INVESTIGATION OF POROUS MATERIAL AS POTENTIAL MANIKIN FOR OUTDOOR THERMAL COMFORT INDEX

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DEDICATION

I dedicate this thesis

To my lovely father and mother, Mr. Kelundapyan and Mrs. Esotha Devi and also my family, who gave me endless love, their patience, trust, constant encouragement over the years, and for their prayers.

To my friends, who gave me moral support in all forms, motivates me always, love and prayers.

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ABSTRACT

Urban Heat Island (UHI) phenomenon leads to the increasing of urban environment temperature and higher human thermal discomfort level. The study of the thermal manikin that used to evaluate human discomfort based on thermal comfort indices is very limited. The purpose of this study is to investigate the suitability of porous material such as red clay, white clay and plaster as the potential manikin for outdoor thermal comfort index. Porous materials such as red clay, white clay and plaster have been selected to determine its evaporation rate by correlating it with evaporation rate of human sweat. The surface temperature of porous material was obtained through data logger and the data was correlated with human thermal perception which was designed based on the ASHRAE standard 55 for comfort evaluation. The last objectives of the study was to correlate thermal comfort indices with porous material surface temperature in order to identify suitable porous material for thermal comfort evaluation. This study used two types of statistical analysis methods which were descriptive analysis and bivariate analysis (Pearson correlation). The result shows that, red clay has a good correlation compared to other porous materials in terms of human sweat evaporation rate and human thermal perception which indicated $r = 0.583$ and $r = 0.685$ respectively with $p<0.01$. Furthermore, Heat Index (HI) had a strong relationship and statistically significant with all the tested porous material surface temperature. More precisely, HI had a strong relationship with red clay surface temperature which indicated $r = 0.733$ with $p<0.01$. Based on this, it revealed that red clay shows a consistent correlation to all parameter compared to other porous materials and this can be concluded that red clay can be the potential manikin for thermal comfort evaluation. The suitable material selection in this study is believed to help humans have a better understanding of thermal comfort assessment.

ABSTRAK

Fenomena Bandar Pulau Haba (UHI) membawa kepada peningkatan suhu persekitaran bandar dan tahap ketidakselesaan haba yang tinggi kepada manusia. Kajian tentang manikin terma yang digunakan untuk menilai ketidakselesaan manusia berdasarkan indeks keselesaan terma adalah sangat terhad. Tujuan kajian ini adalah untuk mengkaji kesesuaian bahan berliang seperti tanah liat merah, tanah liat putih dan plaster sebagai manikin yang berpotensi untuk indeks keselesaan terma. Bahan berliang seperti tanah liat merah, tanah liat putih dan plaster telah dipilih untuk menentukan kadar penyejatannya dengan mengaitkannya dengan kadar penyejatan peluh manusia. Suhu permukaan bahan berliang diperoleh melalui pencatat data dan data tersebut dikaitkan dengan persepsi haba manusia yang direka berdasarkan piawaian ASHRAE 55 untuk penilaian keselesaan. Objektif terakhir kajian ini adalah untuk mengaitkan indeks keselesaan terma dengan suhu permukaan bahan berliang untuk mengenal pasti bahan berliang yang sesuai untuk penilaian keselesaan terma. Hasil kajian menunjukkan bahawa, tanah liat merah mempunyai korelasi yang baik berbanding bahan berliang lain dari segi kadar sejatan peluh manusia dan persepsi haba manusia yang menunjukkan $r = 0.583$ dan $r = 0.685$ masing-masing dengan $p<0.01$. Tambahan pula, Indeks Haba (HI) mempunyai hubungan yang kukuh dan signifikan secara statistik dengan semua suhu permukaan bahan berliang yang diuji. Lebih tepat lagi, HI mempunyai hubungan yang kuat dengan suhu permukaan tanah liat merah yang menunjukkan $r = 0.733$ dengan $p<0.01$. Berdasarkan ini, tanah liat merah menunjukkan korelasi yang konsisten kepada semua parameter berbanding dengan bahan berliang lain dan ini boleh disimpulkan bahawa tanah liat merah boleh menjadi manikin yang berpotensi untuk penilaian keselesaan terma. Pemilihan bahan yang sesuai dalam kajian ini dipercayai dapat membantu manusia lebih memahami penilaian keselesaan terma.

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LIST OF SYMBOLS

%	-	Percentage
℃	-	Celsius
g	-	Gram
°	-	Degree
RH	-	Relative Humidity
Kg	-	Kilogram
W/m^2	-	Watts per meter square
m/s	-	Meter per second
$Kg/m^2.m$	-	Kilogram per meter square meter
m^2	-	Meter square
cm	-	Centimeter
clo	-	Clothing Insulation Unit
ΔP	-	Porous Material and Human Sweat Evaporation Rate
Δt	-	Time Interval
As	-	Surface Area of the Specimen and Human Body

LIST OF ABBREVIATIONS

AT	-	Apparent Temperature
ADAM	-	United States Sweating Thermal Manikin
ASHRAE	-	The American Society of Heating, Refrigerating and Air- Conditioning Engineers
CBD	-	Central Business District
CDC	-	Chinese Center for Disease Control and Prevention
CFD	-	Computational Fluid Dynamics
COST	-	European Science and Technology Cooperation
DOSH	-	Department of Occupational Safety and Health
GKL	-	Greater Kuala Lumpur
HI	-	Heat Index
IBM	-	International Business Machines Corporation
IPCC	-	Intergovernmental Panel on Climate Change
ISB	-	International Society of Biometeorology
ISO	-	International Organization for Standardization
KEM	-	Japanese Sweating Thermal Manikin
MOH	-	Ministry of Health Malaysia
NOAA	-	National Oceanic and Atmospheric Administration
NWS	-	National Weather Services
OSHA	-	Occupational Safety and Health Administration
PASW	-	Predictive Analytics Software
SAM	-	Swiss Sweating Thermal Manikin
SPSS	-	Software Statistical Package for Social Science
TSV	-	Thermal Sensation Vote
UHI	-	Urban Heat Island
UOTD	-	Urban Outdoor Thermal Discomfort

USA	-	United States of America
UTCI	-	Universal Thermal Climate Index
UTM	-	Universiti Teknologi Malaysia
WBGT	-	Wet-Bulb Globe Temperature

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The world is growing towards urbanization and it is an alarming social issue for the developing countries (Lee *et al.*, 2018). Rapid urbanization may densify built-up zones and increase building density, compactness, plot ratio and average building height as well as changing the urban morphology that leads to the increment of air temperature (Suckall *et al.*, 2015). With increasing urbanization, the Urban Heat Island (UHI) phenomenon is becoming more of a concern, with urban heat island intensities continuing to increase, especially in many megacities (Radhi *et al.*, 2013; Doan & Kusaka, 2015; dos Santos *et al.*, 2017; Yao *et al.*, 2017). A UHI is recognized as a climatic phenomenon in which urban areas have higher air temperature than their surrounding rural area as a result of anthropogenic modification of land surfaces, urban expansion, population growth, energy use and its consequent generation of waste heat which cause alarming effects in many metropolitan areas (Ghazanfari *et al.*, 2009; Kolokotsa *et al.*, 2009; Kolokotroni & Giridharan, 2008; Shahmohamadi *et al.*, 2011). The UHI effect can cause a person to experience thermal discomfort and likely to be exposed to heat health illness. With the increase in air temperature, heat-related morbidity and mortality rates have begun to rise in recent years (Kodera *et al.*, 2019). Moreover, frequent exposure to the heated environment will thus contribute to a decrease in thermal comfort, thus increasing the prevalence of heat-related illness (Ohba *et al.*, 2010; Fleischer *et al.*, 2013; Na *et al.*, 2013; Gu *et al.*, 2016; Ministry of Health Malaysia, 2016).

Therefore, it is essential to evaluate outdoor hot environment in order to ensure the health and safety of outdoor individuals (Parsons, 2011).

Thermal comfort has been defined by Hensen (1991) as “a state in which there are no driving impulses to correct the environment by the behaviour”. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined it as “the condition of the mind in which satisfaction is expressed with the thermal environment” (ASHRAE, 2004). Thermal heat balance of human body is highly influenced by the external heat impacts from surrounding environment conditions. In these extreme environments, these thermal comforts and sensations are complex in terms of the human body's physiological and psychological responses. Hoppe (2002) mentioned that the physiological and psychological factors needed to be considered in assessing indoor or outdoor thermal comfort. In terms of outdoor thermal comfort, studies have revealed that a purely physiological approach is inadequate to characterize the outdoors thermal comfort conditions and thermal adaptation as it involves climate, physiological factors (sweating or acclimatization) and psychological factors (perception or expectation) which are important in the assessment of thermal environment (Fang *et al.*, 2019). Therefore, investigation should be made to correlate the physiological and psychological factors of the human body within the microclimate environment for further development and improvement of human thermal comfort evaluation (Lee *et al.*, 2017).

In order to keep people away from heat and discomfort, mitigation and prevention strategies should be introduced. The direct method of exposing human body to direct sunlight or outdoor environment is discouraged due to the induction of death and health problem consequently (Kelundapyan *et al.*, 2021). Therefore, in combination with these mitigation initiatives, the development of thermal manikin in the future research may be useful as a representative of the human simulation model to investigate the occurrence of UHI and to assess thermal comfort under microclimate conditions (Lee *et al.*, 2018). The thermal manikin is able to evaluate the effect of human body and simulate human responses in thermal environment (Fu *et al.*, 2016). With the development of modern technology, the number of sweating thermal manikins has been steadily increasing and many modern thermal manikins are constructed with a sweating function (Lu *et al.*, 2017). The development of sweating manikins has made it possible to simulate human thermal interactions with the environment in a realistic manner (Yang *et al.*, 2014). Since the development of thermal manikin is gaining attention, it is possible to include the combination of human factors such as physiological mechanism of thermoregulation by fabricating thermal manikin, thermal perception by questionnaire survey and thermal comfort indices based on meteorological data to evaluate human thermal comfort in outdoor environment (Lee *et al.,* 2018). Therefore, there is a possibility to relate the usage of porous material as a thermal manikin to assess the human sweat evaporation rate and human thermal perception which indicate the physiological and psychological factors respectively. Consideration on human sweat evaporation rate is important because it is the main parameter that reflects the heat transfer between the human body and the surrounding thermal environment (Yang *et al.*, 2014). In a state of heat stress, the sweating mechanism helps in the thermal regulation of the human body. Therefore, sweating can be considered as the preliminary study for the development of heat indicator to assess thermal comfort.

Based on Menders and Silva (2004), the porous material has the capillary effect and formation of a humid layer on the external surface of the porous material which is almost similar to human skin. The porous material also has the characteristics such as cooling effect and the evaporation rate based on air temperature which is almost the same with human skin. The researcher used the porous material of plaster, white clay and red clay to simulate human perspiration and the materials have shown the capacity to simulate evaporation in human sweating mechanism (Mendes & Silva, 2004). However, there is no indicator of fabrication from porous materials such as red clay, white clay and plaster. Hence, the aim of this study focused on the investigation of the suitability of porous materials such as red clay, white clay and plaster as the potential manikin for thermal comfort evaluation. Thus, physiological and psychological responses based on climatic variable are considered for this study. This study to investigate whether porous material is suitable to become the material in developing the heat indicator for a new generation of manikin that is suitable in outdoor environment of tropical climate.

1.2 Problem Statement

The expansion of urbanization process has worsened the scenario since the urban areas will tend to have higher temperature compared to its rural surrounding area which causes Urban Heat Island (UHI). The urban area resident are subsequently exposed to the UHI effect and therefore can be under increase of health risk due to heat (Ramakreshnan *et al.*, 2018). The high building will trap the heat and it will prevent the heat from escaping to the atmosphere. Hence, the temperature in the urban area will be higher. The resident of the urban area will experience thermal discomfort; for example, heat stress and heat stroke. The increased temperature is the early cause of heat stress on human being. Hence, the human thermal comfort should be assessed to reduce the heat health risk among the society since heat illness is serious and, in some cases, it can cause fatality.

Generally, thermal manikin is like human models that are used in the research to analyse the thermal relationship between human body and the environment. Similarly, it goes to sweating manikin which measures the amount of sweat loss from the skin to the surrounding in particular ambient condition. This manikin can be used to evaluate the effect of human body and simulation of human responses in thermal environment (Fu *et al.*, 2016). Based on previous study, there were a lot of sweating manikins being used worldwide with different materials (Nayak & Padhye 2017). There is no sweating manikin that was made up from red clay, white clay and plaster till date. However, in 2004, Mendes and Silva used the porous material of plaster, white clay and red clay to simulate human perspiration and they stated that the porous material has the capillary effect and formation of a humid layer on the external surface of the porous material which is almost similar to human skin (Mendes & Silva, 2004). Porous materials have shown the capacity to simulate evaporation in human sweating mechanism based on theory. But the researcher never used actual human sweat loss and compared it with the porous material.

At the same time, the current sweating manikin is mainly focused on indoor environment, where it is installed in a climatic chamber and connected to a power supply with a computer-controlled system to investigate the necessary parameters (Lee *et al.*, 2018). These parameters are mostly used to investigate human thermal comfort by simulating human parameters such as sweat rates in a controlled condition rather than investigating it on outdoor thermal comfort. There is still lack of sweating manikin used in actual outdoor environment for thermal comfort evaluation (Lee *et al.*, 2018). However, the assessment of thermal comfort does not only depend on climatic variables but also depends on physiology and psychology factors. Lee *et al.* (2017) suggested that the new generation of manikin should include the combination of physiological mechanism of thermoregulation of human body, human thermal perception and quantitative thermal comfort indices based on meteorological data to evaluate human thermal comfort in outdoor environment. The knowledge gap is existing there, where not a single manikin was used to evaluate human discomfort based on thermal comfort indices.

However, in this study, the correlation between porous material and thermal comfort indices can be formed in order to evaluate the effect of human body in thermal environment. In order to obtain a better assessment of human thermal comfort, sufficient data with these three aspects are needed to be developed with a series of indices to accurately evaluate thermal comfort. Hence, this study intends to determine the suitability of red clay, white clay, and plaster as potential manikin for outdoor thermal comfort evaluation in future.

1.3 Research Questions

The research questions are:

1. What is the correlation between porous material evaporation rate and human sweating process?
2. What is the relationship between porous material and thermal perception?
3. What is the relationship between thermal comfort indices and porous material?

1.4 Research Objectives

This study intends to investigate whether porous material is suitable to become the material in simulating sweating mechanism in terms of evaporation rate that is suitable to be applied in outdoor environment for thermal comfort evaluation. To achieve this aim, the objectives of this study are developed as below:

1. To determine the human sweat evaporation rate, porous material evaporation rate and surface temperature, human thermal perception and thermal comfort indices for the relationship analysis.
2. To analyse the relationship between human evaporation rate and thermal perception with porous material evaporation rate and surface temperature respectively.
3. To proposed suitable thermal comfort indices to be paired with porous material for thermal comfort evaluation.

1.5 Scope of Study

This study covers outdoor spaces at Universiti Teknologi Malaysia (UTM), Johor, Malaysia. The scope of the study focused on the investigation of porous materials such as red clay, white clay and plaster that are suitable to simulate human sweating mechanism in terms of evaporation rate for thermal comfort evaluation. The field investigation of this study was conducted on January 9 to January 16, 2019 at UTM campus from 9:00 am to 6:00 pm with the interval time of 15 minutes. The field investigation of this study was conducted at daytime due to heavy presence of solar thermal / sunlight exposure which is suitable for thermal comfort assessment. Canan *et al.* (2019) suggest that the best field survey for outdoor thermal comfort is at 9:00 am to 6:00 pm. The data collection included field measurement (climatic variable and physiology) and subjective assessment (psychology). The field measurement included microclimate parameter, thermal comfort indices, human sweat evaporation rate, porous material evaporation rate, porous material surface temperature and thermal perception in order to fulfil the objectives. Air temperature, relative humidity, wind speed and solar radiation were parts of climatic variable in this study.

The measurement of the micrometeorological parameters at site was in accordance to ISO 7726. The measurement of human sweat evaporation rate was determined using Peters-Passmore equation while porous material evaporation rate was identified using Mendes and Silva equation. Thermal comfort indices were chosen based on previous study that was applicable in Malaysia. Meanwhile, subjective assessment was based on responses to a questionnaire survey, which was administered simultaneously with field measurement during each survey. Accordingly, the survey instrument was divided into two parts of questions. The first part of the questionnaire recorded the personal information, activity level, and clothing level of the subjects. The respondents were required to provide data on the type of clothing worn and the level of activity to estimate the clothing values and metabolic rates. The second part of the questionnaire was based upon the perception of comfort by individuals with regard to the climatic conditions. Once data collection was completed, human sweat evaporation rate, human thermal perception and thermal comfort indices were correlated with porous material and analysed by using Microsoft Excel and SPSS version 22. This study used two types of statistical analysis methods which included descriptive analysis and bivariate analysis (Pearson correlation analysis).

1.6 Significance of Study

This study will help to find the suitability of porous materials (red clay, white clay and plaster) for thermal comfort evaluation in terms of physiological and psychological responses based on climatic environment. With respect to this, the porous materials such as red clay, white clay and plaster can be chosen as the material for the heat transfer in order to represent a heat indicator of new generation of manikin for outdoor thermal comfort evaluation by reflecting the climatic, psychological and physiological factors. The suitable selection of material in study is hoped to help the human to have a better understanding on thermal comfort assessment and hence, able to design a thermally desired building for human in future. It will be a step forward in the evaluation of outdoor thermal comfort by increasing the awareness of society and government about the effects of human thermal comfort.

1.7 Thesis Outline

This study is divided into five chapters which introduced a new approach for the suitability of red clay, white clay, and plaster as potential manikin for outdoor thermal comfort evaluation. The structure of the dissertation is as follows:

Chapter 2: Literature Review

This chapter discusses about the effects of human discomfort due to outdoor environment. To mitigate the current environment issue, this study is able to point out some useful information in order to determine the suitability of red clay, white clay, and plaster as potential manikin for outdoor thermal comfort evaluation in future. This review is important to gain a better understanding of the topic undertaken.

Chapter 3: Methodology

This chapter presents the framework idea of this whole research, how the research is designed, and the methodology used. This chapter also contains details of research procedures and the selected analysis method. The data collection is divided into two ways which are field measurement and subjective assessment. Once data collection is completed, the data are analysed using Microsoft Excel and SPSS version 22. This study uses two types of statistical analysis methods which are descriptive analysis (minimum, maximum, mean and standard deviation) and bivariate analysis (Pearson correlation).

Chapter 4: Result and Discussion

The chapter discusses on the collection and analysis of data based on the experiment which has been conducted accordingly to the methodology in Chapter 3. This chapter explains the result and discussion for the correlation between evaporation rate of human sweat and porous material, the relationship between porous material and

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LIST OF PUBLICATIONS

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