THE EFFECT OF LONG TERM EXPOSURE ON THERMAL PERFORMANCE OF ROOFING MATERIALS IN MALAYSIAN CLIMATIC CONDITION

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A Thesis submitted in fulfilment of the
Requirements for the award of Degree of
Master of Science (Architecture)

Faculty of Built Environment
Universiti Teknologi Malaysia

MARCH 2012

In loving memory of my father who passed away just before I came for the program

and to my living mum who fanned this dream to reality.

ACKNOWLEDGEMENT

First and above all I praise God the almighty for the guidance, wisdom and perseverance he bestowed upon me during the course of my work and indeed, throughout my life. All glory and honor be unto him. The program was indeed a journey of faith and I would like to acknowledge those entire people God used to guide me through but time, and most especially, space would not let me. I can only mention a few to whom, I cannot sum up how immensely grateful I am;

- To UTM Skudai Johor - My place of learning
- Dr. Dilshan Remaz Ossen - My guide through the process along with aides like GIRG team
- The Hope family - My home away from home
- Mummy, Zhebati and Vala - My supporters, encouragers and providers
- John Anumah - My friend, my love, my teacher
- Juliet, Jayne, Jemila, Msurshima and Chinwe - My friends who stick closer than a brother
- Mr Saidu Mohammed, Wallace, Pst. Zinas, Yakubu Dodo, Ismaeel - The Nigerians who helped me like Nigerians would; helping out even when it was not convenient for them.

Thanks for the opportunity you all gave me to benefit from a part of your lives in kindness and in sacrifice. The Lord reward you all.

ABSTRACT

Owing to exponential increase in world population and high influx of migrants to urban areas, demand for space in form of housing and infrastructure has increased in most urban centers yielding a high number of infrastructural developments requiring clearing of vegetative land cover and replacement by roofs and paved surfaces. The materials used in most cases have higher absorptive heat capacities than the soil and vegetation they replace resulting in the phenomenon known as Urban Heat Island (UHI) where urban areas are hotter than their surrounding rural areas. In tropical regions where solar radiation intensities are higher and rainfall is all year round, thermal performance of these materials is altered by the climatic conditions. The growing population and rising demand for infrastructure calls for careful evaluation of materials used in the urban fabric as a strategy for the mitigation of the UHI phenomenon. This study was carried out on commonly used roofing materials in Malaysian tropical climate; clay and concrete roof tiles adopting two methodologies for the samples. Full scale testing for concrete tiles measured between 12- 19th April, 2011 and exposure rack method for clay tiles measured 1st- 8th July, 2011. Surface and ambient temperature measurements were taken for seven days each by HOBO U-12 Data loggers on samples which had been exposed for varying durations of above 25years, 15years, 10years and less than one year. Climatic conditions such as relative humidity, air temperature and wind speed were recorded using the Environ Data weather station set- up on the study site of the UTM campus. Analysis was made using measures of descriptive analysis on Microsoft Excel and independent paired sample t-tests were carried out on SPSS software. Results showed that after over 25 years of exposure, maximum surface temperature of concrete tile dropped by 12% while the clay rose by 3.68%. Minimum surface temperature of concrete rose by about 2% and no significant changes were observed in the clay tile at night. Thermal performance evaluation of materials used in the urban fabric is essential as a passive solution to mitigating the negative effects of UHI.

ABSTRAK

Peningkatan eksponen dalam penduduk dunia, kebanjiran pendatang yang tinggi ke pusat bandar serta permintaan bagi ruang perumahan dan infrastruktur telah menyebabkan peningkatan pembangunan infrastruktur yang tinggi. Pembersihan hutan dan kawasan hijau telah banyak dilakukan untuk digantikan dengan bumbung dan permukaan berturap. Penggantian bahan-bahan yang mempunyai kapasiti penyerapan haba daripada tanah dan tumbuh-tumbuhan telah mengakibatkan fenomena yang dikenali sebagai Kepulauan Haba Bandar (UHI) di mana kawasan bandar adalah jauh lebih panas berbanding kawasan luar bandar. Di kawasan tropika, keamatan sinaran suria adalah tinggi, hujan sepanjang tahun dan prestasi terma bahan diubah oleh keadaan iklim. Pertambahan penduduk dan permintaan infrastruktur yang semakin meningkat memerlukan penilaian dalam fabrik bandar sebagai satu strategi untuk mengurangkan fenomena UHI. Kajian ini dijalankan ke atas bahan bumbung yang biasa digunakan dalam iklim tropika Malaysia. Tanah liat dan jubin bumbung konkrit digunakan sebagai dua kaedah sampel. Ujian skala penuh bagi jubin konkrit diukur di antara 12-19 April, 2011 dan pendedahan rak kaedah untuk jubin tanah liat diukur pada 1-8hb Julai, 2011. Permukaan dan pengukuran suhu ambien telah diambil selama tujuh hari setiap satu oleh HOBO U-12. Data log di ambil ke atas sampel yang terdedah untuk pelbagai tempoh masa; 25 tahun ke atas, 15 tahun, 10 tahun dan kurang daripada 1 tahun. Keadaan iklim seperti kelembapan relatif, suhu udara dan kelajuan angin telah direkodkan menggunakan EnvironData stesen cuaca set-up di kajian tapak kampus UTM. Analisis deskriptif pada Microsoft Excel dan sampel *T- test* telah dijalankan ke atas perisian SPSS. Keputusan menunjukkan bahawa selepas pendedahan melebihi 25 tahun, suhu permukaan maksimum jubin konkrit menurun sebanyak 12% manakala tanah liat meningkat sebanyak 3.68%. Suhu permukaan minimum konkrit meningkat sebanyak kira-kira 2% dan tiada perubahan ketara telah diperhatikan dalam jubin tanah liat pada waktu malam. Penilaian prestasi terma bahan yang digunakan dalam fabrik bandar adalah perlu sebagai satu langkah penyelesaian yang baik untuk mengurangkan kesan-kesan negatif UHI.

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LIST OF ABBREVIATIONS

ASHRAE	-	American Society of Heating, Refrigerating Air Conditioning Engineers
ASTM	-	American Society for Testing and Materials
BUR	-	Built up Roof
CFD	-	Computational Fluid Dynamic
CRRC	-	Cool Roof Rating Council
EPDM	-	Ethylene Propylene Diene Monomer
EPS	-	Expanded Polystyrene
FSEC	-	Florida Solar Energy Centre
GIS		Geographic Information Systems
HTB	-	Heat Transfer through Buildings
LBNL	-	Lawrence Berkeley National Laboratory
NIR	-	Near Infrared Reflectance
NPS	-	National Park Service
NRCA	-	National Roofing Contractors'Association
ORNL	-	Oak Ridge National Laboratory
PVC	-	Poly Vinyl Chloride
SBS	-	Styrene-Butadiene-Styrene
SJER CDP	-	Southern Johor Economic Region Comprehensive Development Plan
SPF	-	Spray polyurethane foam-based
SR	-	Solar Reflectance
SRI	-	Solar Reflective Index
TPO	-	Thermoplastic Olefin
UHI	-	Urban Heat Island

UHIPP	-	Urban Heat Island Pilot Project
U.S	-	United States
US EPA	-	United States Environmental Protection Agency
UTM	-	Universiti Teknologi Malaysia
UV	-	Ultra Violet
VIS	-	Visible Infrared Solar reflectance
WSRCA	-	Western States Roofing Contractors Association
XPS	-	Extruded Polystyrene

LIST OF SYMBOLS

A_s	-	albedo
α	-	solar-reflectivity or albedo of the surface
a	-	Stefan-Boltzmann constant, 5.6685 × 10^{-8} $Wm^{-2}K^{-4}$
$\mathcal{E}$	-	hemispherical emittance of surface
hc	-	convection coefficient, W m^{-2} K^{-1}
h_a	-	coefficient of heat transfer by 1ong wave radiation and convection at the outer surface
I_t	-	total solar radiation incident on the surface W/m^2
I	-	total solar radiation incident on the surface W/m^2
k	-	thermal conductivity (W/m.K)
Qc	-	convective heat transfer (W)
R	-	thermal resistance (m^2.K/W)
δR	-	difference between thermal radiation incident on the surface and surroundings and that emitted by a blackbody at the outdoor air temperature, W/m^2
T_o	-	outdoor air temperature, °C
t_a	-	air temperature (°C)
t_s	-	surface temperature (°C)
T_s	-	equilibrium surface temperature, K
T_{sky}	-	the effective radiant sky temperature
T_a	-	air temperature, K
x	-	thickness (m)

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Population growth has continued to increase exponentially worldwide. Current projections reveal that from approximately 6.9 billion in 2005, population should rise to between 7.5 and 10.5 billion by the year 2050 (World Population Prospects, 2009). Population growth so far has among other factors placed an increase in demand for infrastructure forcing urban development into areas that were previously vegetative. It has resulted in an increase in land area coverage by “hard” man-made surfaces such as roofs and pavements. In most urban centers, the roofs and pavements now make up about 60% of total land area (Akbari *et al.*, 2008).

Studies (Bingfeng & Pingjun, 2007; Santamouris *et al.*, 2011; Taha, 1997) have linked this land coverage pattern with higher temperatures experienced in urban centers as urban centers are warmer compared to their surrounding rural settlements which have more vegetative and exposed soil areas. This temperature gradient has risen to as high as 2-5ºC difference in nighttime temperatures in the last 30 years between urban centers and their surrounding rural areas (Okeil, 2010). The phenomenon where urban centers are warmer than their surrounding rural areas is known as the Urban Heat Island (U.H.I.).

Studies (Bingfeng & Pingjun, 2007; Santamouris *et al.*, 2011; Taha, 1997) made on the Urban Heat Island phenomenon have shown that the materials used in urban development possess higher absorptive heat capacities than the soil and vegetative land cover which they replace. These "hard" land surfaces take the form of roads, bridges, parking lots, walkways, patios, roofs and walls (Hitchcock, 2009). They tend to absorb solar radiation incident on them and radiate the energy at night; raising surrounding temperatures (Synnefa *et al.*, 2006). The intensity of this phenomenon is greater in high and mid- latitude cities; the area in which tropical countries lies (Taha, 1997).

Some studies have also attributed higher absorptive capacities to darker materials such as asphalt and tar (Wong, 2005). They have shown (discussed further in later section) that lighter colored material surfaces can increase the reflective capacities of these materials and lower their surface temperatures thereby maintaining cooler environments (Bingfeng & Pingjun, 2007; Taha *et al.*, 1992). As a result, careful evaluation of thermal properties of materials used in the development of urban areas is employed as a strategy to mitigate urban heat island. The principal properties governing the thermal performance of materials include reflectance and emittance (Wong, 2005). Materials with high reflectance and emittance tend to attain lower surface temperatures hence transfer less heat to their surroundings through convection (Santamouris *et al.*, 2011).

For buildings in hot and humid regions, the roofs have been said to be a major source of heat gain in buildings (Suehrcke *et al.*, 2008). Roofs constitute about 15- 25% of most United States (U.S) cities' land area coverage and are considered the "hottest" urban surfaces (Hitchcock, 2009). Studies show that the thermal properties of these materials tend to wear out on exposure to weather. In a report from Dallas, records reveal that low slope roof materials in Dallas are replaced on the average every 10- 15 years (Hitchcock, 2009). Some other study by Liu (2005) revealed that the rate of degradation of materials is influenced by surface temperature they attain as higher surface temperatures tend to increase thermal stresses on roofing materials thus shortening their life span. Other factors which contribute to the degradation of building materials and determine its rate include; wind, moisture (rain, hail, snow, frost, and dew), biological growth, atmospheric gases and pollutants (Berdahl *et al.*, 2008). Although not limited to these, the above mentioned factors alter the performance of materials whose rates vary depending on other factors such as location and characteristic of the material.

Concrete and clay tile roofing materials; the most commonly used in Malaysia have durable service life under this climate, however; there is little concern for the thermal performance of the materials in the long run (Kiet *et al.*, 2008). This study investigated the effects of long term exposure on commonly used steep slope roofing materials in the tropics and how it influences the thermal performance of the above mentioned materials. It aims at evaluating the surface temperatures of various exposure lengths of these materials and comparing them for a better understanding of their contributions at various stages to the thermal balance of the environment.

1.2 Statement of the Problem

Malaysia (at 3.1^{o}N and 101.7^{o}E) located in the tropical region, is facing challenges in the building industry as a result of sun and wind. Somewhat contrary to the temperate climate, the tropical region has summer all year round which causes considerable heat gains (Ahmad *et al.*, 2007). In the daytime, heat flow from sun-exposed roof surface is essentially in downward direction which has the tendency to overheat buildings and put extra loads on conditioning systems (Suehrcke *et al.*, 2008). The reverse occurs at night raising nighttime temperatures by about 2-4˚C (35.6˚F- 71.2˚F) higher than surrounding rural environs (Libbra *et al.*, 2011).

High relative humidity, temperature variations and higher number of rain days are the characteristics of hot and humid regions that bear greater responsibility for the drop in the reflectance and thermal performance of roofing membranes with time (Roodvoets *et al.*, 2004). Elevated temperatures affect the durability of roof membranes due to thermal stresses of expansion and contraction (Byerley & Christian, 1994). High humidity causes microbial growth inducing chemical change which progress faster under humid climates thus blackening membrane surfaces causing degradation and modification of albedo temporarily or permanently (Bretz & Akbari, 1997). These affect thermal performance of roofing materials. The above mentioned factors have an effect on the material thermal properties which ultimately affect the thermal performance of the roofing materials under long- term exposure to tropical climates.

1.3 Hypothesis

Microbial growth and long hours of exposure to high solar radiation; a common phenomenon in humid areas degrade building materials. These conditions may lead to albedo modification temporarily or permanently by inducing chemical change (Bretz & Akbari, 1997). Most non- metals have high emittance values examples include concrete and clay tiles and with coatings, they can attain high reflectance values. However, blackening of these materials occur due to microbial growth (Doulos *et al.*, 2004). Conditions that bear a great responsibility in dropping the reflectance of membranes include; high relative humidity, temperature variations with time and high number of rain days (Roodvoets *et al.*, 2004). Therefore, if surface properties of the material are modified due to long term exposure to the environment, then thermal performance of these materials in the long- run is altered.

1.4 Aim

The aim of the study is to evaluate the impact of exposure on thermal performance of roof materials in relation to time; to determine the impact of long term exposure on the thermal performance of roofing tile materials.

1.5 Objectives of the Study

- To evaluate the thermal performance of roof materials
- To determine the effects of exposure on the thermal performance of roof materials and their surrounding environment
- To compare which of the tested material thermal performance is affected more by long term exposure.

1.6 Research Questions

This research aims to be providing answers to these questions;

- What is the thermal performance of concrete and clay tiles in the tropical region?
- What is the effect of the roof thermal performance on the ambient air temperature immediately above the roof surface?
- What is the effect of exposure on the thermal performance of the materials?

1.7 Scope and Limitations

Several factors contribute to the urban heat island phenomenon. They include global warming or climate change, anthropogenic heat released and increased hard surfaces consequently reducing green areas and absorbing more heat (Yamamoto, 2006). Hard surfaces include pavements and roofs which make up about 60% of surfaces in developing cities such as in Dallas and in Johor Bahru, constitute about 40% of total land area (Majid & Hafizul, 2010). However, this study will be focusing on roofs though they constitute only between a fifth and a quarter of most urban surfaces (Akbari *et al.*, 2008), they are remarkably the "hottest" (Hitchcock, 2009). Roofs in the tropics could exceed 60ºC temperatures on hot days depending on the material or albedo.

Thermal performance of roofs can be evaluated through several means. These include measurement of reflectance and emittance as the main influences on surface temperatures (Santamouris *et al.*, 2011). Thermal properties of materials include the thermal mass, convective heat capacity and thermal resistance (Gui *et al.*, 2007). All of these material properties affect the surface temperature of roofs in one way or the other. This study will be evaluating the thermal performance of roofs by the surface temperatures they can attain.

Methods of evaluating the surface temperature of these materials include; computer simulations and scale model testing as employed by Bansel et al (1992), field measurement and testing; Doulos et al (2004), Prado et al, (2005). The scope of this study will be limited to reporting the surface temperature measurements of four (4) concrete tile roofs and two (2) clay tile samples at different stages of exposure and comparing their thermal performance as well as an experiment comparing clay against concrete tile performance. All the measurements were carried out on concrete and clay roof tile samples; the most commonly used roofing material in Malaysia. Comparisons were made of their surface temperatures.

Thermal performance of these roofs was observed on an hourly basis; from the 12th of April to the 19th of April for the concrete samples and 1st to 7th of July, 2011 for the clay tile samples. Temperature losses at night and gains in sunlight were compared against other samples tested simultaneously. The effect of long term exposure on these tiles is also discussed. Statistical comparisons were made using descriptive statistic measures such as; means, range minimum and maximum values in Microsoft Excel 2007. An independent paired sample T-test using SPSS was used to determine the level of significance of the difference of the means obtained.

1.8 Research Gap

Thermal analysis of residential dwellings has a long history of development with a wide variety of tools available of differing technical complexity. However, the majority of the research in the field of household thermal performance modeling has been tuned to the Northern European or North American climate. This has provided motivation for development of innovative methods for decision making about building and behavioral parameters to optimize energy use and minimize the related impact on environment. Microbial growth is more common in humid areas of the country, as implied by the perceptions of roofing contractors around the United States (Bretz & Akbari, 1994).

Surface accumulations reported by Yarbrough & Anderson (1993), such as dirt and microbial growth, may or may not be permanent, depending on their water solubility and may modify the albedo permanently by inducing chemical change in the material. Insolation (particularly ultraviolet radiation), moisture (dew, rain, humidity), temperature (primarily the time-averaged temperature of the roof), and natural and anthropogenic pollutants (particularly aerosols and acid rain) are the major elements that degrade roof coatings therefore as Diakaki *et al* (2008) have stated, the challenge is to prove the more effective and reliable material in the long term.

Concrete and clay roofing tile; the most commonly used roofing materials in this region have a very durable service life due to their ability to withstand the weather conditions. Unfortunately, not much attention is paid to its thermal performance in the long run (Kiet *et al.*, 2008). Studies on roof materials have shown that the change in albedo over time will vary inconsistently between roofs depending on the climatic and atmospheric condition amidst other factors (Bretz & Akbari, 1997). However, it is possible to determine an average pattern of behavior for a geographical area. The summary of literature reviewed reveals that quite a lot of studies have been carried out in various climatic regions and a number of testing methods used to analyze some performance criteria of building envelope elements. Hence, a time related thermal performance of roofing materials in tropical regions is a welcome contribution to the existing body of knowledge.

1.9 Thesis Organization

The thesis is organized into 5 chapters whose summaries are as follows:

Chapter one forms a background to the work. It contains the problem, hypothesis, questions, aims and objectives. A structural frame is also included to highlight what can be expected in the complete study.

Chapter two reviews a variety of related and relevant literature to provide a platform to launch the study. The review discusses the global challenge of UHI, the role of materials in contributing to the problem, the Malaysia urban fabric, materials used and the effects of exposure of these materials on their performance. It further discusses the climate and effects of the urban surface materials used on the climate of the tropical region. The review progresses with highlights of studies carried out on related subjects, methodologies used and conclude with a summary.

Chapter three this chapter is in two parts. The first emphasizes the need for the experiment. The latter describes in detail the order in which the study was carried out. It also considers approaches to carry out the experiment formulating an appropriate method to carry out the experiment. Assumptions, Instrumentation and limitations are also presented.

Chapter four presents the results of surface temperature and climatic conditions of the samples and study area. Principal findings are summarized. The results are discussed as follows;

- Thermal performance of samples
- Effects of the materials on thermal balance of their surrounding
- Comparison of effects of exposure on the material samples
- Analytical comparison of the performance of the samples against each other.
- The chapter concludes with a summary.

Chapter five is the overall conclusion of the thesis which ends by reviewing the objectives and research questions to assess the extent to which they were answered and propose recommendations and further areas of research.

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