THE PERFORMANCE OF PCM-ENHANCED WALLS FOR THE REDUCTION OF PEAK INDOOR TEMPERATURE IN TROPICAL CLIMATE

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by

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T_i	Indoor air temperature
T_{mmo}	Monthly mean outdoor temperature
T_o	Outdoor air temperature
T_{op}	Operative Temperature
T_{pmo}	Prevailing mean outdoor temperature
T_r	Mean Radiant temperature
T_{rmo}	Outdoor running mean temperature
TS_e	External Surface Temperature
TS_i	Internal Surface Temperature

LIST OF ABBREVIATIONS

1-PCM	Single sheet of PCMs (6mm)
2-PCM	Two sheets of PCMs (12mm)
3-PCM	Three sheets of PCMs (18mm)
AC	Air conditioning
ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Avg-peak	Average peak
Avg-min	Average minimum
CB-CPCM	Cement-based composite PCM
CL	Cooling Mode
CP	Cool paint
CR	Cement Render
DSC	Differential scanning calorimetry
DV	Day Ventilation
EPS	Expanded polystyrene
FC	Foamed Concrete
FC-20-UV	PCM-FC cladding panels installed with the dry installation method, which has 20mm unventilated cavity.
FR	Free-Running
FV	Full-day Ventilation
GHGs	Greenhouse gases
GSR	Global Solar Radiation
IWEC	International Weather for Energy Calculation
Min-T	Minimum temperature
MM	Mixed-Mode
NV	Night Ventilation
OSB	Oriented strand board
PCM	Phase Change Materials
PCMTS	PCM thermal shield
PCM-CR	PCM-based cement render
PCM-FC	PCM-based foamed concrete
PCM-FC-1	PCM-FC with (PCM:cement = 1.5:1)

PCM-FC-2	PCM-FC with (PCM:cement = 2:1)
PCM-FCw	PCM-FC cladding panels installed with the wet installation method
PCM-FC-5-UV	Normal FC cladding panels installed with the dry installation method, which has 5mm unventilated cavity.
PCM-FC-20-UV	PCM-FC cladding panels installed with the dry installation method, which has 20mm ventilated cavity.
PCM-FC-20-V	PCM-FC cladding panels installed with the dry installation method, which has 20mm ventilated cavity.
Peak-T	Peak temperature
PMV	Predicted mean vote
PPD	predicted percentage of dissatisfied
Reference-CR	Cement Render without PCM
Reference-FC	Foamed Concrete without PCM
RST-cell	Reduced-scale testing cell
SSPCM	Shape-stabilized PCM
TES	Thermal Energy Storage
TMY	Typical Meteorological Year
TSV	Thermal Sensation Votes
WBGT	wet bulb globe temperature
WV	Without Ventilation
WWR	Window to wall ratio
XPS	Extruded polystyrene

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PRESTASI DINDING YANG DIPERTINGKATKAN PCM UNTUK PENGURANGAN SUHU DALAMAN PUNCAK DI IKLIM TROPIKA

ABSTRAK

Bangunan di Malaysia mengalami suhu dalaman yang tinggi kerana iklim tropika panas dan lembap, yang mengakibatkan penggunaan penyaman udara yang berlebihan untuk penyejukan. Sektor bangunan adalah salah satu penyumbang utama penggunaan tenaga yang tinggi dan dikaitkan dengan pelepasan gas rumah hijau. Walaubagaimanapun, hasil penyelidikan dan piawaian keselesaan menunjukkan bahawa penduduk Malaysia lebih bertolak ansur terhadap cuaca panas dengan julat suhu selesa mencapai hingga 30-32 °C dalam bangunan dengan keadaan semula jadi. Oleh itu, jurang antara tahap suhu dalaman dan tahap keselesaan yang diperlukan dapat diatasi dengan strategi reka bentuk pasif yang baik. Kajian ini bertujuan untuk mengkaji potensi penggunaan PCM sebagai strategi penyejukan pasif untuk bangunan kediaman berkeadaan semula jadi di Malaysia. Pelbagai kaedah telah dilaksanakan dalam kajian ini, termasuk kajian lapangan dalam bangunan yang sedia ada untuk menentukan julat yang sesuai bagi suhu peralihan PCM, penyelidikan simulasi dan mengoptimumkan pengaplikasian PCM di permukaan dalaman dinding, kerja eksperimen makmal untuk pengintegrasian PCM ke dalam permukaan kemasan luaran, dan penilaian eksperimental untuk kemasan luaran berasaskan PCM dalam keadaan cuaca sebenar. Hasil kajian menunjukkan bahawa PCM dengan suhu peralihan antara 26 °C hingga 30 °C boleh disarankan untuk pengaplikasian dalaman, sementara PCM antara 30 °C hingga 36 °C disarankan untuk aplikasi kemasan luaran. Malah, penerapan kepingan PCM di bawah kemasan dalaman dinding menunjukkan keberkesanan sepanjang tahun dalam mengurangkan suhu puncak dalaman dan suhu

puncak permukaan dalaman dinding, yang masing-masing mencapai sehingga 4.9 ℃ dan 8.9 ℃. Sehubungan itu, masa ketidakselesaan terma telah menurun sepenuhnya berbanding 59% pada bulan dengan panas melampau dan 34% untuk sepanjang tahun. Prestasi bertambah baik ketika menggunakan PCM dengan suhu peralihan yang lebih rendah, kuantiti yang lebih tinggi, dan ketika digabungkan dengan pengudaraan malam. PCM yang optimum harus mempunyai suhu dan julat pencairan yang lebih rendah, sementara suhu pemejalan harus cukup tinggi untuk melengkapkan proses pemejalan tersebut. Begitu juga dengan memasukkan PCM ke dalam kemasan luaran dinding menunjukkan keberkesanan dalam mengurangkan kenaikan haba luaran. Oleh itu, pengurangan suhu dalaman dan suhu permukaan dalaman dinding masing-masing mencapai 5.95 ℃ dan 7.25 ℃. Penggunaan bahan ringan, seperti konkrit berbusa, untuk menggabungkan PCM menunjukkan prestasi termal yang lebih baik berbanding dengan lepaan simen. Pelapisan berasaskan PCM berkesan untuk semua orientasi bangunan dan prestasinya telah meningkat dengan ketara semasa menggunakan kaedah pemasangan kering, terutama dengan rongga udara yang lebih besar.

THE PERFORMANCE OF PCM-ENHANCED WALLS FOR THE REDUCTION OF PEAK INDOOR TEMPERATURE IN TROPICAL CLIMATE

ABSTRACT

Buildings in Malaysia suffer from high indoor temperatures due to the hot and humid tropical climate, which results in extensive use of air-conditioning for cooling. The building sector is one of the main contributors to high energy consumption and the associated greenhouse gases emissions. However, the literature and comfort standards showed that Malaysians have more tolerance for hot weather and that the upper limit of comfort range can reach an average of 30 to 32℃ in naturally conditioned buildings. Therefore, the gap between the indoor temperature level and the required comfort level can be tackled by proper passive design strategies. This study aims to investigate the potential use of the PCMs as a passive cooling strategy for naturally conditioned multi-story residential buildings in Malaysia. Various methods have been implemented in this study, including field measurements in the existing buildings to determine suitable ranges for the PCM's transition temperatures, simulation investigation and optimization for the PCMs application in walls' interior surfaces, laboratory experimental work to incorporate the PCMs into the façade's exterior finishing, and experimental evaluation for the PCM-based exterior finishing under the actual weather condition. The results showed that PCMs with transition temperatures between 26℃ and 30℃ can be suggested for interior applications, while between 30℃ and 36℃ are suggested for exterior finishing applications. Furthermore, applying the PCM sheets under the walls' interior finishing showed year-round effectiveness and the peaks of indoor temperature and internal surface temperature

decreased by up to 4.9℃ and 8.9℃, respectively. Therefore, the thermal discomfort time has completely decreased compared to 59% and 34% for the extreme month and the year-round, respectively. The optimum PCM must have a lower melting temperature and melting range, while the solidification temperature should be high enough to complete the solidification process. Likewise, incorporating PCMs into the wall's exterior finishing showed effectiveness in reducing the external heat gain. Therefore, the indoor temperature and wall internal surface temperature decreased by up to 5.95℃ and 7.25℃, respectively. The use of foamed concrete, to incorporate PCM showed better thermal performance compared to cement render. The PCM-based cladding was effective for all orientations and performance has improved when using the dry installation method, especially with larger and ventilated air cavity.

CHAPTER 1

INTRODUCTION

1.1 Background

Buildings were originally built to provide shelter from the outdoor climatic conditions. Their envelope is what separates the internal environment from the outdoor climatic conditions (Lei et al., 2016). They were constructed from the available local materials, which can protect from the local climate and respond to the ambient environment. For example, they were constructed from stone masonry to protect against harsh weather. In this regard, the materials, which are used in the building's envelope, have a direct impact on the building's thermal performance (Dyball, 2013).

Traditional buildings were more climatic responsible. The traditional Malay house, for instance, was built to ensure the best control and utilization of the climate factors for the inhabitants' comfort. The main causes of climatic stress in Malaysia are high temperatures, solar radiation, humidity, and glare (Yuan, 1987; Kamal et al., 2004). Therefore, the envelope of the traditional house was constructed from lightweight materials with low thermal capacity (i.e., timber and attap) to reduce the conduction and storage of heat, while the house was raised on stilts with large openings and minimal interior partitions to encourage natural and cross ventilation, Figure 1.1. Besides, the large overhangs with the low height of walls effectively protect from direct solar radiation and provide great shadings on the external walls and windows. Similarly, the ambient environment has been arranged to facilitate the natural flow of wind, while shading from large green areas, vegetation, and trees help to keep these houses in a cooler environment.

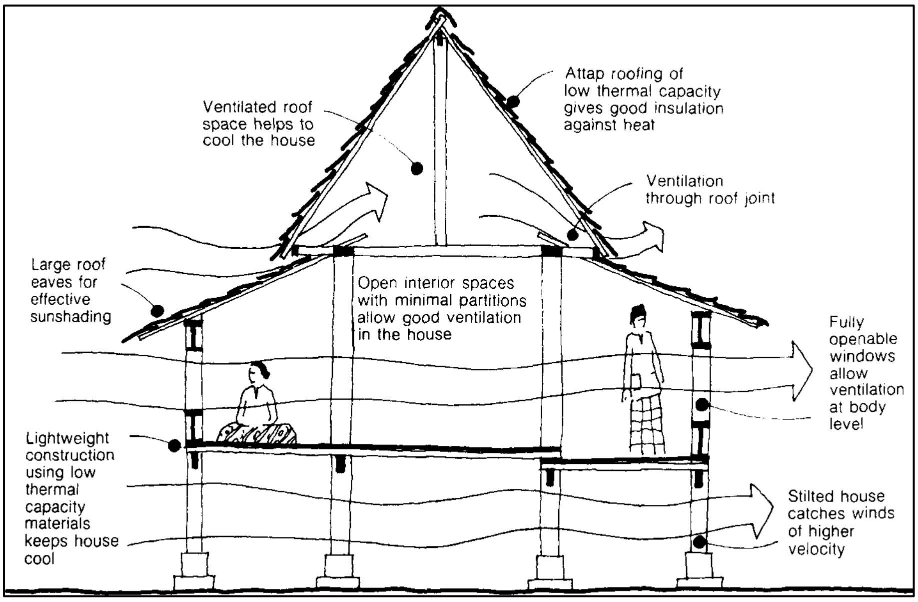

Figure 1.1 Traditional Malay House
Source: (Yuan, 1987; Kamal et al., 2004).

During the industrial revolution, due to the invention of new materials and technologies for buildings, and to urban migration, which caused the rapid growth of the urban population, the focus of the building sector had altered to productivity and economic considerations (Dyball, 2013; Costa et al., 2015; Hassan and Khozaei, 2018). As a result, the building's envelope has become a light layer of materials separating indoor spaces from the outdoor environment, while the air-conditioning systems have been used to provide thermal comfort for occupants. However, as a result of the energy crisis and the negative impacts associated with massive energy use, such as climate change, global warming, and greenhouse gases emissions (GHGs), humans realised that they should reduce energy consumption to achieve the sustainability of the planet (Dyball, 2013).

Worldwide, buildings are responsible for 40% of global energy consumption and, therefore, they are linked to the high GHGs emissions since about 80% of the energy is produced from fossil fuels (Sovetova et al., 2019). Moreover, up to 70% of the consumed energy is used by buildings' air-conditioning and artificial lighting (Wu et al., 2019). Therefore, buildings provide a great opportunity to minimize the high energy consumption and the associated negative impacts through the reduction of cooling and/or heating demands. According to Fateh et al. (2017), a 20% reduction in building energy consumption can decrease the associated CO_2 by 50%. Reducing energy consumption in buildings can be achieved by different approaches and technologies. This can begin with the implementation of passive strategies for the design, cooling, and enhancement of buildings, followed by the use of energy-efficient cooling systems and the integration of renewable energy-based systems (Ascione et al., 2019). Since the building's envelope is the key element that influences the heating and cooling loads of buildings, they are the main target in addressing the energy consumption in buildings (Lei et al., 2016).

Passive design strategies utilize the energy available from the natural environment and, therefore, can be used in buildings for heating or cooling purpose by heat absorption, prevention, or dissipation (Akeiber et al., 2016). They are promising alternatives to conventional heating and cooling systems (Akeiber et al., 2016; Solgi et al., 2019). They may become more helpful for some types of buildings (i.e., residential buildings and some small commercial buildings), which are associated with a low density of lighting, equipment, and occupants (Bradshaw, 2010).

The thermal performance of the buildings depends on the ability of their envelopes to improve air temperature and thermal comfort of the internal spaces by heat exchange (Dyball, 2013). Since the buildings envelop plays a major role in heat gain and/or loss (Nardi et al., 2018), it should be designed to provide more thermal stability for the internal environment. Therefore, it is linked with many passive techniques that address the wall and roof insulation, fenestration areas, and type of glazing. Generally, multiple passive design strategies should be integrated into building design to achieve the optimum result. Besides, incorporating these strategies in the early design stage can reduce the cost compared to in the post-occupancy stage, (Bradshaw, 2010).

Using thermal insulations is the common passive strategy that is being applied for buildings' envelope to reduce the heat gain or losses (Axaopoulos et al., 2014). It works by increasing the thermal resistance (R-value) of the envelope (Al-Sanea et al., 2012). Achieving an optimum performance requires a proper thickness of the thermal insulations, which is influenced by many factors, including building location, construction materials, climatic conditions, and thermal insulation type. However, some of their drawbacks are the required thickness, fire safety, and initial cost (Khalifa, 2013; Axaopoulos et al., 2014; Zhu et al., 2018). Furthermore, they can cause more internal heat to retain inside the house during the summer hot days, which causes buildings to suffer from overheating (Ramakrishnan et al., 2017a).

Thermal energy storage (TES) is a useful sustainable passive technology that can be used in buildings to improve heat exchange, practise energy efficiency, and minimize energy consumption (Barzin et al., 2015). TES capture (charge), store, and reuse (discharge) thermal energy, which may otherwise be wasted or underused (Akeiber et al., 2016; Guarino et al., 2017). For example, the daytime solar energy can be stored by TES to heat the cold nights in locations that require night heating, whereas, the coolness of the night-time can be stored for cooling the warm air in locations that require cooling during the daytime (Iten et al., 2016). One type of TES works through latent heat storage, which depends on the materials' ability to store or release the heat when changing their phase (Akeiber et al., 2016). These materials, that change their phase, known as phase change materials (PCMs).

PCMs can help to lower the temperature and reduce the total hours of thermal discomfort (Akeiber et al., 2016). Besides, reductions in the energy used for cooling purposes could be reached by integrating PCMs into buildings (Chaiyat, 2015). PCMs are attractive for many researchers and have been successfully implemented in buildings for thermal management (Iten et al., 2016). For example, Ascione et al. (2019) achieved a reduction of 11.7% of the summer energy consumption and an increase of 215 h of the summer comfort by retrofitting a building with PCM on the inner surface of the external walls. Sun et al. (2019) achieved up to 23.1% annual average energy reduction by applying the micro-encapsulated PCM in the walls. Ramakrishnan et al. (2017a) refurbished a residential house by applying macro-encapsulated PCM mats on the inner linings of the house's walls, which resulted in a lower severe discomfort period by 65%. Evola et al. (2013) found a reduction in the seasonal thermal discomfort up to 35% with PCMs application in combination with night ventilation (NV). However, PCMs application for buildings in the tropical climate of Malaysia, and particularly for naturally conditioned spaces, has not been investigated well.

1.2 Problem Statement

In Malaysia, the rapid development of urban areas, the huge demand for urban housing, and the sharp increase in land price have caused the housing sector to be designed and constructed in many cases with small and tight spaces, irrespective of the site and climate's requirements, and using low quality and thermal performance materials (Isa et al., 2010). The conventional construction method for buildings uses concrete for the structural parts while bricks and plaster are used as non-structural infill materials (Abdul Kadir et al., 2006). These materials have high thermal conductivities (i.e., average K-values of 1.11-1.95 W/m.k, 0.72-0.89 W/m.k, and 0.72 W/m.k for the concrete, brick, and plaster, respectively), which increases the heat gains and/or losses in buildings (ASHRAE Handbook, 2013). Since Malaysia's climate is tropical (i.e., hot and humid), and due to global warming impacts, the indoor environment of buildings, which do not incorporate any measures to reduce the effects of outdoor weather, becomes hot and thermally uncomfortable. Therefore, occupants tend to use air-conditioning to reduce the temperature and restore their comfort (Tuck et al., 2019).

As people spend most of their time in indoor environments (Shaikh et al., 2017), buildings air-conditioning become one of the major contributors to the total electricity consumption in Malaysia. For instance, electricity consumption has increased by 200% between 1997 and 2018. The commercial and residential sectors are responsible for 49.5% of the total electricity consumption in 2018 (National Energy Balance, 2018). Besides, around 45% of the total electricity consumed in buildings goes to building cooling (Sadeghifam et al., 2015; Mirrahimi et al., 2017). Moreover, the need for cooling is increasing continuously due to climate change and global warming (Huang and Hwang, 2015). Wang et al. (2010) estimated that the cooling demand by 2100 would increase by 350% compared to its level in 1990, whereas heating demand would decrease by 48%.

The problem arises when the energy sector in Malaysia is responsible for 76% of the GHGs emissions (Tang, 2019), which is due to the large part of the energy production that comes from the combustion of fossil fuels, i.e., up to 83.1% (Malaysia Energy Statistics Handbook, 2019). As a result, efforts were made in Malaysia to reduce the GHGs emissions associated with the energy sector. For instance, it was mentioned in the Eleventh Malaysia plan 2016-2020 that a voluntary target was set in 2009 to reduce the GHGs emission by 40% in 2020 compared to its level in 2005.

Therefore, steps have been taken to increase the use of clean and more environmentally friendly energy sources since the energy sector is the major contributor to this emission (Eleventh Malaysia plan, 2015). In line with these efforts, therefore, buildings and construction sectors offer a high potential to reduce energy consumption and the associated GHGs emission.

Several field studies of buildings in the hot-humid climate of Malaysia have reported the peak indoor temperature generally averaging around 31℃ to 35℃ (Kubota et al., 2009; Hassan and Ramli, 2010; Omar and Syed-Fadzil, 2011; Hafizal et al., 2012; Djamila et al., 2013; Omar and Fadzil, 2016; Tuck et al., 2019). Furthermore, field thermal comfort studies have shown that Malaysian have more tolerance for hot weather. For instance, thermal comfort studies have reported comfort temperature averaging around 28℃ and an acceptable temperature range up to 30-32℃ (Abdulshukor, 1993; Dahlan et al., 2008; Hussein et al., 2009; Djamila et al., 2013; Damiati et al., 2016). Similarly, international and local standards and guidelines for thermal comfort in naturally conditioned buildings, such as (BS EN 15251, 2007; BSEEP, 2013; ANSI/ASHRAE Standard 55, 2017; MS 2680, 2017), provide models that estimate the thermal comfort temperatures for Malaysian climate in the same range. Comparing the indoor temperature of buildings with the required comfort temperature in the hot-humid climate of Malaysia indicates that implementing proper building design and passive measures to improve the thermal performance of buildings' envelope can lower the indoor temperatures and decrease the need for air-conditioning cooling. Therefore, the associated energy consumption and GHGs emission can be decreased.

One of the passive cooling strategies, which has been implemented in buildings worldwide, and its usage is increasing more and more, is the use of PCMs (Ascione et al., 2019). This strategy has shown effective improvement in buildings' indoor thermal environment and, therefore, reduction in total energy consumption. However, within the context of Malaysia, PCMs application in buildings is still regarded as a new and promising area of research, particularly for the country's hot-humid climate, which is categorized by a uniform diurnal temperature throughout the year. Therefore, opportunities can be seized to benefit from the PCMs year-round, unlike other climates, in which PCMs can function seasonally (Lei et al., 2017). Moreover, previous studies have shown the effectiveness of NV in cooling down buildings in Malaysia (Kubota et al., 2009; Aflaki et al., 2014; Tuck et al., 2019), and that its performance improves with a high level of thermal mass (Solgi et al., 2019). Therefore, by combining NV and PCMs, the passive cooling of PCMs for the naturally conditioned buildings projected potentials and can be further improved. The benefits of using PCMs for the buildings in the tropical climate of Malaysia and the required characteristics for PCMs to work efficiently to achieve optimal performance remain uncertain and, therefore, require more investigation.

1.3 Research Questions

1. What are the most appropriate temperature ranges according to which the PCM's transition temperatures can be selected to function effectively in naturally conditioned buildings within the tropical climate of Malaysia?
2. What are the optimum transition temperatures and quantity of PCMs that are applied to the interior surfaces of the walls in naturally conditioned buildings in the tropical climate of Malaysia?
3. How are the performance and the effectiveness of PCMs that are applied to the interior surfaces of the walls in reducing the peak temperature and thermal

discomfort year-round in naturally conditioned buildings in the tropical climate of Malaysia?

4. What is the recommended composition of an external PCM-based finishing layer for the building's façade?
5. How are the performance and the effectiveness of the external PCM-based finishing layer in improving the wall's thermal performance to reduce the external heat gain and indoor temperature?

1.4 Research Objectives

This research aims to investigate the PCMs application as a passive cooling strategy for naturally conditioned buildings in the tropical climate of Malaysia to reduce indoor temperatures and thermal discomfort time. Therefore, the main objectives of this research are as follows:

1- To determine the most appropriate temperature ranges of the PCM's transition temperatures for the application in buildings in the tropical climate of Malaysia based on investigating the existing buildings.

2- To investigate the optimum transition temperatures and quantity of PCMs and their performance and effectiveness in reducing the peak temperature and thermal discomfort year-round when applied on the interior surfaces of the walls.

3- To investigate the performance and effectiveness of PCMs incorporated into the exterior finishing of the building's façade in improving the wall's thermal performance to reduce the external heat gain and indoor temperature.

1.5 Research Methodology and Framework

This study uses the quantitative approach, which involves a series of methods that are carefully selected to achieve the objectives and to answer the questions of the study. These methods include field measurements, simulation work, and experimental work. The research framework and the implemented methods are elaborated as follows:

1- Literature review: Reviewing and understanding the available literature is an essential step in any scientific research to ensure having a comprehensive knowledge and strong background on the area to identify a research problem and solve it using scientific methods. Therefore, the background of Malaysia, TES, PCMs, and various recent studies that addressed PCMs application in buildings were reviewed, analysed, and discussed. Based on this, the research problem, objectives, and the required methods to accomplish this research were identified.

2- Field measurement: Field measurements were performed in various spaces of different existing buildings to examine their indoor thermal environment and façade thermal performance in order to determine the most proper temperature ranges of the PCMs' transition temperatures for the application in naturally conditioned buildings in the tropical climate of Malaysia.

3- Simulation work: This method was selected to investigate PCMs application to the interior surfaces of the building's walls. It can facilitate performing an optimization investigation for the PCMs transition temperatures and quantity to achieve optimum performance. Besides, this method makes it possible to investigate the effectiveness of PCMs application all year-round.

4- Experimental work: This method was selected to investigate the effectiveness of PCMs incorporated into the exterior finishing of the building’s façade. Firstly, several PCM-based composites were developed in the laboratory and tested for various properties as well as for the thermal performance in comparison to the reference composites, i.e., without PCM. Subsequently, fieldwork was performed in which the developed PCM-based composites were tested and evaluated as an external finishing for the walls under the actual outdoor climatic conditions.

Figure 1.2 displays the research framework.

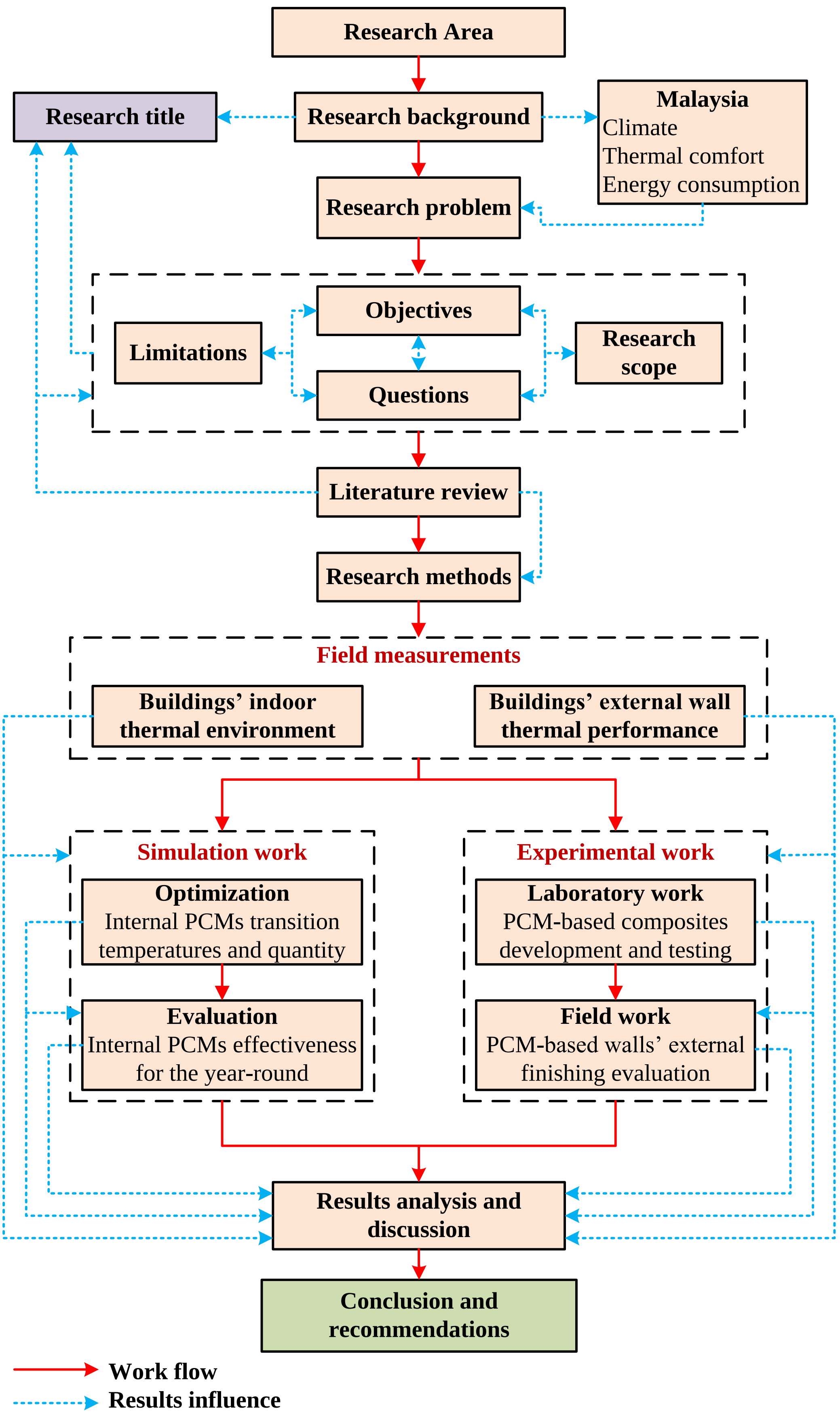

Figure 1.2 Research Framework

1.6 Scope of the Study

This research covers the following:

- The hot-humid climate in Malaysia and, particularly, in Penang Island.
- Multi-story residential buildings are the main target of this research. They are occupied and operated 24 hours a day. Besides, they are the current trends in urban areas, especially the high-rise buildings, which can overcome the increased population by maximizing land use (Gao et al., 2020). Moreover, they are under direct exposer to solar radiation and more susceptible to overheating compared to landed houses, which are shaded by surrounding trees and large overhang.
- Only naturally conditioned spaces are considered in this research (i.e., spaces in which the occupants are free to adapt by opening windows, fans, clothing, and other adaptive measures without using air-conditioning) (ANSI/ASHRAE Standard 55, 2017). In other words, the space can be naturally and mechanically ventilated but is not air-conditioned.
- Buildings with conventional construction materials such as concrete, bricks, and cement plaster, without thermal insulation, are targeted in this research. Besides, the spaces are cubical rooms that are separated from kitchens' activities.
- PCMs are applied to buildings' walls since they are the favoured component in buildings to explore the potential benefits of PCMs application (Cunha et al., 2015; Rao et al., 2018). They provide a large area to incorporate the PCMs. Besides, most of the spaces in multi-story residential buildings are separated from the outdoor environment by the walls.

- Although multiple passive design strategies should be integrated into buildings to achieve the optimum result, this research focuses only on evaluating the effectiveness of the PCMs application as one of the passive design strategies to be considered for the hot-humid climate in Malaysia.
- The effects of different floor levels in the multi-story buildings on the indoor environment and PCMs performance is not in the scope of this research. Therefore, it was treated as a constant variable for all cases.
- The effect of wall colours on the indoor environment and PCMs performance is not in the scope of this research. Therefore, it was treated as a constant variable for all cases.

1.7 Limitations of the Study

Some limitations were faced throughout the various stages of this research as follows:

- Field measurements in the existing buildings: The aim was to conduct field measurements for the indoor environment and the external walls of various multi-story residential buildings. However, there were some difficulties in finding the buildings and getting the required permissions and approvals from the owners, especially when the rooms were needed to be not in use during the measurements. Besides, no measurements were conducted in a space with the absolute west orientation due to difficulties in finding an accessible west-oriented space for the measurements. Additionally, the measurements were conducted for each space during different periods and, therefore, each space might have slightly different weather conditions. Although the target was to conduct the measurements in mostly sunny conditions, it was difficult to achieve this in some cases due to the continuous changes in the sky and weather conditions and the limited period and time that were given by the owners. However, this did not influence the overall result since the aim was to get an overview of the indoor environments rather than comparing the investigated spaces.

- PCMs materials: Searching and finding a suitable commercially available micro-encapsulated PCM within the suggested temperature range to be incorporated into the exterior finishing of the building's façade has taken a long time until the product was found and purchased from a company overseas.
- Equipment and instruments: Limitations were found during the field measurements and laboratory testing due to limited instruments, sensors, and/or equipment, which caused some delay in the work in some cases and difficulties in conducting the testing simultaneously in other cases. However, efforts were made to design and arrange the field measurements and laboratory testing for maximum utilization of the available instruments, sensors, and equipment.

1.8 Significance of the Study

This study is significant research due to the following aspects:

- The study highlights the significant implementation of passive design strategies for buildings in hot-humid climate regions to improve the indoor thermal environment and avoid the extensive use of air-conditioning, which can reduce energy consumption and the associated GHGs emission. This meets the requirements of several Malaysian standards, such as MS 1525 (2014), MS

2680 (2017), Building energy efficiency technical guideline for passive design (BSEEP, 2013), and the Green Building Index (2013).

- PCMs application to buildings is one of the recent attractive methods for passive cooling and energy efficiency of buildings with widely and increasingly use and implementation around the world. However, this technology is still new in the Malaysian context with very limited investigations of its effectiveness under the climatic conditions of Malaysia. Therefore, this research can offer the foundation for the potential use of this technology and the design parameters that are needed to be considered to achieve optimum performance. It can provide buildings' architects and designers with essential information for the effective use of this technology.
- The PCMs technology can be implemented in the construction of new buildings, as well as the retrofitting of the existing buildings without the need for any additional space or major renovation. This provides an opportunity to improve the thermal performance and energy efficiency of the existing building stock.
- This research investigates the effectiveness of a newly developed exterior cladding system to reduce external heat gain, which is achieved by incorporating micro-incapsulated PCMs into foamed concrete. This is a new area for research and can be a valuable contribution to the body of knowledge.

1.9 Thesis Outline

This thesis is organized into six chapters as follows:

- **Chapter 1** presents an introduction to the research, which includes a brief background on buildings' design and construction, energy consumption in buildings, and the needs for passive design strategies such as TES and PCMs. Then, it presents the research problem followed by the research objectives and questions. After that, the research methodology, scope, limitations, and significance are presented with an outline of the thesis organization.

- **Chapter 2** presents a review of the literature associated with the area of research. It starts with a description of Malaysia’s location and climate, buildings’ indoor thermal environment, thermal comfort requirements, and energy consumption patterns, which highlights the role of buildings cooling in increasing electricity consumption and GHGs emissions and the need for passive design strategies. Then, TES and PCMs concepts and principles, categories, required characteristics for application in buildings, and the methods of PCMs’ integration were discussed. After that, PCMs application in buildings is presented highlighting the methods of PCMs application into the walls and the role of NV in improving PCMs performance. Following that, numerous recent works, which incorporated PCMs into the building’s walls, are discussed and analysed concerning the achieved thermal performance, PCMs position, PCMs transition temperatures, and PCMs quantity, in order to understand their role to achieve the optimum performance. Finally, the available literature for PCMs application in Malaysia is presented.
- **Chapter 3** discusses the research methodology, which describes the methods and techniques adopted and used to collect the required data. The chapter starts with an overview and the research direction followed by a detailed research methodology flowchart. Then, the methods that are used for investigating PCMs application for interior and exterior of the building’s walls and the involved instruments, programs, and evaluation parameters are presented.

- **Chapter 4** provides the results' analysis and discussion of the PCMs application to the interior surfaces of the building's walls. This includes the data collected through the field measurements of the indoor thermal environment in the existing buildings and the data obtained from the simulation work, i.e., simulation validation, effects of NV, PCMs application and optimization, and the PCMs' performance and effectiveness year-round.
- **Chapter 5** provides the results' analysis and discussion of the PCM incorporation into exterior finishing of the building's façade. This includes the data collected through the field measurements of the façade's performance in the existing buildings and the data obtained from the experimental study, including materials properties, developed composites' properties and thermal performance, and the thermal performance of the developed PCM-based external cladding under the actual climatic conditions.
- **Chapter 6** provides the overall findings of the study in relation to the PCMs application and its thermal performance and effectiveness in tropical climatic conditions. The chapter also advances recommendations for further studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of Malaysia's location and climatic conditions, characteristic of buildings indoor thermal environment, thermal comfort requirements, energy consumption patterns, and the need for practising building passive design. Subsequently, the theoretical background of thermal energy storage (TES), particularly phase change materials (PCMs), and their roles in the sustainability of our planet and buildings are presented. The various types of PCMs, the required criteria for selecting PCMs for the building application, and the methods to integrate PCMs into buildings are discussed. Finally, numerous previous studies for PCMs application in buildings, particularly in the walls, are reviewed and discussed highlighting the importance of PCM's position, transition temperatures, and quantity as the design parameters, the link between them, and the influential parameters in achieving optimal performance, such as the climatic condition and seasons, the target of the application, wall orientation, wall materials, and indoor environmental condition. Finally, previous studies that addressed the PCMs application in Malaysia are reviewed.

2.2 Malaysia

2.2.1 Location and Climate

Malaysia, with an area of 329,750 sq. km, lies at the latitude of 1º - 7º and longitude of 100º - 119º. It is located within the Tropic of Cancer and Capricorn in South-eastern Asia and consists of two regions, i.e., Peninsular Malaysia and East Malaysia (Malaysian Borneo) (Jawi et al., 2009; Jamaludin et al., 2015; Tang, 2019).

Figure 2.1 Map of Malaysia
Source: (Maps of World, 2020).

Malaysia is a tropical country with an equatorial climate, i.e., being hot and humid. The local climate is characterized by the annual southwest monsoon (May to September) and northeast monsoon (November to March) (Tang, 2019; Malaysian Meteorological Department, 2020). Generally, there are three characteristics for the climate; uniform temperature patterns throughout the year with less than 2℃ annual difference, high humidity averaging around 80%, and abundant rainfall (Jawi et al., 2009; Malaysian Meteorological Department, 2020).

It is not common to have a day without clouds cover in Malaysia, even during dry periods. Therefore, it receives an average of 6 hours of sunlight per day (Malaysian Meteorological Department, 2020). The solar radiation received by any typical location is greater than 5.0 $kWhm^{-2}$. In 2019, the average temperature was 27.63℃, while the average maximum and minimum temperatures were 32.67℃ and 24.24℃, respectively. However, the highest and lowest recorded temperatures were 38℃ and

17.2°C, respectively, compared to 37.5°C and 12.9°C in 2018. Besides, the highest and lowest temperatures' variation in a single day during 2019 were 17.2°C and 0.8°C, respectively (MMD Annual Report, 2018; MMD Annual Report, 2019).

2.2.2 Buildings Indoor Thermal Environment

Generally, the indoor thermal environment of buildings is influenced by external parameters, mainly the outdoor air temperature and incident solar radiation, as well as internal parameters such as occupants, lighting, cooking and appliances. Due to the tropical climate of Malaysia, the hot-humid weather and, especially, the high solar radiation, buildings in Malaysia can experience high indoor temperatures.

Various studies have measured and reported the indoor thermal environment, mainly indoor air temperature (T_i), of various types of buildings in Malaysia. For example, Kubota et al. (2009) conducted measurements in two identical and adjacent typical two-storey terraced houses located in Johor Bahru, which are constructed of reinforced concrete and plastered brick walls. The measurements were performed from June to August 2007, while the houses were unoccupied and empty. This work aimed to compare the effect of various ventilation strategies, which includes without ventilation (WV), day ventilation (DV), night ventilation (NV), and full-day ventilation (FV). The peak and min outdoor air temperatures (T_o) were about 34-36°C and 24-25°C, respectively, while the mean monthly was 28°C. Based on the results, the peak-T_i was on average 33-34°C with DV, while it reduced to 30.5-31.7°C without DV. On the other hand, the min-T_i was on average 26.8-27.6°C with NV, while it increased to 28.6-29.5°C without NV. Applying natural ventilation has caused the T_i to follow the T_o patterns. Furthermore, they noticed that the NV decreased the daytime T_i if no DV was applied.

Tuck et al. (2019) conducted measurements between 15 February and 11 March 2018 in a two-storey corner terrace house in Kuala Lumpur. The house was constructed of reinforced concrete frame and floors, brick walls, and cement board ceiling and concrete roof tiles for the roof (i.e., without thermal insulation). The mean T_o was 28 ± 2°C, while it ranged between 24°C and 38°C. The mean relative humidity was 80 ± 7% with maximum and minimum records of 97% and 34%, respectively. The study aimed to compare various cooling strategies including WV, DV, NV, and FV, which were used in free-running (FR) mode or mixed-mode (MM), i.e., FR + cooling mode (CL) and FR + ceiling fan. The results showed that T_i was fluctuating between 27°C and 37°C in the rooms with FR ventilation on the first floor, while it fluctuated between 27°C and 33°C on the ground floor. The high T_i on the first floor was attributed to solar radiation on the roof. The results also indicated that opening windows at night with NV and FV had better cooling effects than opening them during the daytime.

Omar and Fadzil (2016) conducted field measurements in nine spaces from five different heritage buildings in Penang Island. These buildings have thick clay brick exterior walls with lime plaster, which provides a high thermal mass. The average T_o during the study period for all spaces ranged between 27.8°C and 30°C. The results showed that T_i was greatly reduced during the day, while it exceeded T_o during the night. Besides, the peak-T_i occurred 2-3 hours later to the peak T_o. The peak-T_i ranged between 29°C and 32°C. However, buildings with the lowest peak-T_i showed the highest min-T_i during the night due to the high thermal mass.

Djamila et al. (2013) conducted field measurements as part of a study for thermal comfort in residential buildings at Kota Kinabalu city within 2007-2008. The results showed a mean T_i of 30.7°C with a standard deviation of 1.47°C. Moreover, the

T_i throughout the study varied from 26.5°C to 35.3°C with 95% of all T_i lied between 27.81°C and 33.68°C.

Hafizal et al. (2012) conducted field measurements in six houses (i.e., including terrace house, townhouse, and Malay traditional house) located in Penang Island and Sungai Petani, Kedah. The data was collected from June 2010 to January 2011. The results showed that the traditional house had higher peak-T_i, up to 35.5°C, and lower min-T_i compared to other houses. This was attributed to the main strategy of the traditional houses that utilize the maximum ventilation with the use of lots of openings and gaps causing the T_i to follow the T_o.

Omar and Syed-Fadzil (2011) conducted measurements in a heritage shophouse in George Town, Penang during October 2010. The results reported T_i with a peak ranged between 30.5°C and 31°C and a minimum average of 28.5°C. In contrast, the T_o had a peak of 33°C and a minimum of 25°C. The results demonstrate lower T_i fluctuations and high min-T_i due to the high thermal mass of the walls.

Hassan and Ramli (2010) performed measurements in a traditional Malay house in Penang Island. The measurements were performed from 6.00 am to 6.00 pm for four cloudy days within July and August 2008. The results showed a very small variation between T_i and T_o. For instance, the measured T_i was between 27.3°C and 34.3°C, while the T_o fluctuated between 27.3°C and 34.5°C. The peak-T_i was recorded between 2.00 pm and 3.00 pm.

Table 2.1 summarizes the above measured T_i. As can be seen, the T_i reached a maximum peak of 35.5°C, while the lowest minimum was 26.5°C. Besides, the mean T_o was around 28°C in most cases. High peak-T_i was found in spaces that were affected directly by the incident solar radiation, such as on the top floor space, while lower peak-T_i was obtained in buildings with high thermal mass. Furthermore, applying DV showed high T_i due to the high T_o. On the other hand, low min-T_i was observed with NV, while high min-T_i was found in buildings with high thermal mass.

Table 2.1 Summary of the measured indoor air temperature (T_i) based on different studies conducted in various buildings in Malaysia

Study	**Measurement period**	**Peak-T_i**	**Min-T_i**	**T_o**
(Kubota et al., 2009)	All day	34	26.8	28 (Avg.)
(Tuck et al., 2019)	All day	33-37	27	28 ±2 (Avg.)
(Omar and Fadzil, 2016)	All day	32	29	27.8 - 30
(Djamila et al., 2013)	All day	35.3	26.5	-
(Hafizal et al., 2012)	All day	35.5	-	-
(Omar and Syed-Fadzil, 2011)	All day	31	28.5	25.5 - 32
(Hassan and Ramli, 2010)	6.00 - 18.00	34.3	27.3	27.3 - 34.5

2.2.3 Thermal Comfort in the Tropical Climate of Malaysia

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), thermal comfort is "*the condition of mind that expresses satisfaction with the thermal environment*". Generally, it is difficult to satisfy all people in space due to the large variations between them, i.e., physiologically and psychologically. Therefore, any space can be rated as thermally acceptable if it satisfies 80% of the occupants (ANSI/ASHRAE Standard 55, 2017).

Thermal requirements for naturally conditioned spaces differ from those required for other indoor spaces (ANSI/ASHRAE Standard 55, 2017). Therefore, the adaptive model was developed for naturally conditioned buildings. This model depends on the active relationship between people and their environment, i.e., people react to restore their thermal comfort if discomfort conditions occurred (Toe and Kubota, 2013; Al-Absi and Abas, 2018). Moreover, people were found to prefer a high range of temperatures in warm to hot climates (Djamila et al., 2013). According to Luo et al. (2016), the comfort perception of the individuals is closely linked to their thermal history and that a long-term thermal experience might shift their thermal expectation.

Generally, field thermal comfort studies are conducted, either in chambers or real buildings with various types of indoor conditions, to establish the comfort temperature and comfort range for people in various climatic conditions. Based on the field studies, thermal comfort models are developed and proposed to calculate the comfort temperature and comfort range. The following subsections present various field thermal comfort studies that were conducted in Malaysia and the comfort models that were developed for naturally conditioned buildings and hot-humid climate.

2.2.3(a) Field Thermal Comfort Studies

In Malaysia, field studies were conducted in chambers and real buildings and have reported neutral and comfortable temperatures and comfort ranges. For instance, Abdulshukor (1993) studied the thermal comfort of Malaysians and found that the neutral temperature in a chamber was 28.3℃, while the comfort temperature was 28.2℃. Furthermore, the study reported differences in the thermal comfort temperatures between Malays and Chinese, i.e., 28.7℃ and 27.6℃, respectively, and between males and females, i.e., 28℃ and 28.3℃, respectively. Besides, this study found that the Malaysian comfort zone is between 25℃ and 28.5℃ to 29.5℃ (i.e., depending on relative humidity).

Dahlan et al. (2008) conducted a field thermal comfort study in naturally ventilated high-rise hostels near Kuala Lumpur. They reported a neutral temperature of 30.93℃ when using linear regression of subjects' thermal sensation votes (TSV) with the operative temperature (T_{op}) and 29.87℃ when using the optimum thermal comfort model. Hussein et al. (2009) conducted a field thermal comfort study in air-conditioned and non-air-conditioned buildings (i.e., mechanically ventilated with fans) located in Selangor and Johor Bahru. The obtained neutral temperature using linear regression of TSV with T_{op} were 24.4℃ and 28.4℃ for the air-conditioned and non-