risk of leakage, and guarantee adequate water runoff.

The surface pattern and texture of clay roof tiles are essential in rainfall drainage. The design should promote the smooth movement of water and minimize the likelihood of water pooling or standing on the roof. Tiles with ridges or contours facilitate adequate drainage by directing water to the gutters.

The roof pitch, or slope, is crucial to drainage rainfall. The evaluation considers the compatibility of clay roof tiles with the various roof elevations typically found on Malaysian structures. A sufficient slope ensures water flows readily toward the gutters and does not accumulate on the roof's surface.

The evaluation determines the rate at which clay roof tiles permit water to escape from the roof. Efficient water runoff prevents flooding, structural damage, and possible breaches. By measuring and comparing the water runoff rate, it is possible to determine how well clay roof tiles drain precipitation.

Evaluation of the resistance of clay roof tiles to obstruction is another crucial aspect of the test. The accumulation of leaves, debris, or moss on the roof surface can impede water passage. Clay roof tiles with anti-debris features or coatings are preferable because they aid in maintaining unimpeded rainwater discharge.

The evaluation considers the maintenance requirements associated with clay roof tiles for rainwater drainage. Tiles that are easy to clean, inspect, and maintain contribute to the long-term effectiveness of rainwater drainage. Assessing the maintenance needs helps determine the practicality and sustainability of using clay roof tiles in Malaysian conditions.

By conducting a comprehensive evaluation of these factors, the effectiveness of clay roof tiles in rainwater drainage in Malaysia can be determined. The findings contribute to understanding the performance of clay roof tiles and aid in making informed decisions regarding their suitability for specific applications and climatic conditions.

3.3 Material Properties and Drainage Performance of Clay Roof Tile

Because of their extraordinary material properties, clay roof tiles have been popular for roofing applications for centuries. These tiles are manufactured from natural clay shaped, dried, and fired at high temperatures for their characteristic strength and durability. Several advantageous material properties contribute to the performance and durability of clay roof tiles. The unique combination of their porosity, water absorption rate, surface texture, and strength determine their functionality as roofing materials. The material properties of clay roof tiles make them highly effective at protecting, insulating, and draining buildings while adding aesthetic value.

Table 3.1 Physical properties and chemical composition of raw materials (De Silva et al., 2022)

Property	Waste RHA	CS	Laterite clay
Physical properties			
Finesse modulus	1.72	1.05	0.41
Specific gravity	2.08	2.24	2.50
Bulk density (kg/m^3)	336.9	1276.8	1294.5
Chemical composition			
SiO_2 (%)	84.14	66.83	61.99
Al_2O_3 (%)	4.08	16.84	17.98
Fe_2O_3 (%)	1.15	1.06	6.03

Property	Waste RHA	CS	Laterite clay
CaO (%)	0.97	2.08	1.78
MgO (%)	0.44	1.83	0.54
SO_3 (%)	0.05	0.08	0.04
K_2O (%)	1.34	1.52	1.87
Na_2O (%)	1.69	0.55	1.36
LOI (%)	6.13	9.2	8.40

Table 3.2 The material properties of clay roof tile.

Properties	Explanation
Porosity	The permeability of roofing materials is a crucial factor in drainage efficacy. To some extent, water can permeate porous materials, such as clay roof tiles. Porosity evaluation determines how well a material absorbs and retains moisture, which impacts the drainage process.
Water Absorption Rate	The water absorption rate is essential for evaluating drainage performance. It refers to the quantity of water a substance can absorb in a given amount of time. Lower water absorption rates are preferable because they indicate that the material rapidly sheds water, facilitating effective drainage.
Surface Texture	The drainage efficacy of roofing materials is affected by their surface texture. A smooth surface facilitates the movement of water, preventing pooling and stagnation. Materials with asymmetrical or abrasive surfaces may impede water flow, leading to drainage problems.
Material Strength	Roofing materials must have sufficient strength to maintain structural integrity during extreme rainfall. Strong materials can withstand the weight of water without deforming or collapsing, which could obstruct drainage pathways.

The drainage performance of clay roof tiles is crucial for effectively controlling rainwater discharge from rooftops. With their inherent design characteristics and material properties, clay roof tiles provide exceptional drainage. These tiles are designed with slopes and contours that facilitate the smooth flow of water, thereby minimizing the possibility of water collecting or stagnating on the roof surface. In addition, clay roof tiles' porosity and water-absorption properties enable them to absorb and release water rapidly, ensuring adequate drainage. Clay roof tiles' drainage performance contributes to roofs' overall functionality and durability, preventing water damage, leakage, and structural problems.

Table 3.3 The drainage performance of clay roof tile

Characteristic	Explanation
Water Runoff	The primary objective of drainage systems is to remove water from rooftops effectively. Assessing drainage performance requires determining the velocity and efficiency of water discharge from the roof surface. A sufficient slope, smooth surfaces, and an effective gutter system contribute to optimal water discharge.
Prevention of Water Ponding	When water collects in depressions or low-lying areas on the roof surface, this is known as ponding. It can cause roof damage, leakage, and drainage issues. Evaluating the material properties and roof design characteristics helps determine their effectiveness in preventing water ponding.
Compatibility with Gutter Systems	For appropriate drainage, roofing materials should be compatible with gutter systems. The evaluation considers how well the roofing material interfaces with gutters and downspouts, ensuring that water flows from the roof to the drainage system without interruption.
Resistance to Clogging	Roofing materials resistant to obstruction contribute to the uninterrupted flow of water. On the surface of a roof, debris, leaves, and vegetation can accumulate and block drainage pathways. Evaluating the material's resistance to obstruction helps determine how well it will perform over time, thereby reducing the need for maintenance.
Maintenance Requirements	The evaluation includes assessing the maintenance requirements related to the discharge performance of the roofing material. Easy-to-clean and maintain materials contribute to the long-term efficacy of drainage systems.

3.4 Measurement and Analysis of Rainwater Runoff of Clay Roof Tile

According to De Silva et al., (2022), Table 3.4 contrasts roof runoff water's average pH and total solid concentration for all tile samples and direct precipitation. The pH value of the direct rainwater sample was 7.52, supporting the value reported in previous journals.

The pH value of direct rainwater decreased from 7.22 to 6.49 for roof tiles containing 10% rice husk ash (RHA) and 20% ceramic sludge (CS), indicating that the incorporation of RHA and CS affected the water quality of the runoff. In previous studies, the pH decreased from 7.55 to 7.22 when RHA was added from 0% to 10%, whereas it decreased from 7.51 to 7.41 when CS was added from 0% to 10%.

When combined materials (10% RHA and 10% CS) are used, the pH value is substantially reduced from 7.52 to 6.56, matching the previously reported pH value of roof runoff (Llopart-Mascaró et al., 2021). The pH value, a measurement of how acidic or alkaline the water is, plays a crucial role in plant growth: irrigation water with a pH value outside the normal range may cause a nutritional imbalance or contain a toxic ion. In the current research, the pH values of all tile runoff fall within the optimal range for agricultural purposes which is 6.5 to 8.4 (Bauder et al., 2014)and for irrigation is 5.5 to 7.5 (Brunton, 2011), ensuring that the collected run-off can be utilized as alternative water source for non-potable activities, such as paddy farming, irrigation purposes, gardening and washing.

The total solids (TS) concentration in rainwater was 58 mg/l, while that of runoff from the control tile was 118 mg/l. The range of TS in the runoff from waste-added tiles was 100–139 mg/l (Table 3.4), corresponding to the value recommended for agricultural objectives (i.e. 0–2000 mg/l). With the addition of debris to clay mixtures, the roughness of the roofing material may have changed, leading to an increase in runoff pollutants.

Table 3.4 Water quality properties of runoff (De Silva et al., 2022)

Sample No.	**pH**	**Total Solid Concentration (TS) (mg/l)**
Direct rain	7.52 (± 0.06)	58 (± 0.17)
10 % RHA 0 % CS (control tile)	7.22 (± 0.01)	118 (± 1.9)

Sample No.	pH	Total Solid Concentration (TS) (mg/l)
Waste added tiles		
10 % RHA 10 % CS	6.56 (± 0.03)	100 (± 3.0)
10 % RHA 15 % CS	6.57 (± 0.05)	121 (± 2.1)
10 % RHA 20 % CS	6.49 (± 0.08)	139 (± 2.8)

3.5 Infiltration Rate and Permeability of Clay Roof Tile

The infiltration rate is the rate at which water permeates a clay roof's surface and the underlying strata. It is a crucial factor to consider when evaluating the efficacy of clay roofs in managing precipitation. Understanding the infiltration rate of clay roofs is vital for adequate rainwater drainage in Malaysia, where significant rainfall is typical.

Clay roofs have a certain degree of porosity, influencing the infiltration rate. Porosity refers to interconnected, microscopic fissures or spaces within the clay material. The greater the porosity, the greater the water infiltration potential. Excessive porosity can result in excessive water absorption and roof damage. Findings by Wang et al., (2021), depicts that clay roofing tiles are porous products (water absorption value up to 22% by weight), which may be susceptible to physical, chemical, and biological degradation. Since time passed, the relationship between the capillary characteristics of clay roofing tiles and their properties has been understood.

Table 3.5 Total porosity values and dominant pore intervals for the reference and the treated tiles (Ranogajec, 2013)

Tiles samples	Total porosity (%)	Dominant pore (μm)
Reference tile	32.93	0.5 – 1
Tile immersed in 4 wt% oxalic acid	26.16	2 – 4
Tile immersed in 4 wt% acetic acid	36.09	0.5 – 1

The rate of water absorption by clay roofs influences the rate of infiltration. Clay roofs with lower water absorption rates have slower infiltration rates, which indicates that they repel water more effectively and permit less water to permeate the roof surface. This property aids in preventing water from penetrating the structure and expedites surface runoff.

The static contact angle between a liquid and a solid surface is the primary parameter that characterizes wetting. If the liquid wets the surface, the fixed contact angle is $0 \leq \theta \leq 90°$ and if the liquid does not wet the surface, the contact angle is $90 \leq \theta \leq 180°$. Superhydrophilic surfaces have a contact angle of less than 10°, whereas superhydrophobic covers have a contact angle between 150° and 180°. For instance, from the perspective of wetting phenomena, clay roofing tiles with non-adhesive surface properties will be more durable. In such circumstances, surfaces will have a high contact angle, causing water droplets and dirt particulates to roll off. Regarding the wettability of a tile's surface, this characteristic is significantly influenced by the surface texture of the tile.

Table 3.6 Contact angle and surface energy values of clay roofing tile (Ranogajec, 2013)

Measuring fluid	**Contact angle (°)**	**Kwok, Neumann model (mJ m^{-2})**	**Li, Neumann model (mJ m^{-2})**	**Wu, Equation of state model (mJ m^{-2})**
Water	59.31	47.70	48.27	41.52
Glycerol	82.21	27.81	28.25	20.63

Few publications provide experimental data on the wetting properties of clay roofing tiles, including surface roughness, contact angle, surface energy values, and surface microstructure. Existing literature focuses primarily on the mineralogical, microstructural, and textural properties of building materials without direct correlation to their surface properties. Understanding the reactivity or energy value of the tile surfaces, specifically their interaction with fluids, is crucial for the durability of clay roofing tiles: surface moisture and microorganism adhesion. It has also been demonstrated that surface roughness and hydrophobicity influence bacterial adhesion.

Specifically, surface roughness is a dominant factor for the microbiological development on clay roofing tiles in their natural exploitation environment. The correlation between contact angle values and bacterial adhesion has been critically discussed (Bhushan, 2011). It has been hypothesized that adhesion forces may arise for hydrophobic surfaces because water is more easily removed from the area between the cell surface and a hydrophobic material than from the area between the cell surface and a hydrophilic material, enabling a closer approach and thus stronger adhesion forces (Buergers et al., 2009). The chemical properties of a surface tile are another important factor affecting the hydrophilicity. With an increase in chemisorbed hydroxyl content on the surface, the polar properties and the hydrophilicity value of the surface are enhanced.

3.6 Evaluation of Metal Deck Roof for Rainwater Drainage

Due to their durability, strength, and adaptability, metal deck roofs are commonly used in Malaysia. When assessing the efficacy of metal deck roofs for water drainage, a number of crucial factors must be considered.

Firstly, the pitch or slope of a metal deck roof is vital for water discharge. A roof with a steeper slope enables water to flow more rapidly and efficiently, reducing the likelihood of water pooling or stagnant areas. The profile of the metal deck roof, such as its ribbing or corrugation, can also influence drainage by diverting water along the channels and preventing water buildup on the roof surface.

Coatings and finishes on metal deck roofs can affect the drainage of precipitation. Weather-resistant and non-abrasive layers make it easier for water to travel off the top, preventing water retention and facilitating efficient drainage. In addition, special coatings can provide additional corrosion protection, ensuring the roof's durability and efficacy in the Malaysian climate.

Typically, metal deck roofs incorporate gutters and downspouts to capture and direct rainwater away from the roof. The design, dimensions, and placement of these elements are crucial for ensuring adequate rainwater discharge. The correct dimensions and placement of gutters and downspouts prevent overflow, minimize water damage to the building's foundation, and direct water to appropriate drainage systems.

The load-bearing capacity of metal deck roofs should be evaluated for their ability to withstand intense rainfall. In Malaysia, where intense rainfall is common, it is essential that metal deck roofs can sustain the weight of accumulated rainwater without compromising the structural integrity of the building.

Maintaining and inspecting metal deck roofs on a regular basis is essential for effective rainwater discharge. Maintaining the functionality and performance of the roof in managing rainwater runoff requires the removal of detritus, inspection for blockages or damage, and prompt resolution of any issues.

3.7 Material Properties and Drainage Performance of Metal Deck Roof

The exceptional material properties of metal deck roofs in Malaysia have made them popular for various building types. These roofs are typically constructed from durable, sturdy materials like steel or aluminum. Metal deck roofs can withstand the challenging Malaysian climate, characterized by heavy rainfall, powerful winds, and intense sunlight due to their material properties. With their superior structural strength and resistance to corrosion, metal deck roofs provide long-lasting performance and dependable weather protection. In addition, their waterproofing properties provide an effective barrier against water infiltration, thereby protecting the underlying structure from leakage and water damage. Due to their material properties, metal deck roofs in Malaysia are a reliable and long-lasting option for rainwater discharge and roof protection in various building applications.

Table 3.7 The material properties of metal deck roof

Properties	Explanation
Durability	Malaysian metal deck roofs are renowned for their durability. They typically comprise highly-strength and corrosion-resistant materials, such as steel and aluminum. This durability ensures the top can withstand the harsh tropical climate, including heavy precipitation, powerful winds, and intense sunlight, without significant deterioration.
Strength	The superior structural strength of metal deck roofs enables them to span great distances and support large loads. This durability is necessary for withstanding the weight of precipitation accumulation during Malaysia's extreme rainfall events. The metal deck roof's structural integrity ensures it can effectively manage precipitation without jeopardizing the building's safety and stability.
Waterproofing	Roofs made of metal decking are designed to be impermeable or highly water-resistant. The materials and coatings applied to the roof surface serve as an effective water barrier. This feature prevents water from penetrating the roof and causing leakage or water damage to the structure beneath.

The drainage performance of metal deck roofs in Malaysia is crucial for managing rainwater discharge effectively. These roofs are designed to optimize water flow, assuring adequate drainage during periods of heavy precipitation. The roof pitch, which refers to the roof's slope, is carefully considered to facilitate the rapid flow of rainwater and reduce the danger of water pooling or stagnant areas. Furthermore, the profile design of metal deck roofs, such as ribbing or corrugation, contributes to their drainage performance by producing channels that direct water along specific paths, allowing for a more rapid and controlled runoff. Integrated gutters and downspouts improve drainage by collecting and directing rainfall away from the roof surface. By prioritizing optimal drainage performance, metal deck roofs in Malaysia provide effective precipitation management, thereby reducing the likelihood of water damage and ensuring the structural integrity of buildings in various applications.

Table 3.8 The drainage performance of metal deck roof

Characteristic	Explanation
Roof Pitch	The inclination or slope of a metal deck roof significantly impacts its drainage performance. A roof with a steeper slope enables rainwater to flow more efficiently, reducing the likelihood of water pooling and stagnant areas. The optimal pitch should be considered in the design and installation of the metal deck roof to ensure rapid and effective rainfall runoff.
Profile Design	Metal deck roofs' profile design, such as ribbing or corrugation, affects drainage performance. These profiles generate channels or ridges that direct water along specific paths, allowing for more efficient and regulated discharge. For effective rainwater management, the design should consider factors such as the amount of rainfall encountered in Malaysia and the desired flow rate.
Gutters and Downspouts	Typically, gutters and downspouts are installed on metal deck roofs to remove rainwater from the roof surface. Proper channels and downspouts that are designed and installed guarantee efficient drainage, preventing water from pooling on the top or overflowing. For effective rainwater management, the sizing and positioning of these elements are crucial.
Maintenance and Inspection	Maintaining and inspecting metal deck roofs regularly is essential for optimum drainage performance. Maintaining the functionality of the drainage system requires cleaning the roof surface, removing debris, and inspecting gutters and downspouts for clogs or damage. Proactive maintenance practices reduce the risk of clogs and ensure that the metal deck roof can manage rainfall runoff effectively.

3.8 Measurement and Analysis of Rainwater Runoff of Metal Deck Roof

According to Charters et al., (2021), for corrosion and discharge rates, roof characteristics such as pitch and orientation, the roof's age, exposure time, and the type of roofing material are some of the crucial considerations. As the slope angle increases, the discharge rate drops dramatically. A study on different roof inclinations confirms this correlation, as values in the range of 6.4–6.8 g/(m^{2}a) have been measured for the total accumulated zinc (Zn) in the runoff from a roof with an inclination of 7°, 4.5–5.7 g/(m^{2}a) from an inclination of 45°, and 0.9–2.5 g/(m^{2}a), depending on the exposure direction, respectively (Charters et al., 2021).

This is because as the slope increases, a smaller quantity of rainwater impinges on the roof surface, and the contact time between precipitation and the roof surface decreases, causing the rainwater to run off more quickly (Galster, 2022). Consequently, the quantity of corrosion products rinsed away is less (Charters et al., 2021).

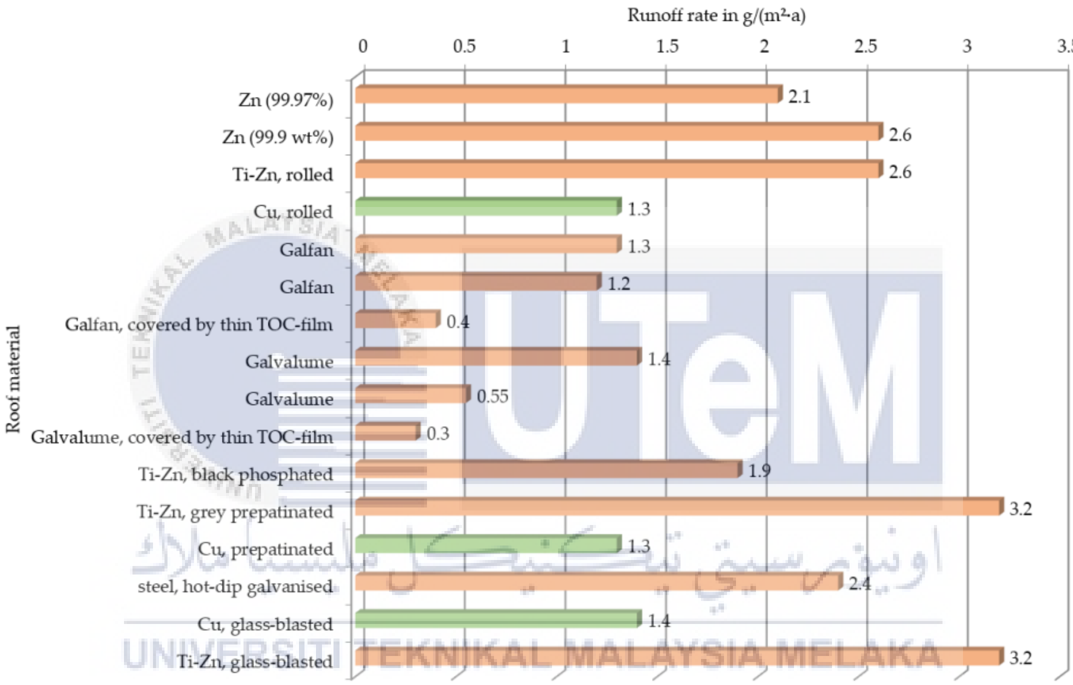

Figure 3.2 Types of roof material and its runoff rate

3.9 Infiltration Rate and Permeability of Metal Deck Roof

The infiltration rate of a metal deck roof is the rate at which water penetrates the roof's surface and permeates the underlying layers. Understanding the infiltration rate is essential for assessing the effectiveness of metal deck roofs in Malaysia in regulating rainwater.

Malaysian metal deck roofs typically have specialized coatings and finishes that increase water resistance. These coatings reduce infiltration by minimizing water absorption and promoting rapid discharge. These coatings create a smooth surface that allows water to run rapidly off the roof, preventing water accumulation and potential leaks. In this instance, the increase in corrosion resistance and decrease in Zn discharge rates primarily depend on the coating thickness.

The base or superstructure material of metal roofs can influence permeability. For example, if a metal deck roof is erected over a permeable substrate, such as a vapour barrier or insulation, the permeability of the underlying layers may affect water flow and drainage performance (Farreny et al., 2011). Adequate runoff is typically prioritised over infiltration in the context of metal deck roofs. The design of metal deck roofs minimizes the water infiltration rate and prevents water from entering the building structure.

3.10 Implementation of Computational Fluid Dynamic (CFD) Simulation

CFD software enables the accurate simulation of fluid flows in order to conduct comprehensive drainage evaluations on roof structures. By initially creating a three-dimensional representation of the roof surface, it is possible to accurately simulate the amount of precipitation that hits the roof by mapping the inlet boundary conditions.

Outlet drainage points discharge the collected runoff according to the force of gravity. The dynamic CFD solvers perform numerical calculations to determine the velocity and volumetric flux outputs throughout the specified domain. Geometric alterations can be used to represent variations in the slope of a roof in three dimensions, allowing for the calculation of drainage rates for comparison. The high-fidelity simulations depict the complete paths of rainwater movement on rooftops, taking into account the effects of surface friction and momentum. The boundary exit velocity flow data is used in post-processing to calculate precise runoff rate measures, measured in liters per second.

These metrics are then used to evaluate the effectiveness of drainage performance improvements resulting from various pitch adjustments predicted in the CFD model. This mitigates the need to depend exclusively on intricate physical prototypes. To summarize, CFD provides a flexible digital platform for simulating real-world fluid drainage patterns caused by environmental elements such as rain and structural factors such as roof slope. This is done inside a dynamic computer modeling environment.

3.10.1 CFD Simulation of the Experimental Study Conducted in a Wind Tunnel

The current work involves the examination of wind loads on a pyramidal roof of a low-rise building with a square floor plan. This analysis is conducted using computational fluid dynamics (CFD) modeling and simulation. Several wind tunnel experimental studies have been undertaken at CSIR-CBRI in Roorkee, India (Kumar Roy et al., 2012). Kumar Roy et al., (2012), conducted a wind load analysis for the pyramidal roof of a low-rise building with a square floor plan. The provided information has been utilized to verify the velocity and turbulence intensity profile. The model dimension remained unchanged to facilitate comparisons of the various parameters. The ANSYS tool has been utilized for simulation, with ICEM CFD being employed for modeling. The results have been obtained using CFD Post. The model is partitioned into a finite number of volumes (cells) using a hexahedral mesh in ICEM CFD. The ANSYS Fluent software use the finite-volume approach to solve the governing equations. For the simulation in Fluent, the realizable k–ε turbulent model has been utilized. The results are obtained in CFD Post, which mostly comprises wind pressure coefficient contours.

3.10.2 Computational Parameters in CFD Simulation

Four building models with pyramidal roofs are constructed in ICEM CFD, each with a different roof slope: 0°, 10°, 20°, and 30°. The dimensions of the pyramidal roof building model were obtained from a prior study (Kumar Roy et al., 2012). Figure 3.3 displays both the domain specifications and the size of the building model. Measurements are captured using a scale ratio of 1/25. The diagram in Figure 3.3 (a) displays the building model, including its dimensions and the dimensions and position of an opening. Another opening, depicted in Figure 3.3 (b), is positioned on the opposite wall C in the same manner. Specifically, it is located 36 mm above the bottom (equivalent to a full scale height of 0.9 m) and is centrally placed 72.5 mm (equivalent to 1.8 m) from the corners. Both holes have identical dimensions, specifically 80 mm × 40 mm (2 m × 1 m).

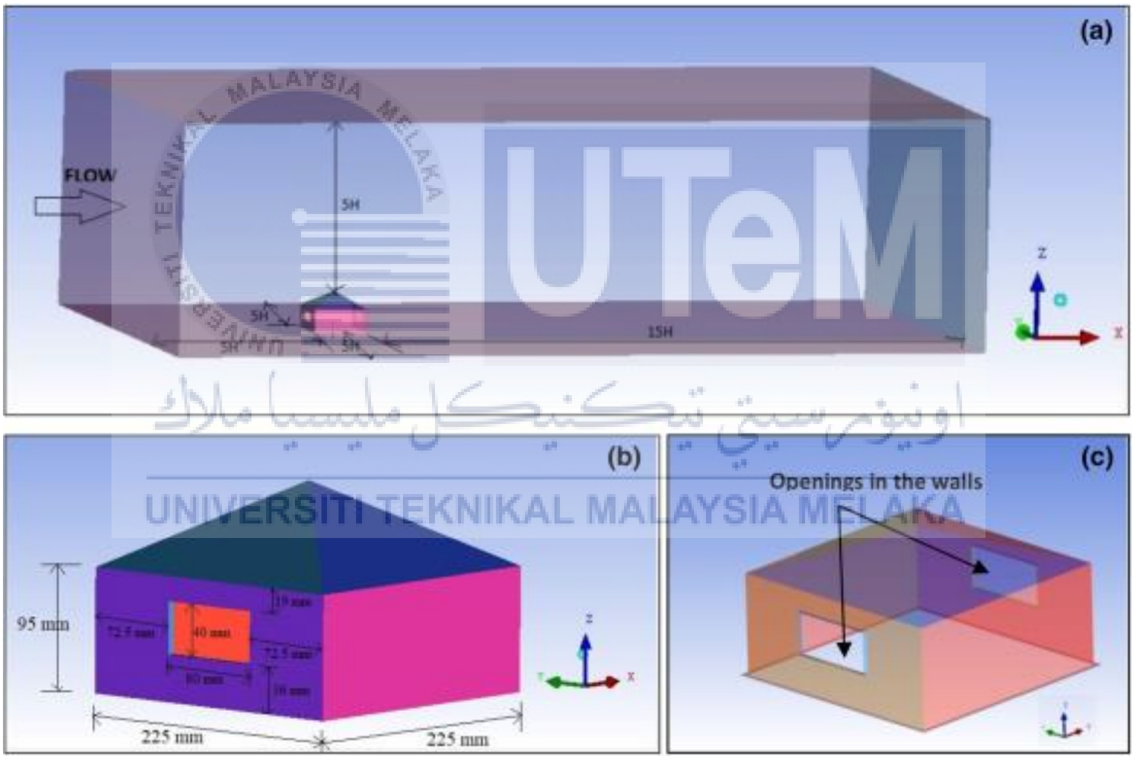

Figure 3.3 (a) Computational domain of the building models, (b) building model created in ICEM CFD and the location of the opening in the walls, with the dimensions and (c) the locations of the two openings in the walls

3.10.3 CFD Domain and Building Model Meshing

The building models are generated using ICEM CFD, as illustrated in Figure 3.3. Given that the accuracy of the simulation processing and results is contingent upon the quality of the mesh, it is necessary to have a finely detailed mesh surrounding the building model. A hexahedral grid with a structural configuration was utilized for the purpose of meshing. Figure 3.4 (a) demonstrates the utilization of a fine meshing technique on the faces of the pyramidal roof building and in the vicinity of the lower area surrounding the model. It is essential to assess the mesh's quality for each model. The investigation demonstrates that the mesh quality exceeds 0.6 in every model, as depicted in Figure 3.4 (b). The ANSYS tool ICEM CFD can be utilized to assess the quality of the mesh. A meshing quality of 0.5 or above, within a range of 0.0 to 1.0, is considered to be good and is suitable for achieving a converged solution in Ansys 2007.

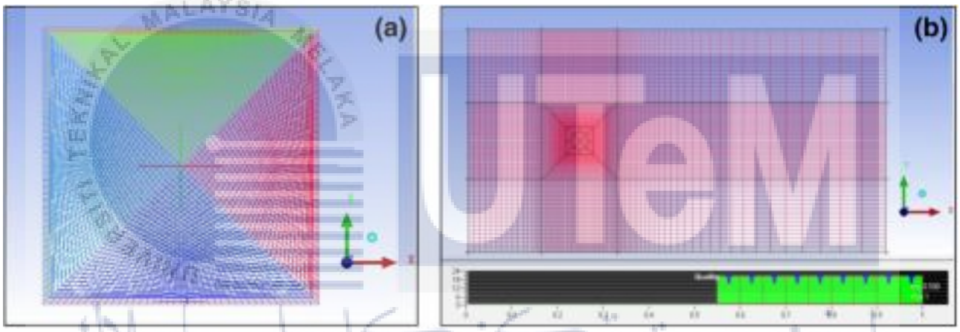

Figure 3.4 (a) Model of building and (b) CFD domain meshing with quality check

3.10.4 Boundary Conditions

In order to accurately simulate the actual flow, it is essential to have adequate boundary conditions for a genuine physical representation of fluid flow. Establishing the specific boundary conditions at the entrance and exit of the flow domain, which is crucial for an accurate solution, is consistently challenging. The velocity inlet at the windward boundary was utilized with the given formulas for the along-wind component of velocity.

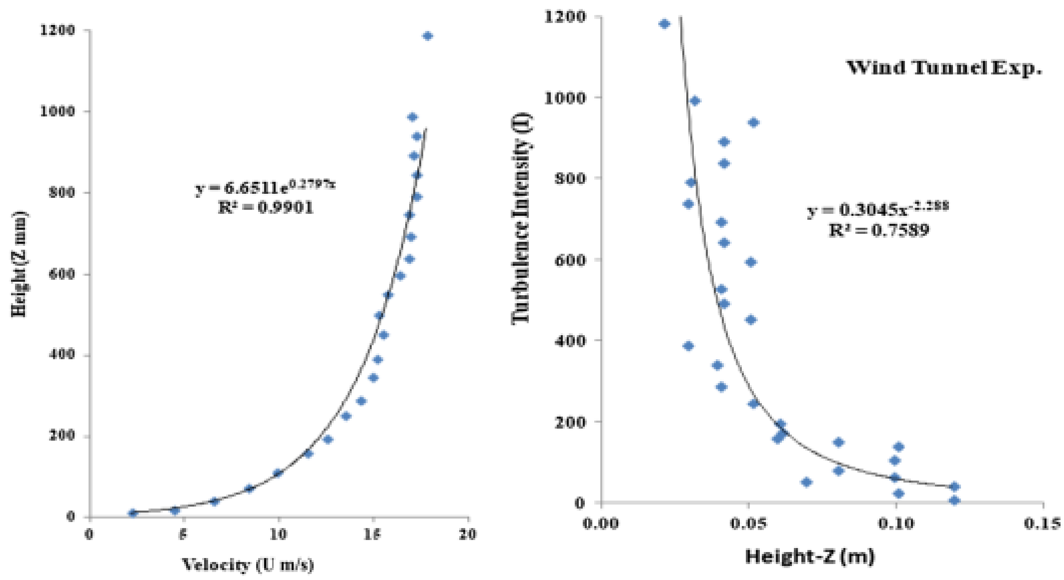

Figure 3.5 Wind tunnel experimental study velocity profile (U) and turbulence intensity (I) used for CFD simulation (Sanyal & Dalui, 2018)

The velocity (U), which varies with eight of the inlet domains, is comparable to the experimental investigations carried out by Kumar Roy et al., (2012). The velocity profile in the atmospheric boundary layer (ABL) is typically depicted in the standard manner illustrated below:

$$U(z)\frac{u*}{\kappa} = \ln\frac{z + z0}{z0} \tag{3.1}$$

It was important to validate the numerical results by comparing them with experimental results. The validation of the velocity profile and turbulence intensity has been demonstrated in Figure 3.5 (Kumar Roy et al., 2012). In the present work, the values of the parameters z_0 and u_* are as follows: $z_0 = 0.0001$ m and $u_* = 0.11$ m/s. The longitudinal turbulence intensity (I) is converted into turbulent kinetic energy (k) for the simulations using Equation (3.2), under the assumption that the $\sigma v << \sigma u$ and $\sigma w << \sigma u$. It has been noted that when the value of k increases, a slight discrepancy is detected in the results, with a difference of a few percentage points (< 5%) in the amplitude of amplification factors:

$$k\ (z) = 0.5\ (I_U U)^2 \tag{3.2}$$

The profile for the dissipation rate of turbulence at the intake, denoted as ε, as described by Richards & Hoxey (1993), is provided as follows:

$$\epsilon\ (z) = \frac{u_*^3}{\kappa(z + z_0)} \tag{3.3}$$

The equation represents the relationship between the height coordinate (z), the von Karman constant (κ), the scaled aerodynamic roughness length (z_0), and the friction velocity (u_*) in a horizontally homogenous (stable) atmospheric boundary layer (ABL) flow. The von Karman constant is approximately 0.42. The scaled aerodynamic roughness length is calculated using a power-law exponent of 0.15, resulting in a value of 0.0012 meters for z_0.

The upper and lateral boundaries of the computational domain are represented as slip walls, meaning that the normal velocity is 0 and there are no changes in the normal gradients of all variables. The exit is characterized by a static pressure of zero.

3.10.5 Solver Settings

The ANSYS software utilizes the finite-volume approach. Fluent is utilized for the purpose of solving governing equations and the corresponding case-specific boundary conditions. The fundamental concept behind the utilization of the finite element approach is to partition the body into discrete subdivisions or isolated regions referred to as finite elements. Size of the stiffness matrix be decided by the number of nodes and the results are revised by increasing the number of nodes and collocation points. Each element of Fluent is associated with governing equations, and these elements are combined to form a global matrix.

As previously mentioned, the clarifications were in a state of equilibrium. The momentum, pressure, and turbulence equations were subjected to second-order differencing. The "coupled" pressure-velocity coupling method was employed due to its effectiveness in addressing steady-state, single-phase flow problems.

The residuals did not meet the commonly used threshold of decreasing to 10^{-4} of their initial values after several hundred repetitions. However, the convergence of the simulations was not solely determined by this check. The drag, lift, side forces, and moments experienced by the pyramidal roof building model were also analyzed during the simulation. Only when these values reached stable levels were the simulations considered to have converged. Despite the simulations being in a steady state, there was a slight fluctuation (<1%) in the "steady" values of the several monitoring parameters.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The chapter presents the final outcomes of a thorough examination into the impact of roof slope and pitch on the rates at which rainwater flows off roofs, with a specific emphasis on clay and metal roofs. This chapter explores the results obtained from experimental observations and Computational Fluid Dynamics (CFD) simulations, providing insights into the interaction between rainwater and different roof materials on different slopes. The study examines both the quantitative components of runoff rates and use CFD models to visually and comprehensively understand the complex dynamics of rainfall landing on various roof surfaces. By integrating these many techniques, a thorough understanding of how the slope, pitch, and material of a roof jointly influence the efficiency and patterns of rainfall drainage. This chapter seeks to reveal valuable insights for making educated decisions in sustainable roofing design and water management techniques by combining empirical findings and virtual simulations.

4.2 Material Selection of Roof Design

Based on previous studies, it is clear that the choice of roofing materials significantly impacts the efficiency of rainwater drainage systems. According to Lai et al., (2018), the porous nature of clay allows for some retention, permitting filtration, in contrast to the imperviousness of metal. The intrinsic inert nature of clay further prevents the risk of metallic ion leaking into runoff. Both types of roofs require the initial redirection of rainfall to prevent the accumulation of early debris and impurities. However, the surface roughness of clay have a greater ability to effectively capture particulates after the initial flush compared to smooth metal panels.

Prior to becoming safe for consumption, clay tile water necessitates the use of sediment filters, UV treatment, and boiling. However, the use of metal decking increases the likelihood of chemical and microbial threats, which necessitates more rigorous treatment methods like as activated carbon filtering. Consequently, this leads to higher infrastructure expenses. The red tones and ceramic thermal mass of clay minimize the transfer of solar heat to the gathered water, in contrast to heat-reflective coated metal decks. This reduces the potential for bacterial contamination.

Clay tile roofing facilitates superior natural hydrological filtration, chemical purity, and reduced heating of rainwater collection, resulting in safer and higher quality water for residential reuse following normal treatment.

Table 4.1 Tabulation of results (Lai et al., 2018)

Parameters	**Units**	**Clay**	**Metal**
Physical			
pH	pH	7.18	5.51
Conductivity	µs/cm	57.73	17.82
Total Dissolved Solid	mg/L	29.03	9.31
Salinity	psu	0.08	0.06
Main ions			
Nitrate, NO^{3-}	mg/L	4.53	3.23
Sulphate, SO^{4-}	mg/L	3.07	2.17
Hardness			
Calcium, Ca	mg/L	9.19	0.42
Magnesium, Mg	mg/L	0.25	0.04
Heavy Metal			
Aluminum, Al	mg/L	0.14	0.49
Zinc, Zn	mg/L	0.04	0.18
Iron, Fe	mg/L	0.03	0.45

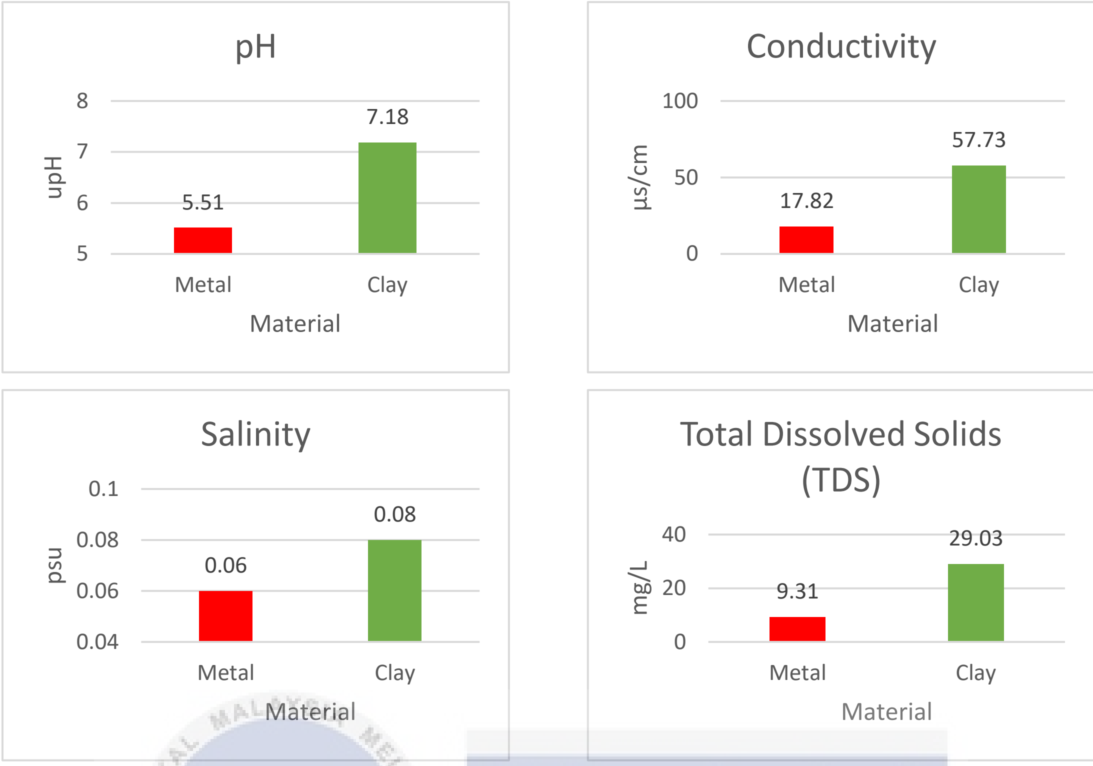

Figure 4.1 Graphs in ascending order of pH value, conductivity, salinity and TDS (Lai et al., 2018)

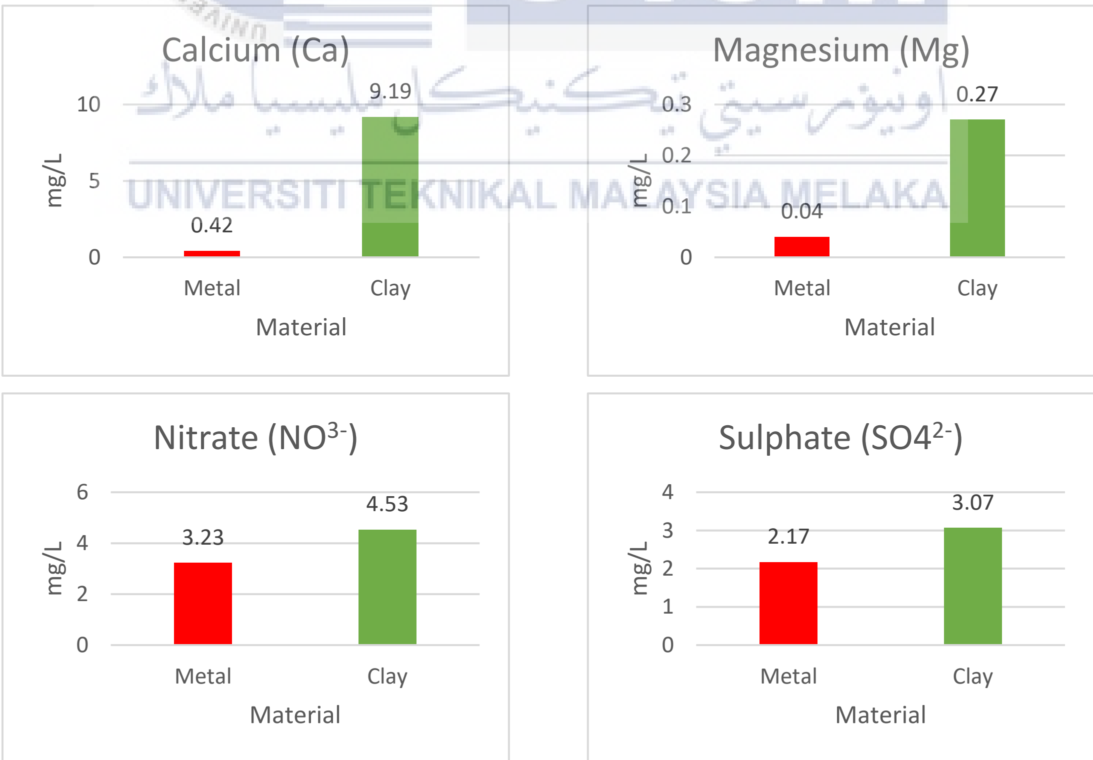

Figure 4.2 Graphs in ascending order of hardness and mineral contents of each material (Lai et al., 2018)

Figure 4.3 Graphs in ascending order of heavy metals content for each material (Lai et al., 2018)

4.2.1 pH value

The analysis of rainwater collected from clay tile roofs shows a relatively neutral pH level, similar to that of natural rainfall. This suggests that clay tiles have a minimal impact on the pH value of runoff water. The metal roof collects rainwater with a low pH value, which contradicts findings from other comparable studies. Nevertheless, the origin of the acidity remains unidentified. The elevated amount of aluminum corrosion observed in metal roofs is attributed to the decrease in pH generated by the runoffs. This indicates that metal roofs are composed of alloy metals that include aluminum.

4.2.2 Conductivity, Salinity and TDS

The graphs illustrate the maximum concentration of active ions in rainwater collected from clay tile roofs, with metal roofs exhibiting a somewhat lower level. Active ions can originate from substances like dissolved salt or weak acids, such as the regularly encountered hydrochloric acid. Calcium and magnesium ions are significant contributors to water hardness. The active ions present in clay tile roof runoffs primarily originate from dissolved salt and hardness, as indicated by the measured non-acidic pH value.

4.2.3 Hardness

The presence of calcium and magnesium on clay tile roofs is likely a result of the breakdown of calcium carbonate and magnesium carbonate compounds from concrete and lime surfaces. The elevated levels of calcium and magnesium present in the runoff from clay tile roofs contribute to the pH graph, as they are alkaline in nature. The rainwater collected from the metal roof has a relatively low mineral content, which reduces the need for extensive treatment in order to make it suitable for household cleaning needs.

4.2.4 Minerals

Increased porosity of clay tiles leads to the proliferation of lichens and mosses, thereby indicating elevated levels of nitrate content. Hence, it is crucial to prioritize maintenance for clay tile roofs due to their surface texture, which has a high propensity to retain moisture and silt. The nitrate content found on a metal roof may originate from the decomposition of fallen leaves or the excrement left by birds or rats. The nitrate content is unlikely to directly affect clay tiles, as clay tiles consist mainly of minerals such as clay and shale. Nevertheless, elevated amounts of nitrates in the nearby surroundings can potentially lead to the erosion of underlying metallic elements, such as fasteners or flashing.

Increased levels of nitrates in the air or water runoff can expedite the process of corrosion on metal roofs, especially if the metal is prone to oxidation. This could result in a decrease in the longevity and structural soundness of the metal roofing material.

4.2.5 Heavy Metals

Due to the acidic nature of its discharge, the metal roof exhibits corroded surfaces and metal frames, which further accelerates the degradation of the aluminum compound on the roof. The zinc concentration graph displayed notable readings on the metal roof as well. The oxidation of alloy metal sheets can lead to the formation of a mixture of corroded metals, such as zinc and aluminum, on the surface of the roof. This mixture is subsequently washed away by the runoffs. The metal roof had the most elevated levels of aluminum, zinc, and iron content, primarily attributed to the accumulation of rust and debris resulting from falling leaves or animal excrement.

4.3 Uniformity of the Velocity Profile in CFD Simulation

The horizontal homogeneity of the velocity profile refers to the fluctuation of velocities within a region on the side of the building model that faces the wind. Between Line numbers 22 and 30, nine vertical locations were established at intervals of 100 mm each to assess the horizontal uniformity of the velocity profile, as depicted in Figure 4.4 (a). The velocity profiles at various positions throughout the height of the domain are depicted in Figure 4.4 (b). The wind velocity at the top of the building is approximately 11 m/s, confirming the accuracy of the velocity profile in the CFD simulation.

It is noted that at Line 29, which is in close proximity to the building within the area, the velocity profile is lower compared to that at Line 28. This phenomenon occurs due to the barrier provided by the positioning of the building, resulting in the convergence of velocity streamlines. As the wind approaches the building, it is compelled to maneuver around and above it. This leads to a decrease in wind velocity, particularly in the immediate region of the structure.

The velocity profile of the vertical sites adjacent to the building model on the side facing the wind exhibits a steady drop compared to the lines at the inlet position, as depicted in Figure 4.4. The white velocity profile corresponds to the intake position, whereas the yellow profile is near the building model. At the height of the building, the magnitude of the velocity is 15% lower than the velocity at the intake. As the distance from the bottom increases, the amplitude of velocity remains consistent with other velocity profiles.

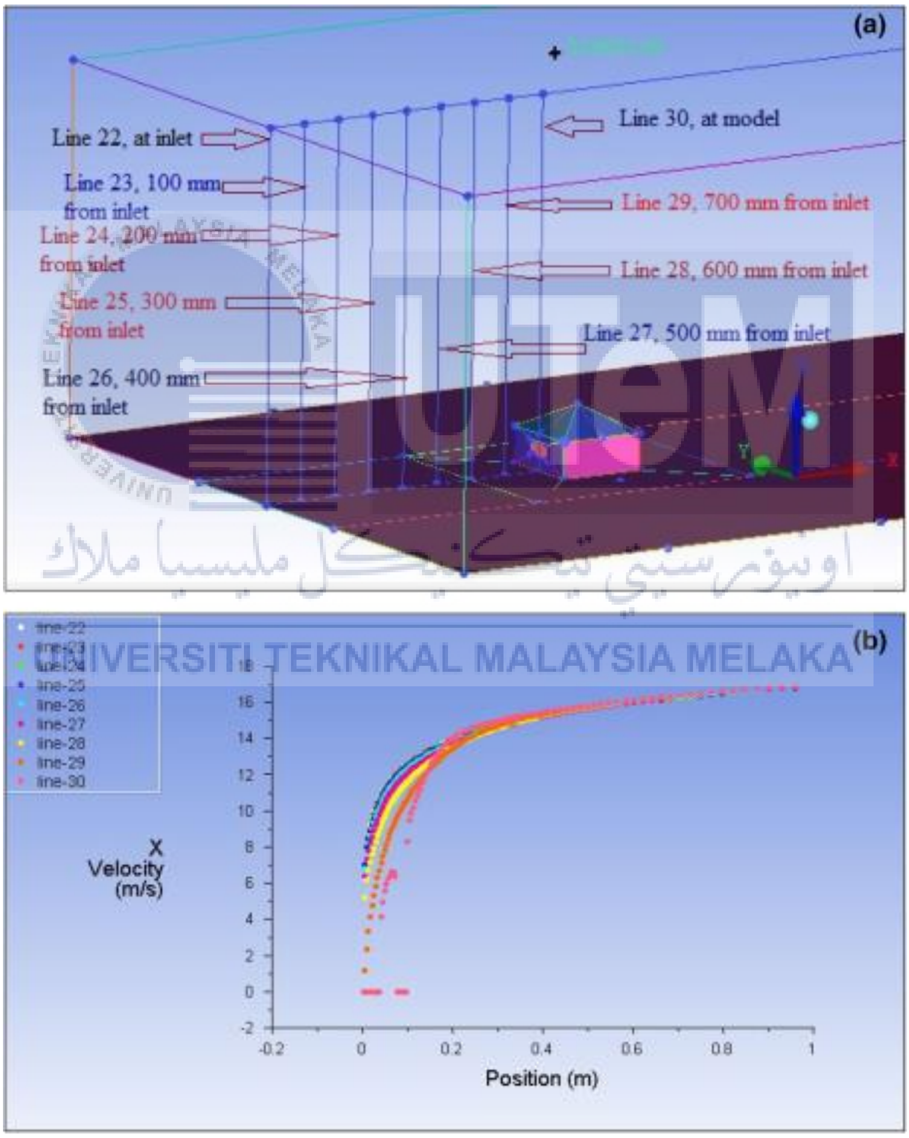

Figure 4.4 (a) Horizontal velocity profile uniformity on the windward side and (b) the position againts velocity graph

4.4 Coefficient of Pressure on the Roof Surface of the Building

In order to further examine the impact of the roof angle on the pressure coefficient on the building's roof surface, Figure 4.5 until Figure 4.8 display the contours of the pressure coefficient (Cp). Ansys Fluent was used to generate pressure coefficient contours for various roof slopes and wind directions. Contours depicting roof slopes of 0°, 10°, 20°, and 30°, as well as wind incidence angles of 0°, 15°, 30°, 45°, 60°, and 75°, are illustrated in Figure 4.5 until Figure 4.8. The roof has been partitioned into four distinct sections, namely face A, face B, face C, and face D. Face A is oriented towards the direction from which the wind is blowing, whereas face C is positioned opposite to face A and is on the side sheltered from the wind, with a wind incidence angle of 0˚. Face B and face D are adjacent faces of the roof and are parallel to the direction of wind flow when the wind incidence angle is 0˚.

In Figure 4.5, the roof is observed to be flat. Among all the incident wind angles, the maximum pressure coefficient is determined to be -0.4. This value is lower than the maximum pressure coefficient of -0.9 obtained from wind tunnel experiments and the maximum pressure coefficient of -0.98 obtained from CFD simulations on a flat roof without any openings, as reported by Kumar Roy et al., (2012) and the windward roof surface of the flat roof structure has a maximum pressure coefficient of -0.8.

In Figure 4.6, the roof has a slope of 10°. Among all the wind angles tested, the highest pressure coefficient observed is -0.57. This value is lower than the maximum pressure coefficient of -0.98 observed in wind tunnel experiments and the maximum pressure coefficient of -0.91 observed in CFD simulations on a pyramidal roof with a 10° slope and no openings, as described by Kumar Roy et al., (2012). Additionally, the windward roof surface of the 10° gable roof building experiences a maximum pressure coefficient of -1.4.

In Figure 4.7, the roof has a slope of 20°. Among all the wind angles tested, the highest pressure coefficient observed is -1.5. This value is greater than the maximum pressure coefficient of -1.1 obtained from wind tunnel experiments, but lower than the maximum pressure coefficient of -1.6 obtained from CFD simulations on a pyramidal roof with a 20° slope and no openings, as described by Kumar Roy et al., (2012). Additionally, the maximum pressure coefficient on the windward surface of the 20° gable roof building is -1.2.

In Figure 4.8, the roof has a slope of 30°. Among all the wind angles tested, the highest pressure coefficient observed is -1.5. This value is greater than the maximum pressure coefficient of -1.1 determined through wind tunnel experiments, but lower than the maximum pressure coefficient of -1.6 obtained through CFD simulation for a pyramidal roof with a 20° slope and no openings, as described by Kumar Roy et al., (2012). Additionally, the maximum pressure coefficient on the windward roof surface of the 20° gable roof building is -1.2.

By examining Figure 4.5 until Figure 4.8, it can be noted that the wind pressure coefficients transition from a negative pressure coefficient to a positive pressure coefficient as the roof slope increases from 0° to 30°. The roof with a roof slope of 0° exhibits negative pressure coefficients due to its flat configuration. The roof, which has slopes of 10° and 20°, exhibits negative pressure coefficients on a majority of its surface due to its resemblance to a flat roof. Figure 4.8 shows that a maximum positive pressure coefficient of 0.3 is recorded for a 30° roof slope at 45° wind directions. However, for a 30° gable roof building, the pressure coefficient is 0, and for a 45° gable roof building, it is also 0.3.

The pressure coefficient values seen at different locations on a roof surface would vary for Computational Fluid Dynamics (CFD) simulations conducted on models with variable roof slope angles. This phenomenon arises from variations in the manner in which airflow is generated and gains speed across sloping surfaces with varied angles.

On roofs with higher inclines, the wind strikes an obstructing surface at a more direct right angle. This results in the divergence and abrupt alteration of wind velocity streams. Regions of increased air velocity form above the inclined slope, resulting in reduced pressure in accordance with fluid dynamics. Unlike flatter roof forms, where wind encounters a gradual increase in slope distributed across a larger area, there is less barrier to redirect the airflow into pockets of fast-moving streams. The airflow velocity remains consistently stable without any significant spikes at any given time.

Therefore, in the context of CFD wind study on structures, the pressure coefficients exhibit greater variations between high and low values for roofs with steeper pitches, due to the erratic movement of the wind. The presence of smooth airflow on flat roofing results in fewer differences in pressure coefficients, which do not significantly disturb the flow of air. Essentially, steeper roof angles cause wind to change direction more suddenly, leading to faster airflow and larger pressure differences as solved by CFD. Gradual changes in slope facilitate seamless transitions in fluid flow, resulting in reduced variations in pressure coefficient values in computational fluid dynamics (CFD) outputs.

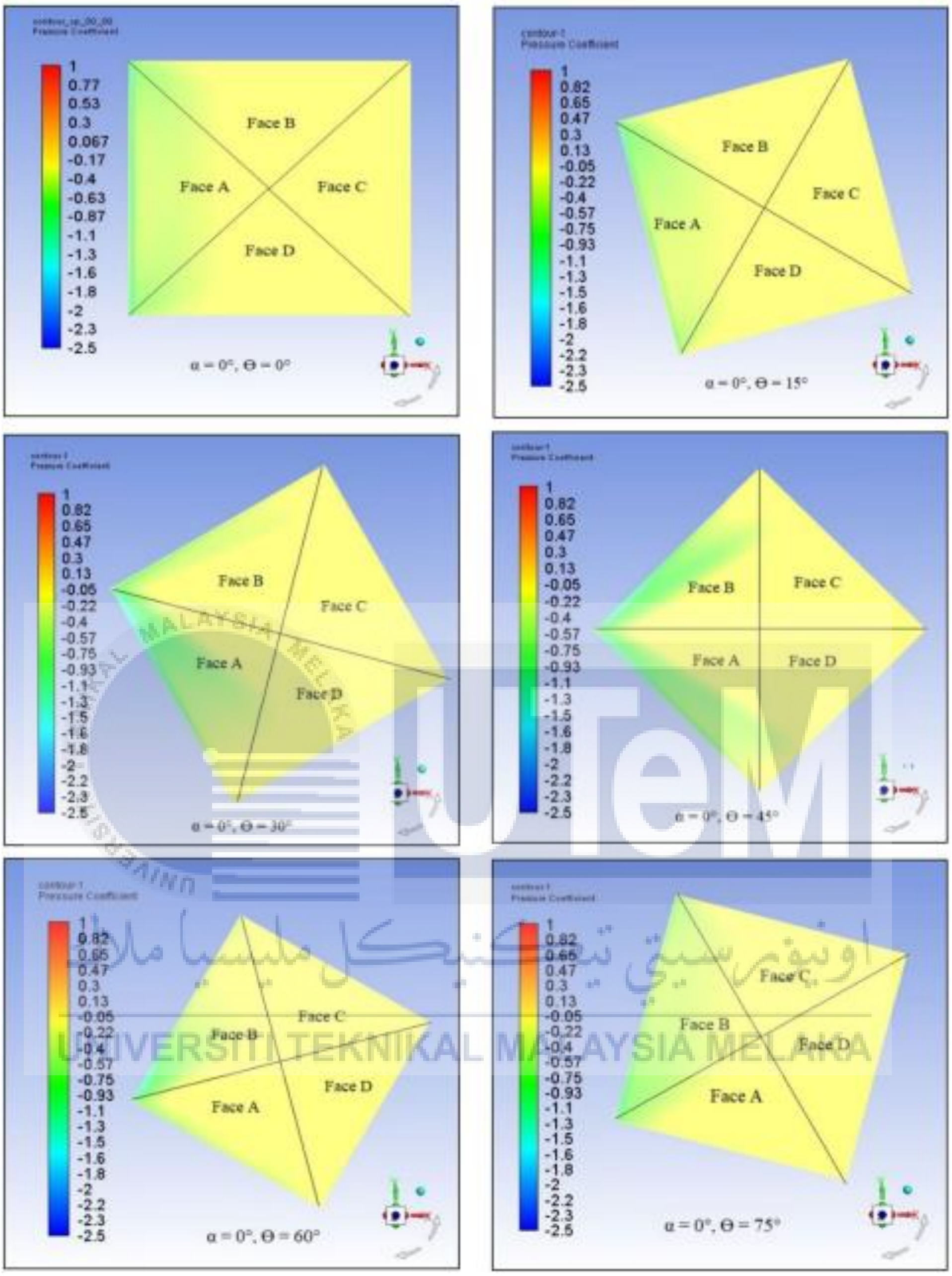

Figure 4.5 Contours of pressure coefficient for 0° roof slope and various wind direction from 0° to 75° @ 15° intervals

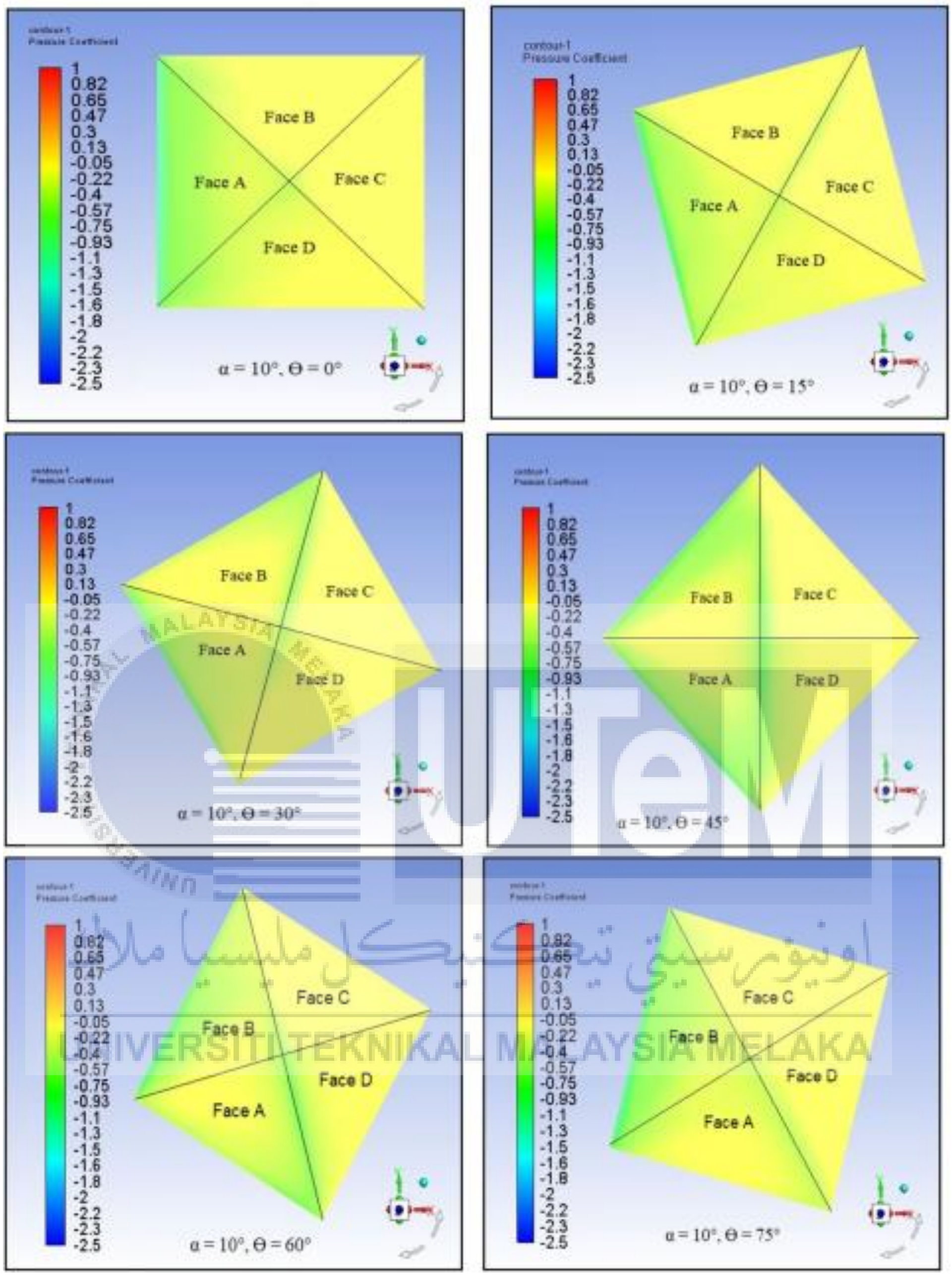

Figure 4.6 Contours of pressure coefficient for 10° roof slope and various wind direction from 0° to 75° @ 15° intervals

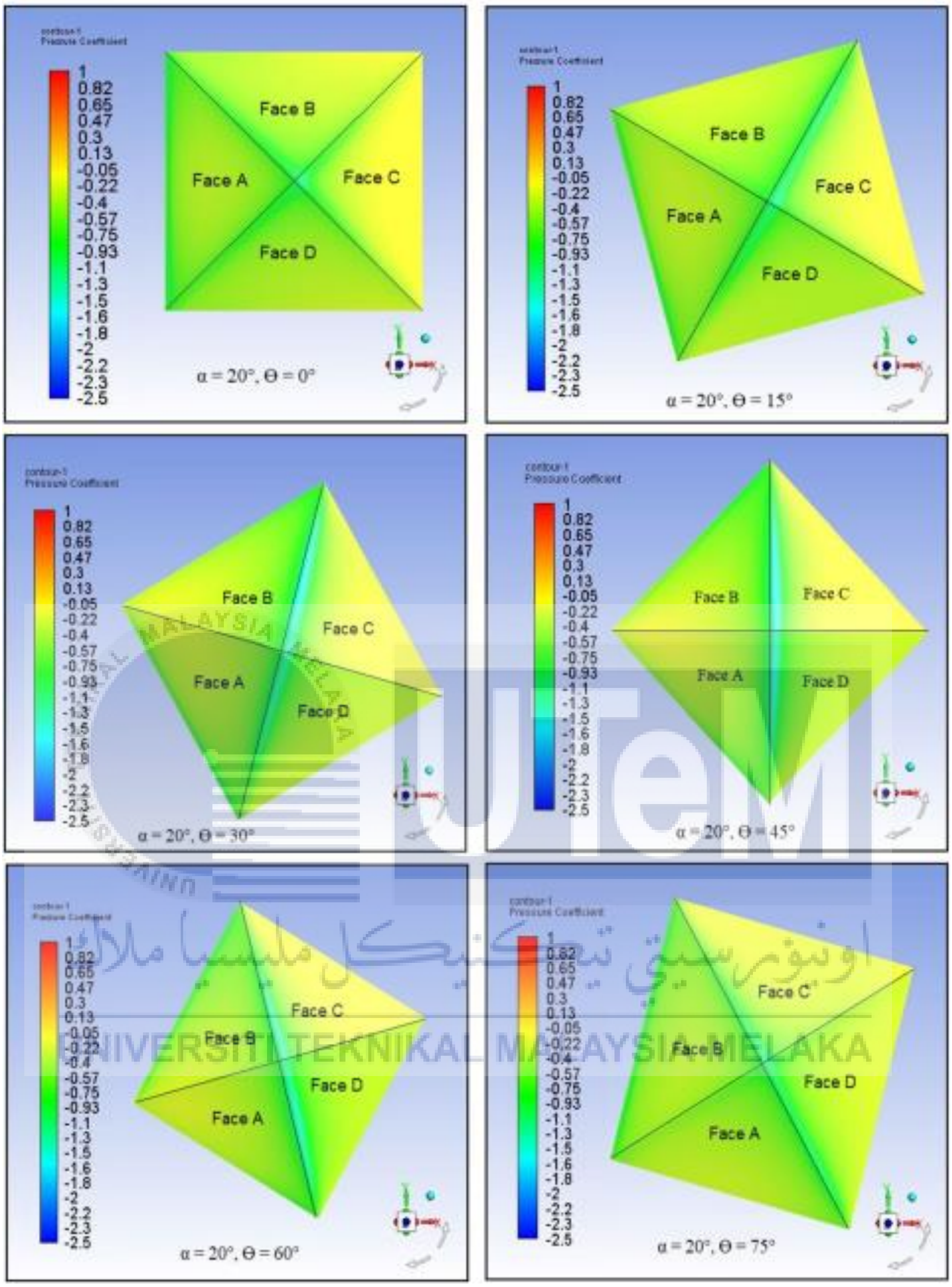

Figure 4.7 Contours of pressure coefficient for 20° roof slope and various wind direction from 0° to 75° @ 15° intervals

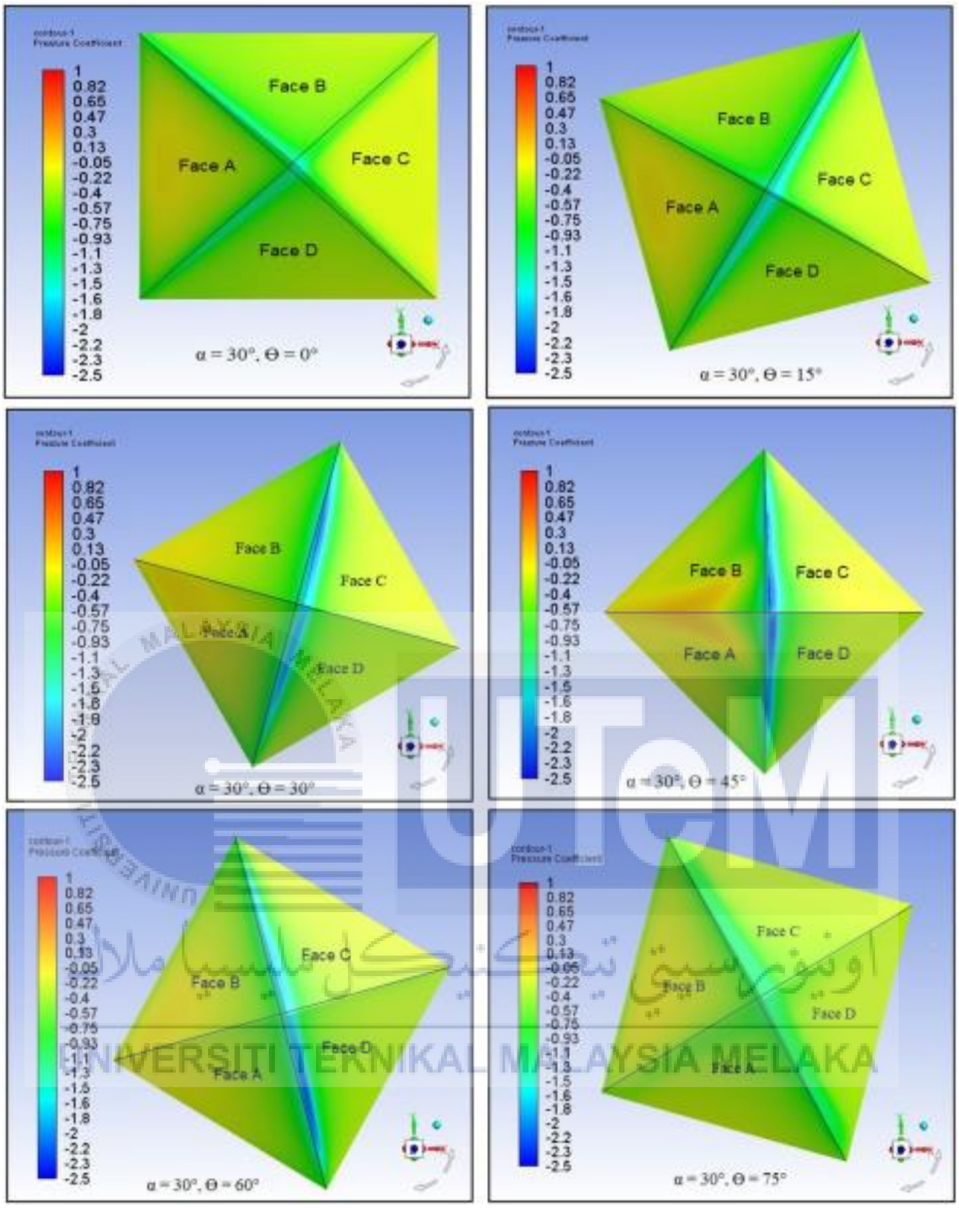

Figure 4.8 Contours of pressure coefficient for 30° roof slope and various wind direction from 0° to 75° @ 15° intervals

By examining Figure 4.9, which displays graphical representations of area weighted pressure coefficients, it becomes evident that the quantity of negative pressure, or suction, varies continuously with changes in wind direction. Based on the graphs, it is evident that when a face is perpendicular to the wind direction, there would be larger pressure coefficients in comparison to the pressure coefficients on parallel faces.

When a face is at a right angle to the wind direction, it exposes a greater surface area to the approaching wind. The greater surface area leads to a more direct impact of the wind, resulting in increasing pressures on the surface. On the other hand, parallel faces have a diminished effective frontal area, since the airflow can move more seamlessly around the surface without immediately impacting it at a right angle. This can lead to decreased pressure coefficients in comparison to the perpendicular surface.

It is worth noting that when two faces are joined at a right angle to the direction of the wind, the entire roof surface experiences reduced wind pressure. This is due to the way the wind is distributed, as the joint between the two faces divides the wind into two parts, resulting in a diminished impact on the roof surface.

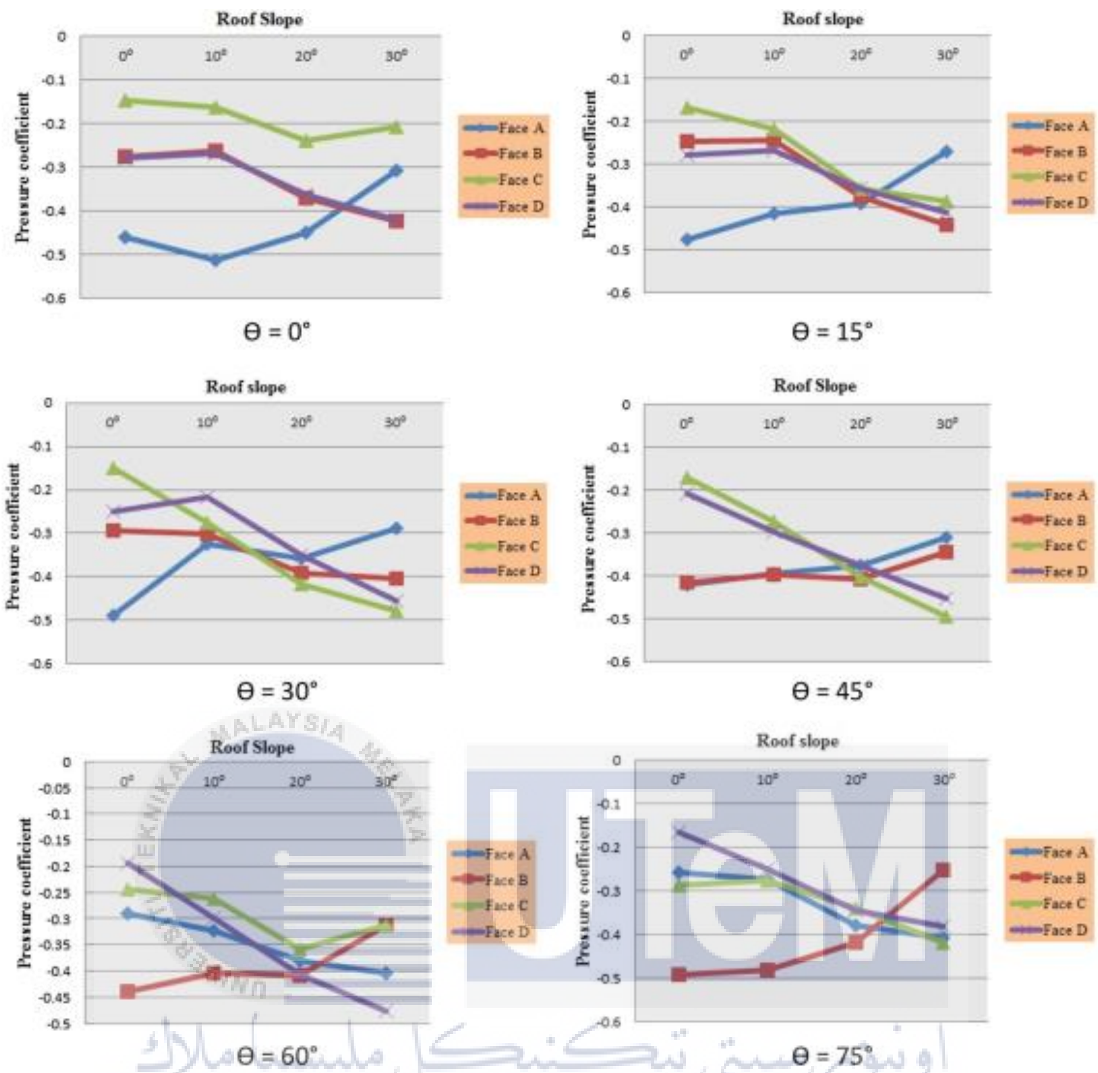

Figure 4.9 The relationship between the change in roof slope (α) and the variation in area-weighted averaged mean pressure coefficients (Cp) is examined for different wind directions (Θ)

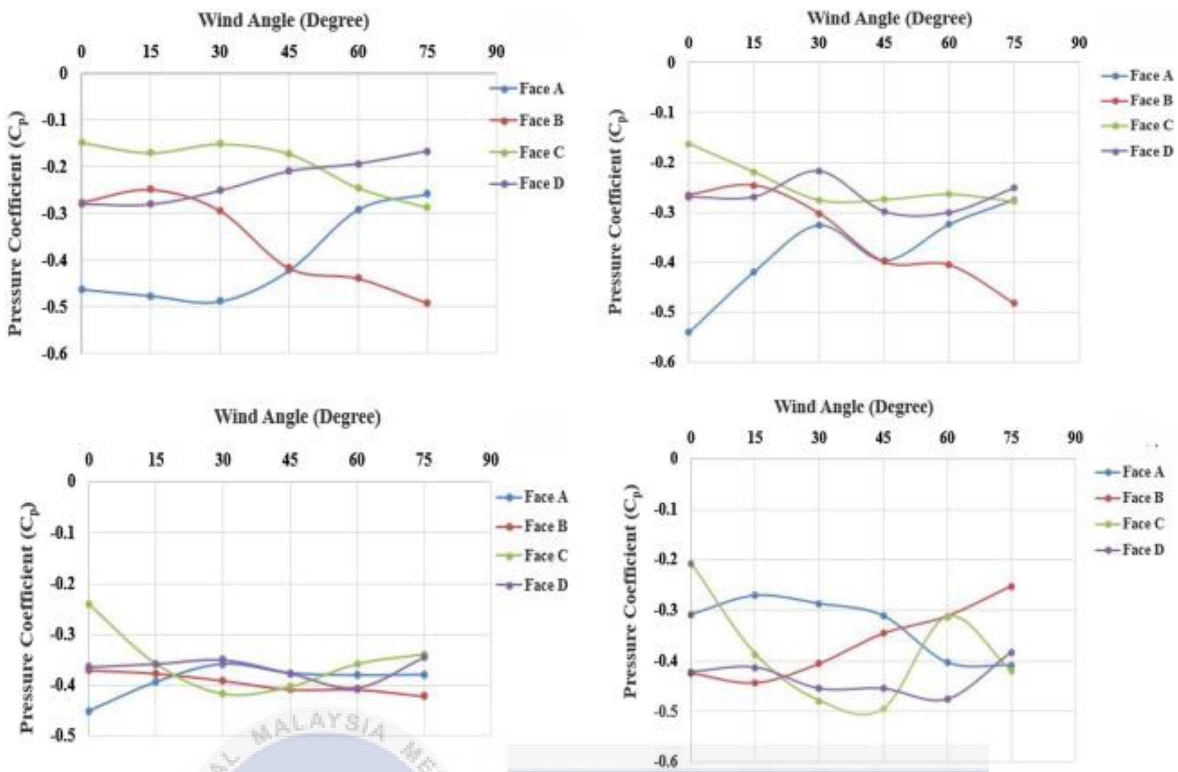

Figure 4.10 The study measured the pressure coefficients (Cp) on several outer surfaces of the roof with varying slopes (0°, 10°, 20°, and 30°) for wind incidence angles ranging from 0° to 75° @ 15° increments

Figure 4.10 displays a comprehensive depiction of the pressure coefficients for all four roof faces (A, B, C, and D) at wind directions ranging from 0° to 75° in 15° increments. The analysis includes roof slopes of 0°, 10°, 20°, and 30°.

Figure 4.10 also demonstrates that area weighted pressure coefficients exhibit continuous variations in response to changes in wind incidence angles. Typically, the side of an object that faces directly into the wind, known as the windward side, is subject to the most pronounced negative pressure or suction. The most extreme negative pressure coefficient observed was -0.540, which occurred when the roof slope was 10° and the wind incidence angle on face A was 0°.

In order to understand how the pressure changes with variations in roof slope, a comparison was conducted using the mean pressure coefficients (calculated as an average weighted by area). Figure 4.11 illustrates this comparison, specifically showing the overall maximum area weighted pressure coefficients for different roof slopes.

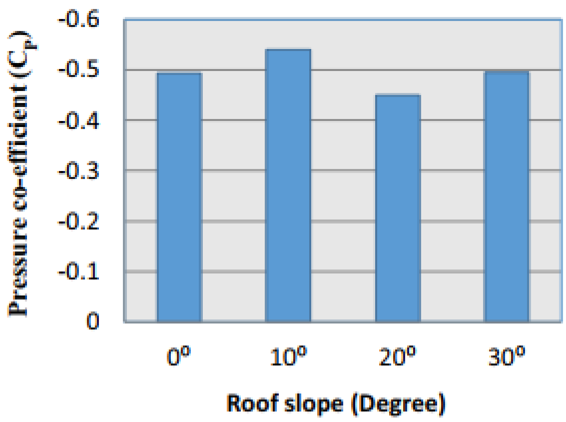

Figure 4.11 Maximum pressure coefficients (area weighted average) for different roof slopes

Based on the information provided in Figure 4.11, it is evident that the roof slope with a 10° angle has the highest maximum negative area weighted pressure coefficient. The area weighted pressure coefficient is nearly equal for roof slopes of 0° and 30°, however it is lowest for a roof slope of 20°.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research aimed to assess the drainage efficiency of clay roof tiles used in residential buildings and metal deck roofs used in industrial buildings in Malaysia. By comparing their effectiveness in rainwater drainage, the study has provided valuable insights that have significant implications for both structural engineering and environmental considerations. The findings demonstrate a significant superiority of clay roof tiles compared to metal deck roofs in relation to the quality of rainwater. By conducting thorough tests that measure pH levels, salinity, conductivity, and total dissolved solids (TDS), it has been regularly shown that clay roof tiles have exceptional performance. The mineral content test highlights the favorable composition of clay tiles, which is mainly due to their mostly mineral-based structure and increased mineral content. In contrast, metal deck roofs exhibit higher levels of heavy metals such as zinc, iron, and aluminum. This can lead to environmental issues and have a substantial impact on the quality of rainwater runoff.

The validation investigation carried out in this research emphasizes the dependability of the realizable k–ε turbulence model in reproducing horizontal homogenous velocity profiles. Validating this process is crucial for improving the precision of aerodynamic simulations, establishing a strong basis for further research on the wind-induced behavior of various roof designs. An analysis of wind pressure coefficients on roof surfaces uncovers fascinating patterns. A face that is perpendicular to the wind direction exhibits larger pressure coefficients in comparison to faces that are parallel. Significantly, when the intersection of two surfaces is at a right angle to the direction of the wind, the entire surface of the roof encounters reduced wind force. These findings have significant consequences for comprehending the aerodynamic characteristics of roofs.

The investigation of wind-induced suction on pyramidal roofs with varying slopes reveals the key factors that affect the area-weighted pressure coefficients. The angle at which the wind approaches becomes a critical component, affecting the pressure coefficients on the surfaces of the roof. The 10° roof slope has the most significant negative area-weighted pressure coefficient, which is of great interest to architects and engineers who are constructing roofs to withstand wind pressures. This study offers significant data for enhancing roof designs, considering not only the effectiveness of drainage but also the structural soundness and functionality of roofs under different wind situations.

The correlation observed in this study between wind direction, pressure coefficients, and roof slope aligns with well-established principles in the field of aerodynamics. Past research has examined the impact of wind direction and roof shape on pressure coefficients. The phenomenon of a face positioned at a right angle to the wind direction having higher pressure coefficients compared to parallel faces, and the impact of joint faces on the overall wind pressure across the roof surface, aligns with the aerodynamic principles previously stated in literature.

Moreover, the result that wind incident angle is a significant element for the area-weighted pressure coefficient coincides with earlier studies emphasizing the relevance of incorporating wind angles in the computation of aerodynamic forces on structures. This link further emphasizes the concept that wind incidence angle is a critical component controlling the distribution of pressure coefficients on roof surfaces.

Ultimately, the thorough assessment of how well drainage works, the quality of rainwater, and the stresses caused by wind on clay roof tiles in residential buildings and metal deck roofs in industrial settings provides a basis for making well-informed decisions in the fields of architecture and engineering. The findings of this study make a valuable contribution to the promotion of sustainable construction methods, highlighting the significance of carefully choosing materials and considering design factors when constructing roofs in tropical regions such as Malaysia. This research combines aerodynamic knowledge, verified simulation models, and real-world data on rainwater quality. It focuses on the overlap between environmental sustainability and structural resilience, providing a comprehensive viewpoint for future improvements in roofing technologies and practices.

5.2 Recommendations

Some important recommendations that can be made to further improve the understanding of this research are as follows. Firstly, performing a comprehensive empirical investigation that thoroughly examine particular facets of rainwater drainage. This may involve doing practical trials on scaled-down models or prototypes to thoroughly examine the effects of roof pitch angles and material properties. Next is engaging in complex projects utilizing Computational Fluid Dynamics (CFD) to investigate delicate aspects of wind pressure distribution and patterns of rainwater runoff. These studies can provide a comprehensive examination of the fluid dynamics associated with rainwater drainage. Furthermore, supporting research endeavors centered around the enhanced analysis of rainwater quality, specifically targeting the detection and measurement of certain pollutants present in rainwater runoff originating from domestic clay roof tiles and industrial metal deck roofs. This may entail cooperation with departments or laboratories specializing in environmental science. Lastly, examine the Life Cycle Assessment (LCA) of both roofing materials, considering issues such as manufacture, installation, maintenance, and end-of-life considerations. Life Cycle Assessment (LCA) studies offer a comprehensive perspective on the environmental consequences of materials across their complete life cycle.

5.3 Project Potential

Following a thorough research investigation on the effectiveness of rainwater drainage in clay roof tiles used in residential buildings and metal deck roofs used in industrial buildings, with a specific focus on the angle of the roof pitch, distribution of wind pressure using Computational Fluid Dynamics (CFD), and the quality of rainwater in Malaysia, several possibilities for further research have been identified. Investigating these prospective study domains can greatly enhance the development of sustainable roofing methods and enhance our comprehension of the complex interconnections between roofing materials and environmental factors in the Malaysian setting. This study provides significant knowledge on sustainable construction techniques, offering essential advice to architects, builders, and construction experts in Malaysia to make informed choices when selecting roofing materials that are appropriate for the local climate. Comprehending the distinct meteorological patterns in Malaysia is crucial for customizing roofing solutions that can efficiently handle precipitation, hence promoting eco-friendly and very effective building designs.

Moreover, the study's results might provide significant knowledge to urban planners and policymakers in Malaysia regarding the impact of roofing materials on rainfall drainage under the country's unique environmental and climatic conditions. Acquiring this information is essential for the creation of robust urban ecosystems in Malaysia that can effectively manage the drainage of rainfall, particularly given the country's vulnerability to climate change and extreme weather occurrences. Engaging in cooperation with local government organizations and pertinent authorities in Malaysia would be crucial in incorporating study findings into urban planning strategies and policies focused on sustainable water management.

It is crucial to comprehend the rainwater quality obtained from different roofing materials in order to promote environmental conservation efforts in Malaysia. The research seeks to identify specific contaminants or pollutants that are prevalent in Malaysia, with the goal of developing approaches that can efficiently mitigate the environmental consequences of rainfall runoff on local ecosystems. By taking into account Malaysia's unique weather patterns, local government entities, and environmental obstacles, this comprehensive method guarantees that the research findings are not only applicable worldwide but also specifically designed to tackle the particular requirements and circumstances of the Malaysian setting.

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APPENDICES

APPENDIX A Gantt Chart for BDP 1

Gantt Chart for BDP 1																	
No	Task Project	Plan/Actual	Week														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Registration of BDP title	Plan														
		Actual														
2	Briefing of BDP and research explanation by supervisor	Plan														
		Actual														
3	Drafting and writing of Chapter 2: Literature Review	Plan														
		Actual														
4	Presentation of Chapter 2 draft with supervisor	Plan														
		Actual														
5	Submission of Chapter 2	Plan														
		Actual														
6	Briefing of Chapter 1: Introduction with supervisor	Plan														
		Actual														
7	Writing of Chapter 1	Plan														
		Actual														
8	Submission of Chapter 1	Plan														
		Actual														
9	Discussion of Chapter 3: Methodology with supervisor	Plan														
		Actual														
10	Drafting and writing of Chapter 3	Plan														
		Actual														
11	Presentation of Chapter 3 draft with supervisor	Plan														

		Actual														
12	Submission of Chapter 3	Plan														
		Actual														
13	Submission of BDP 1 report first draft	Plan														
		Actual														
14	Last correction of the report	Plan														
		Actual														
15	Submission of report to supervisor and panels	Plan														
		Actual														
16	Preparation of slide and presentation for BDP 1	Plan														
		Actual														

APPENDIX B   Gantt C hart for BDP 2

Gantt Chart for BDP 1																
No	Task Project	Plan/Actual	Week													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Drafting of Chapter 4: Results and Discussion	Plan														
		Actual														
2	Writing of Chapter 4: Results and Discussion	Plan														
		Actual														
3	Presentation of Chapter 4 with supervisor	Plan														
		Actual														
4	Submission of Chapter 4 to supervisor	Plan														
		Actual														
5	Drafting of Chapter 5: Recommendation	Plan														
		Actual														
6	Writing of Chapter 5: Recommendation	Plan														
		Actual														
7	Presentation of Chapter 5 with supervisor	Plan														
		Actual														
8	Submission of BDP 2 report first draft	Plan														
		Actual														
9	Last correction of the report	Plan														
		Actual														
10	Submission of report to supervisor and panels	Plan														
		Actual														
11	Preparation of slide and presentation for BDP 2	Plan														
		Actual														

APPENDIX C Turnitin Result Report

PSM 2 - CHECKED

ORIGINALITY REPORT

18%	14%	16%	2%
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5	Y.H. Lai, Y. Ahmad, I. Yusoff, C.W. Bong, S. Y. Kong. "Effects of roof pitch gradient and material to harvested rainwater quality", IOP Conference Series: Materials Science and Engineering, 2018 Publication	1%
6	Jagbir Singh, Amrit Kumar Roy. "Effects of roof slope and wind direction on wind pressure distribution on the roof of a square plan pyramidal low-rise building using CFD	1%