Study on ageing process of cool coatings in tropical climate

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2018

Yang, X. (2018). Study on ageing process of cool coatings in tropical climate. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/75922>

<https://doi.org/10.32657/10356/75922>

**STUDY ON AGEING PROCESS OF COOL COATINGS IN
TROPICAL CLIMATE**

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2018

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TROPICAL CLIMATE**

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A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

July 2018

Acknowledgements

First and foremost, I would like to express my deepest appreciation to my supervisor, Assoc. Prof. Wan Man Pun from School of Mechanical and Aerospace Engineering. Professor Wan shared with me his knowledge about my doctoral topic, provided guidance for my research life, and offered valuable advice on my academic writing. I am fortunate to have this opportunity to learn from such an inspiring and warm-hearted supervisor.

I would also like to thank the research scholarship from Nanyang Technological University, the funding for the MND-A*STAR project “High-performance cool roof coating for green buildings”, and the close research collaboration with ICES A*STAR and SkyCool Pte Ltd.

I would also like to acknowledge the help from my colleagues and friends. Great thanks to Dr. Kishor Zingre, Dr. You Siming, Mr. Poh Zihan, Ms. Zhou Jian, and Dr. Tong Shanshan for their creative discussions and idea exchanges. My thanks also go to the technical staff Mr. Lee Keng Yuen, Mr. Yeo Boon Chuan, and Mr. Ang Koon Teck for their assistance in my laboratory experiments.

Last but not the least, I would like to extend my gratitude to my parents and my wife for their constant understanding and encouragement in these years.

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Abstract

Cool coating is an effective passive cooling technique for reducing the energy consumption of buildings and increasing thermal comfort of occupants. Its thermal performance is determined by two radiative properties, solar reflectance and thermal emittance. However, as cool coating ages, its solar reflectance and thermal emittance change, and consequently its thermal performance degrades. This thesis aims to investigate the ageing process and its effects on cool coatings.

In this thesis, the thermal performance and energy saving benefits of cool coating were evaluated by field experiments in Singapore. Natural ageing experiments were conducted in Singapore, to record the changes of solar reflectance and thermal emittance of cool coatings in local environment. Then laboratory-based experiments were designed to quantify the effects of various environmental factors on cool coating, including soiling, cleaning, and ultraviolet (UV) radiation.

Mathematical models for the changes of radiative properties of cool coatings during ageing were developed based on the results obtained in this thesis. Then they were embedded into an existing Cool Roof Heat Transfer (CRHT) model to improve the accuracy of heat transfer prediction. It shows that for the net heat gain of a test building for three years, the difference between the results from the two models could be up to 78%.

Several kinds of cool coating were tested in this thesis, and it was found that the cool coating would experience less solar reflectance loss during ageing when they have improved surface properties, e.g., smoothness and omniphobicity.

Future work such as investigation on soiling deposition rate in local climate could further improve the understanding of the effects of ageing on cool coatings.

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Nomenclature

English symbols

Symbol	Unit	Description
a_{roof}	m^2/s	Thermal diffusivity of roof
A	m^2	Building envelope surface area
Bi	-	Biot number
$C_{dry\ deposition}$	g/m^2	Surface concentration of dry deposited soiling particles
$C_{dry\ deposition}^{total}$	g/m^2	Surface concentration of total dry deposited soiling particles
$C_{wet\ deposition}$	g/m^2	Surface concentration of wet deposited soiling particles
$C_{wet\ deposition}^{total}$	g/m^2	Surface concentration of total wet deposited soiling particles
c	$J/kg \cdot K$	Specific heat capacity of roof
d	m	Thickness of the building envelope
D	kg/m^3	Mass density of roof
$E(T)$	J	Energy emitted from the surface at temperature T
$E_b(T)$	J	Energy emitted by a black surface at temperature T
$f_{cleaning}^{for\ wet}$	-	Percentage of the restored solar reflectance by rain washing on wet deposited particles
$F_{rain}^{for\ wet}$	-	Percentage of the unrestored solar reflectance by rain washing on wet deposited particles

h_{indoor}^{daily}	$W/m^2 \cdot K$	Daily average overall indoor heat transfer coefficient
$h_{outdoor}^{daily}$	$W/m^2 \cdot K$	Daily average overall outdoor heat transfer coefficient
h_o^*	$W/m^2 \cdot K$	Outside total heat transfer coefficient between building envelope and ambient air
$h_{c,outdoor}^{daily}$	$W/m^2 \cdot K$	Daily average outdoor convective heat transfer coefficient
$h_{r,outdoor}^{daily}$	$W/m^2 \cdot K$	Daily average outdoor radiation heat transfer coefficient
$I_\lambda(r, \lambda, \hat{s}_i)$	$W/m^2 \cdot nm \cdot sr$	Intensity of incident radiation at wavelength λ from the direction $\hat{s}_i$
k	$W/m \cdot K$	Thermal conductivity
n	-	Refractive index
q	W/m^2	Heat flux
Q	W	Heat flow rate
R	$m^2 \cdot K/W$	Thermal resistance
R^*	$m^2 \cdot K/W$	Overall thermal resistance between the ambient and inside environment
t	s	Ageing time
T	K	Temperature
T_{air}	K	Outside ambient air temperature
$T_{Ceiling}$	K	Ceiling temperature
$T_{External}$	K	External surface temperature

T_{indoor}	K	Indoor air temperature
$T_{Internal}$	K	Internal surface temperature
T_{Roof}	K	Roof temperature
T_{sky}	K	Sky temperature
$T_{sol-air}^{experiment}$	K	Solar-air temperature from experiment
$T_{sol-air}^{mean}$	K	Mean of solar-air temperature
$T_{sol-air}^{simulated}$	K	Solar-air temperature from simulation
Tr	-	Transmittance
U	$W/m^2 \cdot K$	Heat transfer coefficient
$V_{dry\ deposition}$	g/s	Accumulation rate of the dry deposition
$V_{dry+wet}^{equivalent}$	g/s	Equivalent accumulation rate for the combination of the dry deposition and wet deposition after exposing to aqueous condition
$V_{wet\ deposition}$	g/s	Accumulation rate of the wet deposition

Greek symbols

Symbol	Unit	Description
α	-	Solar absorptance
β	-	Soiling resistance of the product type
$\Delta\rho_{soiling}$	-	Solar reflectance change caused by soiling
$\Delta\rho_{soiling\ and\ clean}$	-	Solar reflectance change caused by soiling and cleaning

$\Delta\rho_{UV}$	-	Solar reflectance change caused by UV
ε	-	Thermal emittance
$\varepsilon(T)$	-	Total hemispherical emittance at temperature T
$\varepsilon_{\lambda}(T, \lambda)$	-	Total hemispherical emittance at wavelength λ at temperature T
η	-	Converting efficiency of the dry deposited particles to wet deposited
θ_i	sr	Zenith angle
$k_{concentration}^{wet}$	m ² /g	Coefficient for reflectance change caused by wet deposition
λ	m	Wavelength
μ	m ⁻¹	Absorption coefficient
ρ	-	Solar reflectance
$\rho(r)$	-	Total hemispherical reflectance
$\rho_{\lambda}(r, \lambda)$	-	Total hemispherical reflectance at wavelength λ at the location pointed by position vector r
$\rho_{3\ years}$	-	Solar reflectance after ageing after 3 years' ageing
ρ_{aged}	-	Solar reflectance after ageing
$\rho_{initial}$	-	Solar reflectance before ageing
ρ_{soil}	-	Solar reflectance of an opaque soil layer
ρ_{soiled}^{CM}	-	Solar reflectance of cool coating soiled by carbon micropowder
ρ_{soiled}^{RD}	-	Solar reflectance of cool coating soiled by real dirt

σ	$\text{Kg/s}^3 \cdot \text{K}^4$	Stefan-Boltzmann constant
Ω_i	sr	Solid angle

Initialisms

CFD	Computational Fluid Dynamics
CM	Carbon Micropowder
CRHT	Cool Roof Heat Transfer
CRRC	Cool Roof Rating Council
CTF	Conduction Transfer Function
ECRC	European Cool Roof Council
EPA	Environmental Protection Agency
FD	Finite Difference
FE	Finite Element
HVAC	Heating, Ventilation and Air Conditioning
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
NMR	Nuclear Magnetic Resonance
RD	Real Dirt
RF	Response Factor
RTD	Resistance Temperature Detectors
SEM	Scanning Electron Microscope
SOP	Standard Operation Procedures
SVF	Sky View Factor
TGA	Thermogravimetric Analysis
TMS	Tetramethylsilane

TMY	Typical Meteorological Year
UHI	Urban Heat Island
VOC	Volatile Organic Compound

Publications

Xingguo Yang, Kishor T Zingre, and Man Pun Wan. (2016). Effects of UV on radiation properties of cool coating. *7th International Conference on Energy and Environment of Residential Buildings*. Brisbane, Australia.

Kishor T. Zingre, Man Pun Wan, and Xingguo Yang. (2015). A new RTTV (roof thermal transfer value) calculation method for cool roofs. *Energy*, 81, 222-232.

Kishor T Zingre, Xingguo Yang, and Man Pun Wan. (2015). Performance analysis of cool roof, green roof and thermal insulation on a concrete flat roof in tropical climate. *Evergreen: joint journal of Novel Carbon Resource Sciences & Green Asia Strategy*, 2(2), 34-43.

Kishor T Zingre, Man Pun Wan, and Xingguo Yang. *An Investigation of Microclimatic Impact of Cool Coating for Buildings in Low-Latitude and Tropical Climate*. in *ASME 2014 International Mechanical Engineering Congress and Exposition*. 2014. American Society of Mechanical Engineers.

Chapter 1. Introduction

This chapter introduces the background, motivation, objectives, and scopes of this thesis. It answers what this thesis examines, why it is worth investigation, and how the study would be conducted.

1.1 Background

1.1.1 Cooling energy consumption of buildings

Energy is essential to domestic life as well as world development. The consumption of energy sustains operation of society, drives growth of economy, and reforms lifestyle of people [1-4]. Over the last decades the global energy consumption has been rapidly increasing [5]. From 2001 to 2010, the global energy consumption grew from 426 quintillion Joules (404 quadrillion British thermal units) to 553 quintillion Joules (524 quadrillion British thermal units), with an average annual increase of 3%. This figure is predicted to be 665 quintillion Joules (630 quadrillion British thermal units) in 2020 and 865 quintillion Joules (820 quadrillion British thermal units) in 2040 [6, 7].

However the increasing energy consumption has not only put heavy pressure on the energy supply, but has also caused various environmental problems such as global warming and air pollution [8]. These environmental problems are primarily caused by emission of greenhouse gas (e.g., CO₂) and air pollutants (e.g., NO_x and SO_x) during energy production and consumption, from the burning and combustion of fuels [9]. These emissions would become more detrimental as the energy consumption increases. Taking CO₂ as an example, in 2002 the CO₂ emission due to energy generation and consumption was about 7.0 trillion kilograms, while this figure is projected to be increased by 62% and become 11.3 trillion kilograms by 2030. Consequently more solar heat would be trapped and the global warming effect would

become more severe [10]. To mitigate these problems, reducing energy consumption is an important approach.

Buildings consumes significant energy to sustain proper functioning for the safety, convenience, and comfort of the occupants. In fact it is one of the three main end-use sectors of energy consumption (the other two are industry and transportation). Its energy consumption includes heating, cooling, lighting, appliance, equipment, and so on, which accounts for a considerable part of the global energy consumption [6, 11-13]. In 2004 the entire building sector accounted for 24% of the global energy consumption. This proportion gets more significant in developed countries. For instance, in 2004, in the United States of America (USA) it was 40%, and in the United Kingdom (UK) it was 39% [8]. This proportion also gets more significant in hot environment (e.g., the tropical climate zone where the solar irradiation is strong and the temperature is high throughout the whole year), because cooling accounts for an important part of the energy consumed by buildings [8, 14, 15]. In Hong Kong, it was estimated that nearly 60% of the electrical energy is used for cooling in buildings during summer [16]. In Singapore, it was shown that buildings are responsible for about half of the country's total electricity consumption, and cooling is responsible for about 60% of the buildings' total electricity consumption [17, 18]. Other studies also reported similar findings that air-conditioning accounts for 30–40% of the total electricity consumption in residential buildings and 40–60% in commercial buildings [19, 20]. The cooling load in buildings stems from various internal and external heat sources. Internal heat sources include heat generated by building occupants, by lighting, by electrical appliances, and by combustion appliances. External heat sources include the internal heat carried into the building by warm outdoor air, and the heat transferred inwards through the building envelope particularly in the tropical climate zone [21].

Therefore it could be expected that the energy consumption could be effectively reduced when the heat gain through the building envelope is reduced.

1.1.2 Performance of cool coating

Cool coating is a particular category of coating or paint that is able to stay cool under solar irradiation [22]. It is a passive technique for reducing the cooling energy consumption of buildings, which is low cost, effective, environmentally friendly, and easy to apply [23].

Cool coating is characterised by high solar reflectance and high thermal emittance. Solar reflectance is a measure of the ability of a surface to reflect the incident solar irradiation. It is the ratio of the total energy reflected by the surface to the energy incident on the surface. Thermal emittance specifies how well the surface emits energy by radiation. It is the ratio of the total energy emitted by the surface to the energy emitted by a black body at the same temperature [24]. The heat transfer on an opaque building envelope consist of radiation (absorption/reflection of incident solar irradiation and thermal emission) and convection (heat exchange with the surrounding air) [25]. With higher solar reflectance and higher thermal emittance compared to the conventional coating, cool coating absorbs less incoming radiation and emits more heat that is trapped in buildings. Cool coating also enhances the convection since it lowers the surface temperature of the building envelope [26].

When applied on a building envelope, cool coating can reduce the heat gain through the envelope, reduce cooling loads, and increase the indoor thermal comfort of buildings [11, 27, 28]. Consequently, the energy consumption of the building is reduced. In addition, cool coating also reduces peak electricity demand, reduces greenhouse gases emission, and mitigates the urban heat island (UHI) effect [27, 29, 30].

The cooling energy saving benefits of cool coating have been demonstrated by numerous studies. Synnefa et al. [11] indicated that by applying a cool coating (solar reflectance = 0.85)

on the roof of a building (original solar reflectance = 0.2), the cooling load of the test room in the climate of Athens could be reduced from 58.0 kWh/m² to 34.6 kWh/m². An experiment by Konopacki et al. [31] indicated that the surface temperature of the roof with solar reflectance of 0.20 could be up to 79°C (175°F) on a summer sunny afternoon, while the temperature would be decreased to 49°C (120°F) when its reflectance is increased to 0.60. Akbari et al. [32] conducted building energy consumption simulation and on-site monitoring in the United States to evaluate the cooling energy saving by cool coating. This study pointed out that the cooling energy could be saved by up to 80% for the whole cooling season when cool roof was applied. Levinson et al. [33] initiated studies in several warm weather climate zones in U.S.A. including California, Texas and Florida, and the results showed that cool roofs typically reduced 10–30% of air-conditioning consumption and peak demand in summer time. Parker et al. [34] observed a daily energy saving of 44 W/m² (25% of total consumption) and a peak power reduction of 6 W/m² (30% of original peak) after using cool coating on a school building in Florida in the summer of 1998.

Cool coating has gained wide interest for its thermal performance. Various governments and organisations recommended the buildings to be “cool”. One example is the Cool Roof Rating Council (CRRC). It is an independent and non-profit rating entity which was established in 1998. It aims to support research on radiative properties (i.e., solar reflectance and thermal emittance) of roofing surface materials, and to provide education and information about roofing options [35]. Another example is the European Cool Roof Council (ECRC) which was founded in 2011. It aims to promote the scientific research about cool roof, as well as to promote the use of cool roof in Europe [27].

1.1.3 Ageing of cool coating

High solar reflectance and high thermal emittance are the two critical properties that differentiate cool coating from conventional coating. Various “cool” programmes such as ENERGY STAR and CRRC have certification requirements on these two properties of cool coating [36, 37]. Also, in October 2005, prescriptive requirements on cool roof were embodied in California’s energy code, *the Title 24 Building Energy Efficiency Standards*. According to this code, new cool roofs of low-sloped non-residential buildings are required to have a minimum initial solar reflectance of 0.70 and a minimum initial thermal reflectance of 0.75 [33]. These high-level properties promise high-level thermal performance of cool coating.

However, cool coating is prone to degradation during its ageing process. Ageing is a process affected by various environmental factors including soot, dust, sunlight, rainfall, snow, hail, temperature, fungi, etc. [38]. During the ageing process, the pollutants would accumulate on the coating, the temperature swings would cause change of stress, and UV could cause photo degradation. These would decrease the solar reflectance and thermal reflectance of cool coating [39]. For this reason, the ability of cool coating to cool down the buildings would degrade with time.

Bretz et al. [40] observed the cool coating samples lost 10–20% of the initial solar reflectance after several months’ ageing in Tokyo, Japan. Akbari et al. [41] observed that the cool roof samples experienced a decrease in solar reflectance of 0.08–0.47 in 5–8 years in the USA. It was also showed that the fresh cool coating with solar reflectance of 0.85 could reduce cooling energy consumption of a test room in Athens by 40%, while if the solar reflectance decreases to 0.6 during the ageing process, the energy saving would become just 25% [11].

Therefore, to maintain high-level thermal performance of cool coating, the ageing process needs to be eased and high-level solar reflectance and thermal emittance should be

maintained. Actually, California's energy code, as one example, has specific requirements on solar reflectance and thermal emittance for aged cool roofs, that is they should be above 0.55 and 0.75, respectively, after 3 years' ageing [42].

1.1.4 Other passive cooling techniques of buildings

The cooling efficiency of buildings could be improved by both active techniques and passive techniques. Techniques that use external energy for operation, such as heating, ventilation and air conditioning (HVAC) systems, are active techniques; whereas techniques that utilise no apparatus that consume energy are passive techniques [43]. Passive cooling techniques usually involve improvements to the building envelope elements [44]. They have been widely applied due to the energy efficiency, financial viability, and construction sustainability. New materials, and techniques have been developed and used in the passive techniques [28]. Besides cool coating, there are other two popular and effective passive cooling techniques: thermal insulation and green roof.

Thermal insulation is the material that, when applied on the building envelope, retards heat flow into or out of a building [45]. This is because thermal insulation has high thermal resistance, and could change the overall heat transfer coefficient and thermal resistance of the building envelope [46, 47]. Thermal insulation is effective and widely applied in both hot and cold climates [46]. Mohsen et al. found up to 77% of the cooling load could be reduced by applying thermal insulation (polystyrene) on roof and façade of a test house in Jordan [48].

Green roof, also known as eco-roof or vegetative roof, is a roof system that integrates vegetation on top of the building [49]. It basically consists of several layers: vegetation layer, substrate layer, and drain layer [50]. The benefits of green roof include air quality improvement, runoff reduction, acoustic insulation, aesthetic value, and so on [51]. Regarding energy efficiency of building, green roof could noticeably reduce roof temperature

and heat gain through roof. The vegetation layer could reduce the heat from solar irradiation before it entering the buildings, due to the shading and cooling by photosynthesis, evapotranspiration, and respiration. The foliage tends to have high thermal emittance, which enhances the heat release. The substrate layer brings extra insulation and thermal mass to the roof, and the soil moisture induces convective heat loss and produces evaporative cooling. The drainage of water through drain layer also helps remove heat [52, 53]. The energy saving benefits of green roof have been demonstrated by numerous studies [54-56], and it is suggested to be as effective as “brightest-possible white roof” [57]. Nyuk Hien et al. concluded that green roof system could decrease up to 60% of the heat gain through roof in the tropical climate [58].

All cool coating, thermal insulation, and green roof could save cooling energy, therefore sometimes their thermal performance are compared, to evaluate which one is more effective and economical for particular buildings and under particular climates [22, 52, 59].

1.2 Motivation

1.2.1 Context of Singapore

Singapore is one of the most industrialised and urbanised countries in Southeast Asia, situated in tropical zone at latitude 1° N latitude and 104° E longitude. Its climate is characterised by uniformly high temperature, high humidity, high solar irradiation, and abundant precipitation throughout the year. The mean annual temperature is 26.6°C, the mean annual relative humidity is 84%, and the annual solar irradiation is about 1635 kWh/m² [60-62]. Some weather data of Singapore is presented in **Table 1-1**.

Table 1-1 Monthly means of some weather data on Singapore, 2012 [63]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar irradiation (kWh/m ² /day)	4.25	5.13	5.03	4.83	4.53	4.33	4.25	4.37	4.49	4.52	4.02	3.77
Temperature, (°C)	25.7	25.8	26.2	26.7	26.9	26.8	26.5	26.5	26.5	26.5	26.3	26.0
Wind speed, (m/s)	4.93	4.30	3.20	2.30	2.69	3.79	3.86	4.33	3.39	2.72	3.13	4.57
Precipitation, (mm)	200	177	198	200	176	157	156	166	172	198	246	272

This hot and humid climate causes heavy cooling loads on buildings in Singapore, and about 64% of the cooling loads of residential buildings was due to the heat gain through the building envelope [21]. Millions of people in Singapore work and live in air-conditioned buildings, consuming energy to maintain a proper indoor temperature [64]. By 2008, 74.7% of households in Singapore had already installed air-conditioners, while 15 years before the figure was only 11%. And this figure is growing with the development of economy [65, 66]. It was estimated that about 57% of the country's total electrical energy was consumed by buildings in Singapore [67], and typically about 50% of that was used by air-conditioning system [68]. In 1991 the energy consumption in Singapore was 950.8 kWh/resident, then the figure increased by almost 100% to 1803 kWh/resident in 2001 [61]. By 2011, the average annual electricity consumption per household had reached 5640 kWh [69].

Contrary to her high energy consumption, Singapore has far from sufficient domestic power supply. She is almost totally reliant on imported oil and natural gas for power generation. The renewable energy sources in Singapore is also limited due to the geographical area [60].

These facts highlight the importance of controlling the energy consumption of buildings. When the cooling techniques are more energy-efficient and more widely-used, a great saving of energy could be achieved.

1.2.2 Research gaps

Cool coating has been demonstrated to be effective in saving cooling energy of buildings by a number of overseas studies [32-34, 70, 71]. However, several topics regarding the thermal performance, ageing effects, and heat transfer process of cool coating are still worth further studies. Below are some research gaps about the application and thermal performance of cool coating in tropical climate.

Firstly, thermal performance of cool coating are affected by the local climate and weather. In Singapore and surrounding tropical countries, which have long cooling seasons and no/short heating seasons, potential benefits of cool coating would be particularly significant [11, 72]. However, till now few studies have been conducted to evaluate the thermal performance and energy saving of cool coating in this area.

Secondly, the solar reflectance and thermal emittance of cool coating would change during the ageing process, and the process is highly affected by the local environment. Though some studies have been conducted overseas [73-76], few studies so far have been conducted to track these changes in Singapore or surrounding tropical countries.

Thirdly, many environmental factors (airborne particles, solar irradiation, precipitation, temperature, microbial growth, etc.) take part in the ageing process of cool coating [38].

Currently the effects of some factors remain not fully understood, and hence, more studies are needed to evaluate the individual effect of them.

Moreover, a robust heat transfer model is essential to quantitatively analyse the impact of cool coating on the heat transfer of the building envelope. The model would be a function of various parameters, including weather information, building material properties, and radiative properties (solar reflectance and thermal emittance) of coating [77]. Numerous models have been developed, and many cases of heat transfer of buildings have been calculated based on them (as would be introduced in next chapter). However, solar reflectance and thermal emittance are usually taken as unchanging in these models. An improved heat transfer model could better evaluate the thermal performance of cool coating during its service life, where the radiative properties of cool coating change with ageing process.

1.3 Objectives and scope

This study aims to fill the research gaps regarding the ageing process of cool coatings in tropical climate. The study would mainly focus on the thermal performance of cool coatings. The changes of the radiative properties of cool coatings would be treated as the signs of the degradation during the ageing process. This study would monitor how the radiative properties would be affected by the ageing. Several environmental factors would be selected as the dominant factors in the ageing process, based on the existing researches, to be investigated in this study. The investigations would be based on natural and laboratory-based experiments, which could be seemed as the reproduction of the natural ageing phenomenon. This study would also develop a cool roof heat transfer model, based on the existing model and the results obtained from this study. This study would provide experimental data, SOP, empirical results, and the new heat transfer model to other researchers.

The work of this thesis includes:

- (1) Evaluation of the thermal performance and energy saving benefits of cool coating in the climate of Singapore. Field application of cool coating would be conducted on a test building in Singapore, and relevant temperatures and energy consumption of the building would be monitored before and after the cool coating application.
- (2) Investigation of the changes of radiative properties of cool coating in the local climate by natural ageing experiments. Groups of cool coating samples would be prepared and their solar reflectance and thermal emittance would be tracked during a long-term ageing process.
- (3) Investigation of the effects of various environmental factors (e.g., dirt deposition, wind blowing, rain washing, and UV radiation) in the ageing process. A series of laboratory-based experiments would be conducted to quantify the effects of these factors.
- (4) Improvement of the existing models of the heat transfer of cool coated roof. Equations that describe how the radiative properties of cool coating vary with ageing time would be embedded into a novel cool roof heat transfer model developed by spectral approximation method. Evaluation of the long-term thermal performance of cool coating during ageing process would be conducted based on the new model.

1.4 Thesis outline

This thesis have eight chapters. Chapter 1, the introduction, introduces the background, motivation, objectives and scope of this study. Chapter 2 gives the literature review. Chapter 3 presents a field study on the temperature reducing performance and energy saving performance of cool coating in Singapore. Chapter 4 presents the natural ageing experiments of cool coatings in Singapore. Chapter 5 presents the studies on two important factors in the ageing process, soiling and cleaning. Chapter 6 presents the studies on another factor, UV. Chapter presents an improved heat transfer model for cool coating which reflects the changes of its radiative properties, and evaluates the long-term thermal performance of ageing cool

coating. At last, Chapter 8 is the summary of this thesis and the recommendation for future work.

Chapter 2. Literature Review

This chapter provides a review of the academic studies concerning the application, the thermal performance, the heat transfer models, and the ageing process of cool coatings.

2.1 Applications of cool coatings

2.1.1 Benefits of cool coatings

Cool coating is an emerging passive cooling technique. It is cheap, long-lasting, environmental friendly, can be applied on new and existing building envelopes, and requires no active use of energy for operation [78].

Cool coating saves significant cooling energy for building. Some studies regarding the cooling energy saving benefits of cool coating are introduced in Section 1.1.2 , and more studies would be introduced in the following section.

Besides energy saving, there are other benefits of cool coating. Firstly, it transfers less heat to the surroundings than conventional coating, which increases outdoor thermal comfort [79]. When used on a large scale, it can even cool down the city. Modelling studies reported that an average air temperature reduction of 1–3°C could be achieved in the day time, by increasing the surface albedo of the city [80]. Secondly, it reduces heat load of building, which would then increase the lifetime of building envelope coating, lessening maintenance cost and waste [81]. Third, it reduce the air pollution emission from power plants, as less cooling energy is required [82, 83].

2.1.2 Cool coatings in various climates

In northern California, the USA, it was found that increasing the solar reflectance of the roof coatings from 0.20 to 0.60 could reduce the roof temperature by about 25°C in hot summer

afternoons. For standard weekdays in summer, the average daily air-conditioning savings were respectively 18% for a medical office building, 13% for another medical office building, and 2% for a drug store [84, 85].

In Poitiers, France, which has a moderate climate, cool roof was found to be able to decrease the mean outside roof surface temperature by more than 10°C, based on the study on a low-rise building [86].

In Rome, Italy, which has a Mediterranean climate, experimental results from an industrial building demonstrated that the cool coating was able to decrease the peak roof temperature by up to 18°C, and save the cooling energy by 38% [87].

Even in London, U.K., which possesses a temperate climate with relatively low temperatures, cool coating could still reduce the roof surface temperature by an average of 2°C in the middle of the day, according to a study on a naturally ventilated office building with a flat roof [88].

Moreover, studies in cities in India, Egypt, and Italy that are under various climates all showed cooling energy saving by cool coating [22, 89, 90].

2.1.3 Discussions

As introduced, cool coating has significant benefits in cooling down the building and saving the cooling energy. And it was suggested that the saving would be the greatest in climates with intense solar irradiation and long cooling seasons, tropical climate as an example [91]. However, few studies have been conducted in the tropical climate to evaluate the thermal performance of cool coating.

Secondly, many existing studies regarding the energy saving of cool coating were based on computational simulations, and in the validation part what they mostly measure were the air

and building surface temperatures. However, few studies monitored the real-time energy consumption of the building coated.

To fill the research gap, this thesis would evaluate the performance of cool coating in the climate of Singapore by a field experimental study, and the cooling energy consumption of the test building would be measured.

2.2 Heat transfer models of cool coating

Heat transfer models describe the working principle of cool coating, and help to evaluate the thermal performance of cool coating. In this section, the basic heat transfer theory and a heat transfer model of cool coating would be introduced. Then a heat transfer model for cool coated single-skin roof based on the spectral approximation method would be presented. After that the shortcoming of existing heat transfer models would be discussed.

2.2.1 Heat transfer theory of cool coating

Cool coating is characterised by high solar reflectance and high thermal emittance [23]. Consider an opaque surface (e.g., a medium thick enough that no electromagnetic waves can penetrate through it) illuminated by the thermal radiation (e.g., sunlight). Some of the radiation will be absorbed by the surface, and the rest will be reflected away. Absorptance (α) is a measure of the ability of the surface to absorb the incident radiation, as defined in **(Eq. 2-1)**. Reflectance (ρ) is a measure of the ability of the surface to reflect the incident irradiation, as defined in **(Eq. 2-2)**. Since the surface is sufficiently thick to be opaque (i.e., no transmission), it could be concluded that the sum of absorptance and reflectance is unity, as in **(Eq. 2-3)**.

Depending on the directions and the wavelength of the incoming radiation and the reflected energy, there are a number of definitions for the reflectance of the surface. For example,

spectral reflectance refers to the ratio of the reflected energy to the incoming radiation of a certain wavelength, and directional reflectance refers to the ratio of the reflected energy at a certain outgoing direction to the incoming radiation at a certain incident direction. (More definitions could be found in the reference [24].) In this thesis, the main concern about reflectance is the ability to reflect all the incoming thermal radiation, regardless of its direction or wavelength. Therefore, the reflectance in this study means the total (spectrally-integrated) hemispherical reflectance. It is the ratio of the total energy reflected into the subtending hemisphere by the surface to the energy incident on the surface, integrated over the solar spectrum, including specular and diffuse reflections. It could be calculated by (Eq. 2-4) [24].

$$\alpha \equiv \frac{\text{absorbed part of incoming radiation}}{\text{total incoming radiation}} \quad (\text{Eq. 2-1})$$

$$\rho \equiv \frac{\text{reflected part of incoming radiation}}{\text{total incoming radiation}} \quad (\text{Eq. 2-2})$$

$$\alpha + \rho = 1 \quad (\text{Eq. 2-3})$$

$$\rho(r) = \frac{\int_0^\infty \rho_\lambda(r, \lambda) \int_{2\pi} I_\lambda(r, \lambda, \hat{s}_i) \cos \theta_i d\Omega_i d\lambda}{\int_0^\infty \int_{2\pi} I_\lambda(r, \lambda, \hat{s}_i) \cos \theta_i d\Omega_i d\lambda} \quad (\text{Eq. 2-4})$$

where $\rho(r)$ is the total hemispherical reflectance (r is the position vector), $\rho_\lambda(r, \lambda)$ is the spectral reflectance at wavelength λ , $I_\lambda(r, \lambda, \hat{s}_i)$ is the intensity of incident radiation at wavelength λ from the direction $\hat{s}_i$, θ_i is the incident zenith angle, and Ω_i is the incident solid angle.

Thermal emittance (ε) is a measure of the ability of the surface to emit radiative energy. It is the ratio of the actual emissive power of the surface to that of a black surface at the same temperature, as indicated by **(Eq. 2-5)** [24]. A black surface is an idealised physical surface that absorbs all incident radiation. At a given temperature, it is also a black surface that emits the maximum possible radiative energy. Therefore, for a black surface $\varepsilon = 1$, and for other surfaces ε vary between 0 and 1.

Like reflectance, there are also a number of definitions for emittance, including spectral emittance and directional emittance [24]. In this thesis, the emittance refers to the total (spectrally-integrated) hemispherical emittance. It is the ratio of the total emissive energy from the surface regardless of the outgoing direction or wavelength to the emissive energy from a black surface at the same conditions. It is the weighted average of spectral directional emittance over the whole spectrum in the hemisphere that is adjacent to the surface. It could be calculated by **(Eq. 2-6)** [24].

$$\varepsilon \equiv \frac{\text{energy emitted from a surface}}{\text{energy emitted by a black surface at same temperature}} \quad \textbf{(Eq. 2-5)}$$

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty E_\lambda(T, \lambda) d\lambda}{E_b(T)} = \frac{1}{n^2 \sigma T^4} \int_0^\infty \varepsilon_\lambda(T, \lambda) E_{b\lambda}(T, \lambda) d\lambda \quad \textbf{(Eq. 2-6)}$$

where $\varepsilon(T)$ is the total hemispherical emittance at temperature T , $E(T)$ is the energy emitted from the surface at temperature T , $E_b(T)$ is the energy emitted by a black surface at temperature T , n is refractive index, σ is Stefan-Boltzmann constant, and $\varepsilon_\lambda(T, \lambda)$ is the spectral emittance at wavelength λ at temperature T .

Practically the spectral emittance of a surface would vary with the wavelength of the emissive energy. But if some surfaces have their spectral emittance constant for the whole spectrum,

they could be termed as gray. For gray body, it could be concluded that its absorptance equals its emittance, as shown in **(Eq. 2-7)**.

$$\alpha(T) = \varepsilon(T) \quad \textbf{(Eq. 2-7)}$$

However, for most materials, the spectral emittance and absorptance are dependent on the wavelength, especially in the UV and visible range which conveys a significant part of the energy of solar irradiation. Hence, **(Eq. 2-7)** does not necessarily hold in the engineering fields concerning solar energy.

2.2.2 A basic heat transfer model of cool coating

A building envelope receives solar irradiation which is short wave radiation, and reflects or absorbs it. For a bare concrete surface with the solar reflectance of 0.3, about 30% of the incoming radiation is reflected to the sky, and the remaining solar irradiation is absorbed by the concrete slab. Then part of the absorbed heat is emitted as long wave radiation, which could be easily trapped by the atmosphere and warms up the earth. With higher solar reflectance than the bare concrete and conventional coating, cool coating could absorb less solar heat into the building. With higher thermal emittance, cool coating releases more heat to the sky in the form of long wave radiation. Therefore, other factors (e.g., solar irradiation, convective and conductive heat transfer) being equal, the cool coated building would be cooler than the normal building [33]. The radiation balances of building envelopes with and without cool coatings are illustrated in **Figure 2-1**.

Figure 2-1 Heat balance of building envelope (a) without cool coating and (b) with cool coating

The above model basically shows the origins of the cooling loads through building envelope, and illustrates how the cooling loads are affected by the solar reflectance and thermal emittance. Then the next model would focus on the heat transfer through building envelope. Consider an opaque roof with constant radiative and thermal properties (e.g., reflectance, emittance, and thermal conductivity) on the surface and in the roof slab, and ignore the internal heat generation, heat storage, and evaporation heat loss. The heat transfer could be treated as a one-dimensional phenomenon, as illustrated in **Figure 2-2**.

Figure 2-2 Heat transfer of building roof

The heat exchanges of roof mainly consist of radiation (e.g., solar heat gain and thermal emission) and convection (e.g., heat exchange induced by surrounding air) [92]. The heat transfer components could be described by the following equations (**Eq. 2-8**), (**Eq. 2-9**), and (**Eq. 2-10**).

$$q_{radiation} = \alpha I - (\varepsilon_{External} \sigma T_{External}^4 - \varepsilon_{Sky} \sigma T_{Sky}^4) \quad (\text{Eq. 2-8})$$

$$q_{convection} = h_{External} (T_{External} - T_{Sky}) \quad (\text{Eq. 2-9})$$

$$q_{conduction} = \frac{T_{External} - T_{Internal}}{R} = \frac{\Delta T}{R} \quad (\text{Eq. 2-10})$$

where $q_{conduction}$ (W/m²) is the heat flux conducted through building envelope, $q_{radiation}$ (W/m²) is the vector sum of absorbed solar irradiation and emitted long wave radiation, α is the absorptance (here $\alpha = 1 - \rho$), $q_{convection}$ (W/m²) is the convective heat flux on the surface of building envelope, I (W/m²) is the intensity of incoming solar irradiation (beam + diffuse), $\varepsilon_{External}$ is the thermal emittance of the external surface, ε_{Sky} is the thermal

emittance of the sky, σ is the Stefan-Boltzmann constant, T_{Sky} (K) is the sky temperature, $\varepsilon_{External}\sigma T_{External}^4$ is the radiation emitted from the external surface, $\varepsilon_{Sky}\sigma T_{Sky}^4$ is the radiation received by the external surface, $h_{External}$ (W/m²·K) is the convective heat transfer coefficient, ΔT (K) = $T_{External} - T_{Internal}$ is the temperature difference of external and internal surfaces of the envelope, and R (m²·K/W) is the thermal resistance of the building envelope [93].

Sky temperature T_{Sky} is a fictitious temperature that aids in the convenient calculation of the long wave radiation exchanges with the sky. Assuming the sky as a uniform blackbody, the sky temperature is the temperature at which the radiation emitted from the sky equals the radiation received by the building envelop from the real environment (in practice, this usually includes the radiation from not only the sky, but also the ground, surrounding buildings, etc.) [94]. This parameter combines the effects of various factors, such as ambient air temperature, cloud characteristics, atmosphere composition, sky view factor (SVF) etc. [95-97]. It would vary according to the real-time environmental condition. Other two parameters ε_{Sky} and $h_{External}$ depends on the environmental condition as well. Many researchers proposed measuring methods and empirical equations for T_{Sky} , ε_{Sky} , and $h_{External}$ [94, 95, 98-100]. However, accurate determination of these three parameters are still rare in the calculation of heat transfer of building, due to the complexity and variability of the conditions of building and weather.

At the steady-state, there is **(Eq. 2-11)** [101].

$$\begin{aligned}
 q_{conduction} &= q_{radiation} - q_{convection} \\
 &= \alpha I - (\varepsilon_{External}\sigma T_{External}^4 - \varepsilon_{Sky}\sigma T_{Sky}^4) \quad \textbf{(Eq. 2-11)} \\
 &\quad - h_{External}(T_{External} - T_{Sky})
 \end{aligned}$$

When the term “sol-air temperature” $T_{sol-air}$ is introduced (as calculated by **(Eq. 2-12)**), the equation **(Eq. 2-11)** could be further simplified, as shown in **(Eq. 2-13)**.

$$T_{sol-air} = T_{Sky} + \frac{\alpha I}{h_{External}} - (\varepsilon_{External}\sigma T_{External}^4 - \varepsilon_{Sky}\sigma T_{Sky}^4)/h_{External} \quad \textbf{(Eq. 2-12)}$$

$$q_{conduction} = h_{External}(T_{sol-air} - T_{External}) \quad \textbf{(Eq. 2-13)}$$

Sol-air temperature $T_{sol-air}$ is a fictitious temperature that aids in the convenient calculation of the heat transfer through surface. It is the outdoor air temperature which, in the absence of radiative heat exchanges, would produce the same rate of heat transfer through the building envelope as the combined heat transfer produced by the actual outdoor air plus the solar irradiation [102]. Based on this definition, the heat transfer could be calculated as

$$q_{conduction} = \frac{T_{sol-air} - T_{Indoor}}{R} = \frac{\Delta T_{sol-air}}{R} \quad \textbf{(Eq. 2-14)}$$

Where T_{Indoor} (K) is the indoor air temperature, $\Delta T_{sol-air}$ (K) = $T_{sol-air} - T_{Indoor}$ is the temperature difference, and R (m²·K/W) is the overall thermal resistance of the building envelope.

It is convenient to calculate the heat transfer by **(Eq. 2-14)**, and many organisations and researchers have recommended values for the parameter $T_{sol-air}$, or have proposed equations for it [103-106]. However, the sol-air temperature is dependent on the local weather and

would not necessarily be consistent with the recommendations. Therefore, errors and inaccuracies are inevitable when using $T_{sol-air}$ and the recommended values.

The above are brief introductions of the heat transfer theory and some models of the building envelope. Some further equations were derived from these models, and used to estimate the heat gain through the roof by integrating the equation for the steady-state downward heat transfer over a certain period of time [107].

2.2.3 An improved heat transfer model of cool coating

To quantitatively analyse heat transfer of building envelope, numerous methods have been developed and utilised, e.g., finite difference (FD), finite element (FE), response factor (RF), and conduction transfer function (CTF) methods. These methods are implemented in some building energy simulations programs, e.g., EnergyPlus [108], eQUEST [109], and TRNSYS [110]. Nevertheless, these methods have their limitations, and are not always the most fitting ones for the cooling load calculation [25]. Besides these methods, another choice is the spectral approximation method [111, 112]. This method uses the orthogonal functions and trigonometric polynomial to solve partial differential equations for heat transfer problem. It could reduce the complexity of the calculations when appropriately used. A cool roof heat transfer (CRHT) model based on this method would be introduced as below [25].

In this heat transfer model, it is assumed that the roof slab has homogeneous and constant material properties (e.g., mass density), thermal properties (e.g., thermal conductivity and specific heat) and radiative properties (i.e., solar reflectance and thermal emittance), and the thickness of roof is much smaller than its length and width. Hence it could be assumed that the heat transfer occurs only in the direction perpendicular to the roof surface, i.e, along the y axis in **Figure 2-2**. The governing differential equation for conduction heat transfer within the cool roof is:

$$\frac{\partial T}{\partial t} = K^{roof} \frac{\partial^2 T}{\partial y^2} \quad (\text{Eq. 2-15})$$

where $K^{roof} (\text{m}^2/\text{s}) = \frac{k}{c \cdot D}$ is thermal diffusivity of the roof, k (W/m·K) is the thermal conductivity of roof material, c (J/kg·K) is the specific heat capacity of roof material, and D (kg/m³) is the mass density of roof material.

This homogeneous linear partial differential equation can be solved with two boundary conditions in space and an initial condition in time. The boundary condition on the cool roof surface is (as shown in **Figure 2-2**, the roof surface is where $y = 0$):

$$\begin{aligned} q(y = 0, t) &= -k \left(\frac{\partial T}{\partial y} \right)_{y=0} \\ &= I \cdot (1 - \rho) - h_{c_o}^{daily} (T_{Roof} - T_{Outdoor}) \\ &\quad - \varepsilon \sigma (T_{Roof}^4 - T_{Sky}^4) = I \cdot \alpha - h_{outdoor}^{daily} (T_{Roof} - T_{Outdoor}) \\ &= h_{outdoor}^{daily} (T_{sol-air}^{experiment} - T_{Roof}) \end{aligned} \quad (\text{Eq. 2-16})$$

where $T_{sol-air}^{experiment}$ (K) = $\frac{I \cdot \alpha}{h_o^d} + T_o$ is the solar-air temperature obtained from experiment, and

$h_{Outdoor}^{daily}$ (W/m²·K) = $h_{c_o}^{daily} + h_{r_o}^{daily} \cdot \frac{T_{Roof} - T_{Sky}}{T_{Roof} - T_{Outdoor}}$ is the daily average overall

(combination of convection and radiation) outdoor heat transfer coefficient, $h_{c_o}^{daily}$ is the

daily-averaged outdoor convective heat transfer coefficient (W/m²·K), $h_{r_o}^{daily}$ (W/m²·K) =

$\varepsilon \sigma (T_{Roof}^2 - T_{Sky}^2) (T_{Roof} + T_{Sky})$ is the daily-averaged outdoor radiation heat transfer

coefficient [113], ρ is the reflectance of cool coating, $\alpha = 1 - \rho$ is the absorptance of roof, ε

is the thermal emittance, σ is the Stefan-Boltzmann constant, T_{Roof} (K) is roof temperature, T_{sky} (K) is sky temperature, and $T_{outdoor}$ (K) is outside air temperature.

The boundary condition on the ceiling surface (as shown in **Figure 2-2**, the ceiling surface is where $y = L$) is:

$$q(y = L, t) = -k \left(\frac{\partial T}{\partial y} \right)_{y=L} = h_{Indoor}^{daily} (T_{Ceiling} - T_{Indoor}) \quad (\text{Eq. 2-17})$$

where h_{Indoor}^{daily} (W/m²·K) is the daily average overall (combined convection and radiation) indoor heat transfer coefficient, $T_{Ceiling}$ (K) is the ceiling temperature, and T_{Indoor} is the indoor air temperature (K).

The initial condition is the steady-state solution of **(Eq. 2-15)** at $t = 0$.

By solving the equations, the transient heat flux through the roof can be obtained as:

$$q = U(1 + Bi) \left\{ T_{sol-air}^{simulated} - \left[T_i \left(1 - \frac{Bi}{h_i} \right) + \frac{Bi}{h_i} T_{sol-air}^{mean} \right] \right\} \quad (\text{Eq. 2-18})$$

where $Bi = h_i L / k$ is the Biot number, $T_{sol-air}^{mean}$ is the mean of $T_{sol-air}$, $T_{sol-air}^{simulated}$ is a function of outdoor conditions (solar irradiation, outdoor air temperature and wind speed), as expressed in Fourier series as **(Eq. 2-18)**.

$$T_{sol-air}^{simulated} = T_{sol-air}^{mean} + \sum_{n=1}^N T_{sol-air,n} \cos(nwt - \psi_n) \quad (\text{Eq. 2-19})$$

where w is the angular velocity, and ψ is the radian.

The detailed solving steps are presented in the reference [25]. This model was also validated by experimental results in that reference. It is a generalised model that can be used for the heat transfer of roofs in any climate. This model consists of many empirical parameters and variables needs to be obtained from experiments, such as T_{sky} and $T_{sol-air}^{experiment}$. There are also some assumptions and approximations in this model, such as using the daily mean results instead of real-time results in some calculations. These make the calculations more practical and convenient, though some inaccuracies would be introduced.

2.2.4 Discussions

The definitions of the radiative properties (i.e., ρ , α , and ε) and heat transfer theory of the building envelope are introduces above. A series of heat transfer models are presented as well, which enables the calculation of the heat flux through the building envelope. These models rely on the accurate values of several parameters including sky temperature, sol-air temperature, and so on. Many research efforts have been devoted to obtaining these values. However, the effects of the changing of solar reflectance and thermal emittance are overlooked in the existing models. Solar reflectance and thermal emittance of cool coating are usually considered as constant. While in fact these two parameters would change during the ageing process. Till now no models have been proposed to describe how these two parameters vary with time, and therefore they are incapable of determining the accurate heat transfer of cool coating during the long-term ageing process. An improved heat transfer model is needed in which the solar reflectance and thermal emittance would be treated as functions of time. This concept is illustrated in **Table 2-1**.

Table 2-1 Features needs to be improved for existing models

Existing models	Improved model
$\rho = \text{constant}$	$\rho = \rho(t)$
$\varepsilon = \text{constant}$	$\varepsilon = \varepsilon(t)$
$Q_{\text{Conduction}} = Q_{\text{Conduction}}(\rho, \varepsilon)$	$Q_{\text{Conduction}} = Q_{\text{Conduction}}(t)$ $= Q_{\text{Conduction}}(\rho(t), \varepsilon(t))$

2.3 Changes of solar reflectance and thermal emittance of cool coatings during ageing

The general principle of assessing the effects of ageing on cool coatings is to monitor the changes of specific properties (e.g., solar reflectance and thermal emittance) prior to and after aging [114]. The two major experimental approaches used in ageing studies are the natural ageing method and the accelerated ageing method [115]. The natural ageing method is to expose the cool coating samples in natural environment, under the real conditions that the aging occurs. The accelerated method is to put the samples under conditions that are more intense than usual, aiming to reproduce the effects (though would not be exactly the same) that require much longer time in natural ageing. One example is to illuminate the cool coating samples with artificial light sources that are much stronger than the natural environment. This method is usually employed in laboratory-based experiments, where the conditions are under control, to analyse the effects of factors of interest.

2.3.1 Changes of solar reflectance

Ageing of cool coating is a process consisting of many environmental phenomena including soiling, irradiation, precipitation, wind blowing, temperature cycling, microbial growth, etc. [38]. These phenomena cause both individual and synergistic effects on cool coating [115].

This process might change the solar reflectance and thermal emittance of cool coating, which then affect its thermal performance. Many studies have been conducted under various climates to quantify these changes.

Byerley et al. [116] monitored the heat flux, surface temperature, and solar reflectance of a white roof coating for over 3.5 years in Tennessee, the USA. It was observed the greatest drop in energy saving performance of the coating occurred within the first one or two years. The rate of degradation appeared to be less during the third year. The solar reflectance of the coating decreased from 0.56 to 0.43 during the first year of weathering.

Akbari et al. [41] examined the degradation of cool roof samples from different climate zones in the USA, and found the solar reflectance of the samples decreased by 0.08–0.47 in 5–8 years. The sample from Plantation, Florida, had the maximum decrease 0.47 after about 6 years' natural ageing.

Ichinose et al. [117] conducted natural ageing experiments with paints. They monitored the fluctuation of solar reflectance of the paint samples for several months. The date and amount of precipitation during the ageing experiment were also recorded. It was noticed after the first precipitation, the solar reflectance of samples decreased sharply. But thereafter, the reflectance decreased slightly regardless whether the precipitation was present or absent. It was hypothesised that the surface was contaminated in the first precipitation and afterwards the precipitation could hardly further contaminate the surface. The contamination could be due mainly to the adhesion of pollutants (e.g., airborne particles).

Cheng et al. [73] examined the ageing process of painted metal, clay and concrete tile roof products with or without cool colour pigments in seven cities in the diverse climates of California, the USA, for up to six years. The measurement results showed that for the white painted PVDF samples, the reflectance loss of the seven test sites ranged from 4% to 23% of the starting solar reflectance during the first year. After that, the samples experienced

different fluctuations of solar reflectance. Some samples lost significant solar reflectance (up to 40%) at the end of the fourth year, while some samples losing only 4%.

Sleiman et al. [118] evaluated the solar reflectance loss of roof samples after three years' natural exposure, based on two databases: one database was from the U.S. Cool Roof Rating Council (CRRC) and the other one was from U.S. Environmental Protection Agency (EPA)'s Energy Star rating program. More than 1500 ageing data were collected mainly from Florida, Arizona, and Ohio. The results showed the almost all the samples experienced loss of solar reflectance during three years' ageing, and the extent of reflectance loss was affected by the climate of test site. Furthermore, a model was proposed for predicting the solar reflectance of three years old samples, as shown in **(Eq. 2-20)**.

$$\rho_{3\text{ years}} = \rho_{soil} + \beta(\rho_i - \rho_{soil}) \quad \textbf{(Eq. 2-20)}$$

where $\rho_{3\text{ years}}$ is the predicted solar reflectance of roof samples after 3 years' ageing, ρ_i is the initial solar reflectance, ρ_0 presents the solar reflectance of an opaque soil layer, and β represents the soiling resistance of the product type. With $\rho_{soil} = 0.20$, the best-fit values of β for product types in the CRRC edited database range from 0.76 for field-applied coating to 1.09 for shingle.

2.3.2 Changes of thermal emittance

Cheng et al. [73] noticed that the thermal emittance of the samples did not change much after 4 years' natural exposure in California, the USA. Some other researchers also reported that the thermal emittance of painted products did not change with exposure duration [119, 120].

The reason might be that the thermal emittance of cool coatings is close to that of soil particles, what is the main surface contaminant on cool coating. (The initial thermal

emittance of many cool coating is about 0.90, and the thermal emittance of soil is also about 0.90 [121, 122].) Therefore, even when part of the surface of cool coating is covered by the soil particles, the overall thermal emittance does not change significantly.

2.3.3 Discussions

As introduced above, numerous studies have been conducted regarding the changes of solar reflectance and thermal emittance of roofing materials. However, many of the samples used in these studies are not field-applied paint cool coating, which is the dominant type of cool coating used on residential building in Singapore. As illustrate in **Figure 2-3**, the painted PVDF metal samples used in the study [73] is different from the field-applied paint coating used on the building envelope in Singapore. The surface morphology and properties of them would be different. Moreover, few of these studies were conducted in the tropical climate, while the ageing process is highly weather dependent and localised. Therefore the findings from these studies may not be applicable to the cases in Singapore.

Figure 2-3 (a) Painted PVDF metal sample used in the study [73]; (b) field-applied paint coating used on residential buildings in Singapore

Precipitation, together with pollutant particles, was found to be able to significantly change the solar reflectance of cool coating. It might be guessed based on this finding that wet deposition of pollutant, other than the dry deposition, is a main cause for the change of solar reflectance. The effects of precipitation, wet deposition, and dry deposition, would be investigated in this thesis, which was not thoroughly discussed in existing studies.

A model (Eq. 2-20) has been proposed to predict the changes of solar reflectance of cool coating. However, noticeable deviation could be observed between the model prediction and the measurement results. Moreover, this model could only predict the solar reflectance after three years' ageing, but not able to predict the reflectance before or after that.

To address these research gaps, this thesis would investigate the ageing process of cool coating in the climate of Singapore with the field-applied paint cool coating samples. An ageing model would also be developed.

2.4 Environmental factor involved in ageing: soiling

2.4.1 Effects of soiling on solar reflectance

Soiling has been suggested as the most significant contributor for the solar reflectance loss of cool coatings [38, 73, 75, 123].

Cheng et al. [73] proposed a mathematical model of the reflectance of a soiled substrate. Supposing a soil layer with solar reflectance ρ_{soil} and transmittance Tr_{soil} on a substrate with original reflectance ρ_{sub} , the total reflectance of the soiled substrate could be calculated by (Eq. 2-21).

$$\rho = \rho_{soil} + Tr_{soil}^2 \cdot \rho_{soil} + Tr_{soil}^2 \cdot \rho_{soil} \cdot \rho_{sub} + \dots \quad (\text{Eq. 2-21})$$

In the study, soiling particles on the samples were collected and the concentrations of the elements in the contaminants were analysed. A model was proposed based on the results, trying to link the absorptance α of the soiled coating with the concentrations of elements, as shown in **(Eq. 2-22)**.

$$\alpha = 0.00152[Fe] + 0.0199[Cr] + 0.0158[C] \quad \textbf{(Eq. 2-22)}$$

where $[Fe]$ is the concentration of iron in mg/m^2 , $[Cr]$ is the concentration of chromium in mg/m^2 , and $[C]$ is the concentration of elemental carbon in mg/m^2 . The root-mean-square deviation of the model was 0.008. This model highlighted the significance of iron, chromium and elemental carbon in affecting the solar reflectance of cool coating. However, the concentrations of elements would become different when the pollutant sources vary. It remains uncertain whether this model is applicable to the environment of Singapore.

Berdahl et al. [123] measured the spectral reflectance of two roof samples that had been exposed outdoors for 18 years before and after being washed with mild soap solution. Spectral effective absorption coefficients of the soil on the samples were found to be consistent with that of propane soot. (Absorption coefficient (m^{-1}) is the absorbed portion per unit path length when the electromagnetic radiation travels through an infinitesimally thin medium. It characterises how easily the medium could be penetrated [124].) This study concluded that the decrease of solar reflectance of cool roof was mainly due to the soot particles accumulation. It was also suggested that soot accumulation rate would vary significantly with geographical locations, climate, soot sources, etc. In the study, a zero-order optical model was built to link the change of reflectance with the soil layer, as shown in **(Eq. 2-23)**.

$$\rho/\rho_0 = \exp(-2\eta\mu d) \quad (\text{Eq. 2-23})$$

where ρ is the solar reflectance of soiled cool coating, ρ_0 is the solar reflectance of the clean cool coating, μ is the absorption coefficient of the soil layer, d is the thickness of the soil layer, η is a constant-of-order unity. Nevertheless, this model failed to reflect the effect of the surface distribution of soot.

Herngren et al. [125] indicated that fine particles could contain relatively high concentrations of radiation-absorbing pollutants (e.g., metals and hydrocarbons), which would significantly affect the solar reflectance of building façade.

2.4.2 Artificial soiling methods

There are two types of soiling mechanisms, namely dry deposition and wet deposition. Dry deposition is the process whereby the deposition of the particles occurs in the absence of liquid medium [126], whereas wet deposition is the process whereby the particles are transferred to the material surface within a liquid medium [127]. Wet deposition occurs mainly in the form of rain when the soiling particles get absorbed in the droplets and then impact on the building envelope. It is common in real world, especially in Singapore which has abundant precipitation [128].

Wet deposition also occurs in the forms of dew, snow, frost, and rime [129], though the last three ones hardly happen in tropics. Dew appears in many tropical and subtropical areas when the temperature of the building envelope, which could be decreased by cool coating, gets lower than the dew point [130, 131]. As for Singapore, the information of mean dew point and mean daily minimum air temperature of every month are summarised in

Table 2-2. It could be observed that the minimum air temperature is higher than the dew point. In a field experiment of cool coating, which would be introduced in Section 3.4.2 , it

was also observed that the minimum surface temperature of cool coating every night was about 24°C, which is higher than the dew point. These results suggest that dew is uncommon in Singapore. Therefore, it could be assumed that wet deposition happens in the form of rainfall in the climate of Singapore.

Table 2-2 Dew point and daily minimum temperature of every month in Singapore

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Daily												
Minimum												
Temperature,	23.9	24.3	24.6	25.0	25.4	25.4	25.0	25.0	24.8	24.7	24.3	24.0
(°C) [132]												
Mean Dew Point,	22.5	22.5	22.9	23.7	23.9	23.4	23.4	23.3	23.1	23.1	23.0	22.4
(°C) [133]												

Pesava et al. [134] investigated the dry deposition of atmospheric particles on building envelope. They developed a method to mimic the dry deposition process by using a fan to blow the soiling particles onto the sample surface.

Sleiman et al. [74] investigated the relationship between solar reflectance loss and the amount of the soil (soot) deposited on the surface of cool coating. An accelerated set soiling method was developed by spraying soil surrogate mixture onto the sample surface. This study found that the ratio of soiled reflectance to unsoiled reflectance (ρ/ρ_0) decreased linearly with the increase of deposited soot concentration.

2.4.3 Discussions

Two models (**Eq. 2-21**) and (**Eq. 2-23**) were proposed to predict how the solar reflectance of coating would be affected by the soiling, mainly based on the optical theory of the light travelling through soil layer. However these two theoretical models have their limitations and are not practical when used to predict the changes of solar reflectance of cool coating after soiling. The first model ignores the angular distribution of the incident and reflected radiation. The second model ignores the reflectance of the soil layer. Both of them assume that the whole coating surface is covered by a soil layer with a uniform thickness, which rarely happens in natural ageing. Thickness of the thin soil layer would be difficult to measure. It is also difficult to measure the reflectance of the soil layer only but eliminate the interference of the substrate beneath the soil layer, especially when then soil layer could not cover the whole substrate surface. Improved theoretical optical models could be developed for predicting the effects of soil layer, but the feasibility remains to be proved.

Artificial dry deposition method [134] and wet deposition method were developed. These methods could be utilised to reproduce the soiling process of cool coating in laboratory, and to prepare soiled cool coating samples. The dry deposition method uses a fan to blow the soiling particles onto the substrate samples. It mimics the wind blowing in natural environment, but this would introduce unrepeatability in the experiment due to the uncertainty of the wind field. In this thesis, new dry deposition method and wind blowing experiments are proposed, taking them as two different process.

A spraying method was proposed for artificial wet deposition [74]. This method combines soiling and water flushing, which mimics the rain washing in natural environment, in one process. In order to investigate the individual effects, new wet deposition method and water washing experiments are proposed in this thesis. The new method also improves the controllability of the wet deposition of soiling particles.

Sleiman et al. [74] proposed that relationship between solar reflectance and soot concentration on the surface of coating. However, the range of soot concentration tested in the study was limited in the range of 1.2-7.6 mg/m², and correspondingly the solar reflectance of the coating sample was only decreased to about 0.71. Further experiments are needed to investigate whether this model still holds when the coating is soiled to a lower level of solar reflectance. Similar experiments could also be conducted with the real dirt collected from building roof.

2.5 Environmental factor involved in ageing: cleaning

2.5.1 Effects of cleaning on solar reflectance

Ichinose et al. [117] washed soiled cool panel samples (aged for 102 days) with neutral cleanser and soft sponge, and that reflectance was restored to approximately the original level. Levinsona et al. [135] investigated the impacts of soiling and cleaning on the solar reflectance of 15 polyvinyl chloride (PVC) roof membranes. The reflectance of soiled samples were measured before cleaning, as well as after by wiping, after rinsing, after washing, and after bleaching. The results showed that for the biomass-free samples, wiping removed about 50–80% of the initial optical depth of the soil layer in the 300–1500 nm range, then rinsing, washing, and bleaching restored more reflectance regardless of whether the soil layer contained biomass or not. After bleaching, almost all the lost solar reflectance was restored.

Egodawatta et al. [136-138] investigated the build-up process of soiling particles on road surface, corrugated steel, and concrete roof. A brush was used to collect the accumulated particles. Wash-off process was also investigated by flushing the roof sample surface with different intensities of simulated rainfall. The washed off particles were collected as well. Total suspended solids (TSS) and particle size distribution of the build-up and wash-off

pollutants were analysed. Models were proposed for build-up and wash-off processes as (Eq. 2-24) and (Eq. 2-25).

$$B = aD^b \quad (\text{Eq. 2-24})$$

where a and b are empirical coefficients, B is the build-up load on surface, and D is the antecedent dry days.

$$F_W = \frac{W}{W_0} = C_F(1 - e^{-kIt}) \quad (\text{Eq. 2-25})$$

where C_F is capacity factor, F_W is fraction of wash-off, I is rainfall intensity, k is wash-off coefficient, t is time, W is the weight of the material mobilized after time t , and W_0 is the initial weight of the materials on the roof surface.

It was noticed that the intensity of flush would affect the wash-off process. In their experiment, 20 mm/h flush could remove 75% of the accumulated particles, whilst 115 mm/h flush could remove almost all the particles. It was also noticed that the large size particles ($> 100 \mu\text{m}$) were more easily removed by the flush.

2.5.2 Discussions

As introduced above, manual cleaning procedures and simulated rain washing method were proposed by researchers, though the substrate samples in these studies (panel, PVC, concrete, etc.) have different morphology and properties with the cool paint coating examined in this thesis. For the manual cleaning, human error would be inevitable when the study intends to quantify the cleaning effect. For instance, a different force used to wipe or scratch the sample

surface would cause a different cleaning effect, as well as a different damage to the surface of the coating. What is more, the cool coating painted on building envelope would be exposed to natural cleaning for most of its service life other than manual cleaning. Therefore mimicking wind blowing and rain washing might be a more suitable choice for this thesis. The simulated rain washing method could be employed in the investigations on the change of solar reflectance of cool coatings.

Soiling particles build-up and wash-off models were proposed for roof surface in study [138]. However, these models were built in the context of Queensland, Australia based on the experiment data with build-up time less than one month. Further studies are needed to find out whether these models are applicable for long-term ageing of cool coating in the tropical climate. Moreover, the accumulated soiling particles were collected by a brush, which could hardly gather all the particles, especially the fine ones. These fine particles could affect the solar reflectance significantly [125], and consequently should not be overlooked in the studies on solar reflectance of cool coatings.

2.6 Environmental factors involved in ageing: UV, moisture, temperature and thermal shock

2.6.1 Effects of UV

Ultraviolet (UV) radiation is the electromagnetic radiation with wavelength between 100 nm and 400 nm [139]. However, most of the radiation between 100 nm and 300 nm has been absorbed by the atmosphere before reaching the Earth [140]. Therefore, the UV discussed in this thesis refers to the radiation from 300 nm to 400 nm. It is believed to be one important factor for the ageing of cool coatings [38, 74, 115]. The energy of the UV photon is larger than 3 eV [38], and would deteriorate the cool coating by the combined effect of photolysis and photo-oxidative reaction, which is more commonly known as UV degradation [141]. UV

would cause yellowing, chalking, oxidisation and other changes of cool coating, and many studies have been conducted on these topics [142, 143].

Asmatulu et al. [144] reported that the molecules with energy level between 300 kJ/mol and 450 kJ/mol are the most sensitivity targets that absorb UV. In cool coatings, the C-C polymeric bond can be partially broken by the UV from sunlight. The polymer molecules would be broken into small molecules and initiates the cross-linking reactions for extra polymerisation and oxidation.

The UV degradation mechanism of the C-C bond is shown in **Figure 2-4** [141]. As the cool coating degrades, short chains of carbonyl groups would be produced and might detach from the coating and be removed.

chalking of TiO_2 could be observed in aqueous environment, while no chalking was observed when it is dry [117]. In addition, the rainwater may bring some radiation-absorbing pollutants onto cool coating, which is known as the process of “wet deposition”.

2.6.3 Effects of thermal shock

When being heated up by sunlight or other heat sources, some coating materials may experience accelerated chemical reaction and loss of volatile organic compound (VOC). When the temperature changes gradually or dramatically, differential thermal expansion would happen and cause stress on coating materials [38]. Variation of temperature could affect the adhesion of the cool coating as well, which then affects its dirt pick up ability [145].

2.6.4 Discussions

As introduced, UV, moisture, temperature and thermal shock are believed to be factors involved in the degradation of cool coatings. Numerous studies have been conducted to investigate their effects on the mechanical or chemical properties of coatings. But till now few studies have been conducted regarding their effects on the radiative properties (i.e., solar reflectance and thermal emittance) of cool coatings. This thesis would fill the research gap.

2.7 Environmental factor involved in ageing: microorganisms

2.7.1 Effects of microorganisms

Microorganisms cause not only an aesthetical discoloration of the building envelope [146], but also problems of bio-deterioration of coatings [147], corrosion of infrastructure [148], and a potential risk for public health [149]. The formation and evolution of microorganisms might change the solar reflectance and accelerate the ageing process, especially in the humid tropical climate zone. A study showed that a mortar lost about 25% in solar reflectance in the

range of 400–700 nm after being colonized by algae for 15 days, and then lost more than 30% after 30 days [150].

It was indicated that the most common microorganisms on the envelope of buildings are algae, fungi, and blue-green bacteria [149]. They can resist cycles of drying and rehydration. Other species that can colonise on the external concrete walls include lichens and mosses [151].

A study in Singapore by Wee and Lee [152] found that *Trentepohlia odorata* is one of the earliest algal colonisers on the envelopes of buildings. It would modify the harshness of the habitat, to allow blue-green algae and other microorganisms to grow [153]. The common genera and species of algae and fungi on Singapore buildings include *Chlorococcum*, *Scytonema*, *Schizothrix*, *Anacystis*, *Aspergillus* (especially *Fumigatus*) *Cladosporium*, and *Penicillius* [154].

Cheng et al. [155] performed membrane lipid analyses to quantify microbial biomass and determine microbial community structure on roofing materials from seven outdoor testing sites in California, the USA. Fungi and cyanobacteria were found to be the dominant species of the microorganisms on the roof samples.

Görs et al. [147] used ergosterol chlorophyll α as biomarkers to quantify living fungi and algae on artificial surfaces (concrete, plastic, coated metal, wallpaper, etc.). It was observed that aeroterrestrial algae preferred to colonise on the sun-protected building façades, which concurred with the findings of Schumann et al. [156].

2.7.2 Discussions

The above studies investigated the colonisation of microorganisms on building envelopes. However, a new trend of cool paints for building envelope is that more and more cool paints are now antifouling [157]. It is claimed that the addition of antifouling biocides to the paints

could prevent the settlement, adhesion and growth of microorganisms on the coating surface. In this thesis, algal resistance tests were conducted on three coating samples under Singapore Standards, and no algae growth was observed (see Appendix A). Therefore this thesis would not investigate the effects of microorganisms on the solar reflectance and thermal emittance of cool coatings.

2.8 Summary

In this chapter, the methodologies and results of numerous studies of cool coating are reviewed, regarding the heat transfer performance and theory, the ageing process, and effects of several environmental factors. Many lessons could be learned from these studies, but limitations also exist, as discussed in the previous sections. More research work is required for further understanding of the phenomena during ageing of cool coatings. Studies of heat transfer performance of cool coating, especially by field experiment, are needed in tropical climate. The accuracy of heat transfer model of cool coatings could be improved by incorporating the changes of solar reflectance and thermal emittance of cool coating during the ageing process. The effects of various environmental factors involved in the ageing process are also worthy of more investigations. These research gaps would be the focuses of this thesis.

Chapter 3. Cooling and Energy Saving Performance of Cool Coatings in the Climate of Singapore

3.1 Introduction

Many studies have been conducted on the cooling performance and energy saving benefits of cool coatings, as introduced in the literature review. However most of them are conducted overseas where the climates are different from Singapore, and most of their results regarding energy saving are based on computational simulations and calculations, rather than based on real-time monitoring. This chapter would present a field experimental study in Singapore on the cooling and energy saving performance of cool coating. This study focuses not only on the surface temperatures of the building envelope, but also on the heat flux across the roof slab, as well as the power consumption of the air-conditioning system.

3.2 Methodology

This study evaluated the cooling performance and the energy saving performance of cool coating. The cooling performance was evaluated by comparing the surface temperatures before and after applying the cool coatings on the roof of a test building. The energy saving performance was evaluated by comparing the power consumptions of the air-conditioning system before and after the cool coating application. Besides, the inlet and the outlet air temperatures of the condenser, and the outlet air temperatures of the evaporator were also measured, which would also highlight the cooling effects of the cool coating. The heat flux across the roof slab was calculated based on the measurement results.

The on-site experiments consisted of two rounds. The first round was during 14th January 2013 to 19th April 2013, collecting the data of the test building before the application of cool coating. The second round was during 24th April 2013 to 9th May 2013, which was after the

application of cool coating on the roof. Solar reflectance of the roof surface was 0.80 after the cool coating, compared to the initial value of 0.27 when the concrete roof was bare. Thermal emittance of the roof was 0.94 after the cool coating, compared to the initial value of 0.92. Then the results from the two rounds were compared.

3.3 Test building, instruments, and field set-up

3.3.1 Test building

The field experiment was conducted on a single-storey air-conditioned building located in Nanyang Technological University (NTU), Singapore. NTU is in the west part of Singapore, and near the industrial areas in the southwest of Singapore, which has relatively high temperature. The test building is of rectangular shape with a total roof area of about 40 m². The original roof is made of bare concrete, and is flat with minimal slope for rain drainage, which is typical of residential buildings in Singapore. This building has 1-2 occupants, with 3 computers operational when it is occupied. The internal heat load is estimated to be around 1 kW. The roof slab is 100 mm thick, and 10 mm plaster was added onto the ceiling. The building is served by two split type air-conditioners, each providing a maximum cooling capacity of 18,000 BTU/hr (5.3 kW). The photograph of the test building is shown in **Figure 3-1**. The location of NTU is shown in **Figure 3-2**.

Figure 3-1 Test building of the field experiments of cool coating

Figure 3-2 Location of NTU in Singapore (satellite image) [158]

3.3.2 Instruments

An albedometer (CMA 11, Kipp and Zonen) was used to record the solar irradiation reaching the building roof during the experiment, as shown in **Figure 3-3**. The albedometer is compatible with the ASTM Standard E1918-16 (Standard Test Method for Measuring Solar

Reflectance of Horizontal and Low-Sloped Surfaces in the Field) [159]. It was calibrated to an accuracy of $\pm 1.4\%$ reading.

Figure 3-3 Albedometer

The solar reflectance of the roof and the cool coating was measured by a portable solar reflectometer (SSR-ER version 6; Devices and Services), which is shown in **Figure 3-4**. The reflectometer is compatible with the ASTM Standard C1549-16 (Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer) [160]. It was calibrated to an accuracy of ± 0.002 . What this instrument measures is the near normal-hemispherical reflectance, which is commonly used as an approximation of the total hemispherical reflectance for solar heat transfer calculation of building envelope [161, 162].

Figure 3-4 Reflectometer

The thermal emittance of the roof and the cool coating was measured by a portable Emissometer (AE1, Devices and Services), which is shown in **Figure 3-5**. The emissometer is compatible with the ASTM Standard C1371-04a(2010)e1 (Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers) [163]. It was calibrated to an accuracy of ± 0.01 . The roof and the cool coating are neither highly specular (see Appendix B) nor transparent to infrared radiation, which fulfils the requirements of the ASTM Standard. The emissometer was calibrated with two standards, one with the emittance of 0.06, the other with the emittance of 0.88, which is close to the emittance of the cool coating. Therefore, the measurement of the thermal emittance of cool coating in this study would be accurate and reliable.

Figure 3-5 Emissometer

The cool coating thickness was measured by a coating thickness gauge (Elcometer 456; Elcometer (Asia) Pte. Ltd.), which is shown in **Figure 3-6**. The thickness gauge is compatible with the ASTM B499-09(2014) (Standard Test Method for Measurement of Coating Thicknesses by the Magnetic Method: Nonmagnetic Coatings on Magnetic Basis Metals) and ASTM standard D7091–13 (Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals) [164, 165]. It was calibrated to an accuracy of $\pm 1\%$ reading.

Figure 3-6 Thickness gauge

The roof surface temperatures and the ceiling surface temperatures were measured by surface-type resistance temperature detectors (RTDs) that were encapsulated in stainless steel detector probes with 4 mm in diameter and 25 mm in length (4 wire RTDs, Omega). The RTDs were calibrated to an accuracy of $\pm 0.5^{\circ}\text{C}$ by a stirred silicone oil bath thermal calibrator (Calsys-40/200, Tempsens Instruments (I) Pte. Ltd.). When installing the RTDs on roof and ceiling, the detector probes were covered by small pieces of sticky insulation tapes, then the insulation tapes were covered by reflective tapes. These two layers of tapes firmly attached the RTDs onto the building envelope to measure the surface temperature, and

Figure 3-8 3-phase clamp-on power meter: (a) clamps; (b) panel

3.3.3 Field set-up

The albedometer was installed 1.5 m above the roof surface. It consists of two pyranometers, with one facing up measuring the incoming solar irradiation, and one facing down measuring the reflected radiation by the roof. Schematic diagram for the albedometer installation is shown in **Figure 3-9**.

Figure 3-9 Schematic diagram for the albedometer installation on roof

Six RTDs with two data loggers were installed to measure the temperatures of roof surface, ceiling surface, inlet and outlet of the condenser (on the roof), and inlet and outlet of the evaporator (inside the building). The temperatures, the radiation, and the current of the air-conditioning system were monitored by the instruments throughout the experiment. The test

building roof was coated with cool coating between the two rounds of measurements. The experimental set-up and the locations of the sensors are shown in **Figure 3-10**.

Figure 3-10 Experiment set-up: (a) albedometer and RTDs on roof; (b) RTDs inside room; (c) power meter for air-conditioning system; (d) cool coating application on roof

3.4 Results and analysis

3.4.1 Solar irradiation

Due to different weather conditions, the daily mean solar irradiation received by the roof during the experiment period ranged from a minimum of 62 W/m^2 on 19th January 2013 to a maximum of 750 W/m^2 on 26th January 2013. On most of the days, the daily average solar irradiation was above 400 W/m^2 . The daily average solar irradiation was categorised as **Table 3-1**.

Table 3-1 Daily mean solar irradiation range

	Daily mean solar irradiation (W/m ²)			
	0 – 200	201 – 400	401 – 600	601 – 800
Number of days	16	22	46	21

Four pairs of days were chosen from the two rounds of the experiment, as shown in **Table 3-2**. In each pair-compared days, the solar irradiation should be at the same level. Therefore, it could be assumed that the changes of temperatures and power consumption of the test building were due to the application of cool coating.

Table 3-2 Four pairs of days with same level of solar irradiation

Pair	Before cool coating (daily average solar irradiation)	After cool coating (daily average solar irradiation)
1	24 th March (538.1 W/m ²)	24 th April (531.1 W/m ²)
2	6 th April (282.8 W/m ²)	25 th April (286 W/m ²)
3	12 th February (235.5 W/m ²)	26 th April (254 W/m ²)
4	22 nd March (325.6 W/m ²)	27 th April (335.5 W/m ²)

3.4.2 Roof temperature

The roof surface temperatures of the four pairs of days are shown in **Figure 3-11**. It could be observed that the roof surface temperature went up about noon when the solar irradiation was strong, and went down in the evening and at night when the solar irradiation was weak. For Pair 1 days (24th March and 24th April), the roof surface temperature was higher than the other three pairs of days. One important reason would be the strong solar irradiation on Pair 1

days, as shown in **Table 3-2**. It could be also observed that the roof surface temperature reduced after the application of cool coating. This reduction was significant during the daytime. In the nighttime, though not as significant as during the daytime, noticeable reduction of temperature still existed.

Figure 3-11 Roof surface temperatures on the four pairs of days

The roof temperature data are summarised in **Table 3-3**. The peak temperature reduction of roof surface was up to 19.2°C, 7.1°C, 12.1°C, and 11.1°C, respectively, for the 4 pairs of days.

Table 3-3 Summary of roof surface temperature

Pair	Peak roof temperature (°C)		Peak temperature reduction (°C)
	Before cool coating	After cool coating	
1	58.0	38.8	19.2
2	41.8	34.7	7.1

3	38.6	26.5	12.1
4	45.8	34.7	11.1

3.4.3 Inward heat flux through roof

After obtaining the surface temperatures of roof and ceiling, the heat flux through roof slab could be calculated (see Appendix C.1). The results are shown in **Figure 3-12**. It could be observed again that the heat flux on the Pair 1 days was relatively high, mainly due to the fact that the solar irradiation on the Pair 1 days was much higher than the other three pairs of days, as shown in **Table 3-2**.

Figure 3-12 Heat flux across roof on the four pairs of days

The peak heat flux occurred about noon of each day. The peak heat fluxes of the four pairs of days are summarised in

Table 3-4. Significant reduction was observed after the application of cool coating, accounting for from 48% to 64% of original heat flux.

Table 3-4 Summary of inward heat flux through roof slab

Pair	Peak heat flux (W/m ²)		Peak reduction
	Before cool coating	After cool coating	
1	133.6	60.0	56%
2	82.8	38.8	53%
3	66.6	24.3	64%
4	86.7	45.3	48%

3.4.4 Inlet air temperature of the condenser

Cool coating not only reduces the cooling load of a building, but can also cool down the ambient environment. In this experiment, this microclimate cooling effect was evaluated by monitoring the inlet air temperature of the condenser, which was mounted on the roof, as shown in **Figure 3-10** (a). Though the RTD sensor for the inlet air temperature of the condenser might be affected by the exhaust air, its reading could still be taken as the indicator of the ambient air temperature.

Measurements of the inlet air temperature of the condenser are summarised in **Table 3-5**. Lower mean and peak temperatures at the condenser inlet could be observed after the application of cool coating. The daily mean temperature reduction of four pairs of days was 0.3°C, 1.6°C, 0.2°C, and 0.5°C, respectively.

Table 3-5 Summary of inlet air temperature of the condenser

Pair	Daily mean inlet temperature (°C)		Peak inlet temperature (°C)	
	Before cool coating	After cool coating	Before cool coating	After cool coating
1	29.2	28.9	41.1	40.9
2	29.2	27.6	41.1	40.0
3	28.9	28.7	42.3	40.5
4	29.3	28.8	41.8	40.9

3.4.5 Outlet air temperature of the condenser

The outlet air temperature of the condenser was also monitored. The results are summarised in **Table 3-6**. It could be noticed that after the application of cool coating, the mean and peak temperatures of the outlet air were both reduced. The daily mean temperature reduction of four pair of days were 5.3°C, 1.8°C, 1.3°C, and 2.8°C, respectively. This reduction is believed to be caused by the combination of cooler inlet air of condenser as well as reduced cooling load of the test building.

Table 3-6 Summary of outlet air temperature of condenser

Pair	Daily mean outlet temperature (°C)		Peak outlet temperature (°C)	
	Before cool coating	After cool coating	Before cool coating	After cool coating
1	36.2	30.9	42.7	39.7

2	36.2	34.4	42.7	42.3
3	34.8	33.5	42.6	42.6
4	35.9	33.1	53.6	43.9

3.4.6 Outlet air temperature of evaporator

A temperature of 22°C was preset for the air-conditioner, and the outlet air temperature of the evaporator inside the test building room was monitored throughout the experiment. The results are summarised in **Table 3-7**. After the application of cool coating, higher daily mean and peak temperature at the evaporator outlet were observed. The daily mean temperature increase of four pairs of days was 5.3°C, 1.8°C, 1.3°C, and 2.8°C, respectively. This indicated reduced cooling load due to the cool coating.

Table 3-7 Summary of average outlet temperature of evaporator

Pair	Average evaporator outlet temperature (°C)		Temperature increase (°C)
	Before cool coating	After cool coating	
1	8.0	12.0	4.0
2	8.0	11.3	3.3
3	8.0	12.3	4.3
4	8.0	11.5	3.5

3.4.7 Energy consumption measurement

The electrical current of the air-conditioning system of the test building was continuously monitored during the experiment, and the power rate was calculated accordingly (see Appendix C.2). The data on the four pairs of days are summarised in **Figure 3-13** and **Table 3-8**. A significant reduction of daily mean power consumption was observed, ranging from

15% to 20%. It could also be observed that generally the power consumption during night is lower than that in the daytime.

Figure 3-13 Power consumption of the air-conditioning system on the four pairs of days

Table 3-8 Power consumption summary

Pair	Daily mean power consumption (kW)		Reduction after cool coating
	Before cool coating	After cool coating	
1	2.0	1.7	15%
2	2.0	1.6	20%
3	1.9	1.6	16%
4	2.0	1.6	20%

3.5 Simulation work

A computational simulation model was proposed and validated based on this test building, by Zingre et al. [166]. Based on that model, the air temperature above the roof could be noticeably reduced by cool coating. On a sunny day with solar radiation of 676.9 W/m^2 , the air temperature reduction caused by cool coating would be 0.9°C , 0.7°C , and 0.6°C for the height of 0.5 m, 1 m and 1.5 m above roof. These results highlight the cooling effects of cool coating. More detailed information about the simulation work could be found in Reference [166].

3.6 Summary

In this study, the cooling effects and energy saving performance of cool coating were evaluated by a field experimental study. After the application of cool coating onto the test building roof, the solar reflectance was increased from 0.27 to 0.80 while the thermal emittance was increased from 0.92 to 0.94.

Significant reduction of the roof surface temperature was observed. On sunny days when the daily mean solar irradiation intensity was about 535 W/m^2 (Pair 1 days in this study), the peak roof surface temperature was reduced by 19.2°C , from 58.0°C to 38.8°C , and the peak heat flux was decreased from 133.6 W/m^2 to 60.0 W/m^2 about noon. For the Pair 2 and Pair 4 days, the daily mean power of the air-conditioning system was reduced by up to 20%, from 2 kW to 1.6 kW, after the application of cool coating. Meanwhile, reduced air temperature was observed at inlet and outlet of the condenser which was on the roof. This indicated that the air above the roof was cooled down, due to the application of cool coating. Increased outlet temperature of evaporator was also observed, which suggested reduced cooling load of the building. Based on the measurement results of the four pairs of days, the average power consumption saving was 18%, or 8.4 kWh/day. After this field study,

computational simulation method was also used to evaluate the impact of cool coating on the surrounding microclimate. Noticeable reduction of ambient air temperature could be achieved by the application of cool coating.

This study demonstrated the huge potential benefit of cool coating in the tropical climate based on the direct measurement of temperature and power consumption in the field experiment. It fills the research gap.

Chapter 4. Natural Ageing Study of Cool Coatings

4.1 Introduction

This chapter introduces the methodology, test materials, instruments, and results of the natural ageing experiments of cool coating samples. It aims to figure out how the solar reflectance and thermal emittance change during the ageing process in the local environment under tropical climate.

4.2 Methodology

To find out the rate and extent of ageing process of cool coatings under natural conditions, this study would conduct outdoor natural ageing experiments with cool coating samples, and monitor the change of solar reflectance and thermal emittance of them as they age.

Cool coating samples were prepared by applying cool coating paint onto the substrate coupons. Then the samples were exposed to natural environment on a roof for a period of time, while a group of samples were kept in dry cabinet indoors as the control group. The radiative properties (solar reflectance and thermal emittance) of the samples were measured before the natural ageing, as well as periodically during the ageing process. Comparison of the measurement results would indicate the changes.

4.3 Sample preparation

4.3.1 Selection and preparation of substrate materials

Test samples of cool coatings were prepared in this study by applying cool paint on selected substrate materials. As the representatives of the typical roofing materials for both the industrial and residential buildings in Singapore, three substrate materials were selected [167, 168], namely ferrocement (600 mm(L) $\times$ 600 mm(W) $\times$ 30 mm(H) thick ferrocement; Eng

Seng Tech Pte Ltd), stainless steel (NTK U-22 stainless steel; LCP Building Products Pte Ltd), and aluminium alloy (Aluminium flat sheets, 1 mm thickness , PVDF 2 coats, RAL 9006 colour; Kalzip Asia Pte Ltd).

The preparation of these substrates began with cutting the materials into 65 mm (L) × 65 mm (W) square pieces, a size that fits the measuring instruments and test chambers. After that the coupons were manually washed with phosphate free detergent (Extran MA 03 Phosphate-Free; Merck Pte Ltd) to remove the dirt and oil on their surface. The pieces of substrates were then stored indoors for at least 72 hours for adequate drying and conditioning at room temperature of $23 \pm 2^{\circ}\text{C}$ with relative humidity of $50 \pm 5\%$, before the cool paint was applied. The procedures are shown in **Figure 4-1**. This preparation process was in compliance with ASTM D3276-07 (Standard Guide for Painting Inspectors (Metal Substrates)) [169], ASTM D6237-09 (Standard Guide for Painting Inspectors (Concrete and Masonry Substrates)) [170], ASTM D1730-09(2014) (Standard Practices for Preparation of Aluminum and Aluminum-Alloy Surfaces for Painting) [171], and ASTM G147 (Standard Practice for Conditioning and Handling of Nonmetallic Materials for Natural and Artificial Weathering Tests) [172].

Figure 4-1 Procedures of preparing the substrates: (a) cutting substrates; (b) washing substrates; (c) washed substrates; (d) conditioning substrates.

4.3.2 Application of cool paint on substrates

The cool coating used in this study was a water-based acrylic paint from a commercial coating company SkyCool Pty Ltd., which had been used in building industry for years [173, 174]. This coating would be marked as “Coating 1” in this thesis. It contains solar reflective pigments (e.g., rutile grade Titanium Oxide (TiO_2)) and a quantity of gas (e.g., CO_2) filled microspheres. More information about its composition (filler, suspension agent, binder, etc.) and formulation is revealed in the reference [175].

The quality of coating application has a significant impact on the coating performance. Therefore, to improve the robustness and repeatability of the sample preparation, the experimenters went through a training conducted by the professional applicator, Speedo Marine (Pte) Ltd. The spraying technique followed the Singapore Standards SS 5: B10 (Methods of Test for Paints, Varnishes and Related Materials. Part B10. Spraying Properties.)

[176]. This ensured repeatability of the coating finishing, surface roughness, surface uniformly, and thickness of the coating. The dry coating thickness range of 400-600 μm was recommended by the paint manufacturer, and this thickness can ensure the optimal solar reflectance of the coating.

The procedures of the spraying are shown in **Figure 4-2** and **Table 4-1**.

Figure 4-2 (a) Spraying substrate coupons with the sprayer; (b) sprayed coupons; (c) sample arrangement for the first round of spraying; (d) sample arrangement for the second round of spraying.

Table 4-1 Procedures for spraying the substrate coupons with cool paint

No.	Detailed procedures
1	As the beginning, two rows of six substrate coupons were placed on a customised spraying platform. The neighbouring coupons in the same row were kept with 3-cm gaps. The top and bottom rows were kept at a constant distance of 9 cm throughout the whole spraying.
2	The sprayer (Ultra 390; Graco Inc) was operating at the pressure of 10000 kPa (1500 PSI) with 30 cm spacing between the sprayer nozzle and the coupons.
3	To achieve the desired coating thickness in the range of 400 μm to 600 μm , the coupons were sprayed for two rounds. In each round it sprayed seven times, each time spraying from the left end to the right end of the rows in a time frame of 6 seconds.
4	After the first round of spraying, the two rows of samples were rearranged before the second round. The top row was shifted to the bottom and vice versa. Then the first left sample changed place with the first right sample, the second left sample changed place with the second right sample, and so forth. Then each sample was rotated clockwise for 180°. This rearrangement minimised the error that the top/left samples might receive different amount of paint from the bottom/right samples.
5	After that, the fresh painted substrate coupons were dried for three hours on roof, before they were moved indoors for further conditioning for at least 72 hours.

4.4 Instruments and test site

After adequate drying and conditioning, the coated cool coating samples were measured for the coating thickness, solar reflectance, thermal emittance, and spectral reflectance. The

coating thickness was measured by a thickness gauge, the solar reflectance was measured by a reflectometer, and the thermal emittance was measured by an emissometer. These instruments have been introduced in Section 3.3.2 . The instrument for the measurement of spectral reflectance is described below.

Spectral reflectance describes the solar reflectance of a sample at different wavelength over a spectrum. In this study it was measured by an UV/VIS/NIR spectrophotometer (LAMBDA 950; PerkinElmer Inc.) equipped with a 150 mm diameter Labsphere integrating sphere, following the ASTM standard E903-12 (Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres) [177]. The measurements of the spectral reflectance were conducted in the range of 300-2500 nm, which covered the solar spectrum [178], at a fixed interval of 5 nm. The solar spectrum consists of three parts, namely UV (300–400 nm), visible light (400–700 nm) and near-infrared (700–2500 nm). These three parts convey respectively about 5%, 43%, and 52% of the total energy of the whole solar spectrum [140, 178]. The image of the spectrophotometer is shown in **Figure 4-3**.

Figure 4-3 Spectrophotometer

The cool coating samples were then placed on the outdoor exposure racks to experience natural ageing for a period of three years, as shown in **Figure 4-4**. The racks are made of

stainless steel, which ensures that the samples would not be infected by rust from the racks. The wire mesh design prevents rainwater pooling on the rack surface, as well as minimises heat conduction from the rack to the samples. The exposure racks were mounted on the rooftop of Building N3.1 in NTU, Singapore. The location of NTU is shown in **Figure 3-2**, in Section 3.3.1 .

Figure 4-4 Exposure racks

4.5 Results and discussions

The natural ageing experiments lasted for three years. As introduced in the literature review, the change of solar reflectance of cool coating is highly affected by the soiling accumulation on the surface. Therefore, the surface of the samples should not be touched to interfere with the natural soiling accumulation process. Since all the measurements of solar reflectance, thermal emittance, and spectral reflectance are made by contact methods, the measured samples would not be placed back on the exposure racks. Instead, the next measurement should be based on the samples picked from the remaining ones.

Below shows the measurement results obtained before the ageing, after one year of ageing, after two years of ageing, and after three years of ageing, as in **Table 4-2** and **Figure 4-5**.

Table 4-2 Solar reflectance and thermal emittance measurement results

Timeline	Solar reflectance				Thermal emittance
	Total (300–2500 nm)	UV (300–400 nm)	VIS (400–700 nm)	NIR (700–2500 nm)	
Year 0	0.80	0.14	0.86	0.80	0.88
Year 1	0.71	0.16	0.72	0.74	0.88
Year 2	0.64	0.14	0.64	0.67	0.88
Year 3	0.55	0.12	0.52	0.63	0.87

Figure 4-5 Spectral reflectance measurement results

The solar reflectance (full spectrum, 300–2500 nm) of the cool coating decreased by 0.25, from 0.80 to 0.55, over the period of three years, in the natural environment of Singapore. The decrease in the first year was 0.09, from 0.80 to 0.71. The decrease in the second and the third year was 0.07 and 0.09, respectively. It was also observed that after the 3-year ageing, the decrease of solar reflectance in UV part was 14% from 0.14 to 0.12, the decrease in visible part was 40% from 0.86 to 0.52, and the decrease in near-infrared part was 21%, from 0.80 to 0.63. In other words, the reflectance decreased over the whole spectrum, but the decrease in the visible part was more significant than in the other two parts. Within the visible part, the decrease in the low end (mainly responsible for colour violet and blue) was more significant than in the high end (mainly responsible for colour red and orange). This solar reflectance is probably due to the combined effects of soiling and UV, which would be discussed in Chapters 5 and 6.

Meanwhile, the thermal emittance of the cool coating experienced little change in the three years. One possible reason might be that the thermal emittance of contaminants on the surface of cool coating was close to that of cool coating, thus it remained almost the same even when part of the coating surface was covered by contaminated. These results concurred with the findings by Akbari et al. [41] and Cheng et al. [73].

As the control group, the solar reflectance and thermal emittance of samples kept in the dry cabinet had little change during the three years. This suggests that all the changes of solar reflectance and thermal emittance were caused by the natural weathering.

4.6 Natural ageing of some other cool coatings

As references, several other models of cool coatings popular in the market of Singapore were tested in that natural ageing experiment. The changes of their solar reflectance and thermal

emittance are summarised in **Table 4-3**. After three years of natural weathering, the solar reflectance of these cool coatings decreased by about 0.19 to 0.28, while the changes of their emittance were within 0.02. These changes were close to those of the Coating 1, indicating they have the same ageing trends.

Table 4-3 Ageing results of other cool coatings (brands and models are anonymised)

Coating	Solar reflectance		Thermal emittance	
	Before ageing	After ageing	Before ageing	After ageing
Model 2	0.84	0.65	0.89	0.87
Model 3	0.84	0.62	0.88	0.87
Model 4	0.82	0.55	0.85	0.86
Model 5	0.84	0.56	0.84	0.86

Natural ageing experiments with shorter duration (several months) were conducted with Coating 1 and other two new models of coating from the same coating company. The new models, marked as “Coating 1-2”, and “Coating 1-3”, have smoother surface and higher omniphobic properties. More detailed information about the new coatings would be introduced in Section 5.2.4 . Detailed experimental information and the results are presented in Appendix D.1 . The photographs of the cool coatings taken during the ageing period are presented in Appendix D.2 . Obvious soiling accumulation could be observed in the photographs. The results indicated that the solar reflectance loss would be much more significant (loss of 0.27 in 5 months) when the samples were exposed to more intense pollutant sources. The results also suggested that the solar reflectance loss would be affected by the surface conditions of cool coating.

4.7 Summary

The natural ageing experiment of cool coating samples lasted for three years on the campus of NTU, Singapore. Coating 1 and other four cool coatings commercially available in Singapore market were tested. The results indicated that the solar reflectance of cool coating generally decreased by 0.19-0.28 after 3 years' ageing.

Taking Coating 1 as the example, its solar reflectance loss was 0.09, 0.07, and 0.09 during the first, the second, and the third year. It can be found that the solar reflectance loss of each year was similar, which differs from the findings of some previous studies which concluded that the solar reflectance in the first year would be the most significant.

However, the rate of loss of solar reflectance would be affected by the pollution intensity and the surface morphology and certain properties (e.g., roughness).

Thermal emittance of the cool coating samples, nevertheless, had little change during the three years of ageing. This finding concurred with the results of existing studies.

Chapter 5. Studies on Ageing Factors: Soiling and Cleaning

5.1 Introduction

Soiling is the accumulation process of airborne pollutants depositing on the surface of the material. Atmospheric pollutants contain a wide variety of dirt particles. These dirt particles mostly originate from sources such as soil, sea salt, and exhaust of vehicles, which vary in particle sizes (from smaller than one micron to above several millimetres) to chemical composition [179]. There are two types of soiling mechanisms, namely dry deposition and wet deposition, as introduced in Section 2.4.2 . Soiling is the most significant factor for the reflectance loss of cool coatings in the ageing process, as concluded by many studies [38, 73, 75, 123].

Cleaning, on the contrary, would remove part of the contaminants, and restore part of the lost reflectance. There are two types of cleaning in the natural environment, wind blowing and rain washing.

These different types of soiling and cleaning would cause different effects on the solar reflectance and thermal emittance of cool coating. This study designed various laboratory-based experiments to investigate these effects. Dry and wet deposition mechanisms, as well as wind blowing and rain washing mechanisms, were replicated in the laboratory. This provides repeatable and controllable access to investigations on these phenomena. This chapter would introduce the designs of the experiments, the preparation of the test samples, the measurement, and the results and analyses.

5.2 Soiling agents and cool coatings

To standardise the procedures for mimicking soiling, two types of soiling agents were chosen to be used throughout this study, namely “real dirt” (marked as RD) and carbon micropowder (marked as CM).

5.2.1 Real dirt

Contaminants accumulated on building envelope are determined by the pollutant source [180]. In the natural exposure experiment, as introduced in Chapter 4, the cool coating samples were exposed in NTU, which is near the industrial zones in the southwest of Singapore. With the aim to obtain the containments that are close to those in the natural exposure experiment, as well as to represent the worst-case-scenario in Singapore’s atmospheric environment, the ICES building located in Jurong Island, which has high concentration of heavy industries, was chosen as the sample collection site for the soiling particles. The location of ICES building is shown in **Figure 5-1**.

Figure 5-1 Location of ICES in Jurong Island (satellite image) [158]

The soiling particle sample (real dirt) was collected from the fresh air intake filter of the air-conditioning units on rooftop of the ICES building. If not trapped by the filter, these particles would land on the roof. Hence it is reasonable to assume they are the same as the soiling contaminants on the roof, and could be used to replicate the soiling process in laboratory.

Minimum sample preparation of real dirt was carried out, in order to preserve its chemical and physical properties. The samples were only filtered with a sifter (mesh size 0.45 mm) to remove big particles prior to the inspection.

Morphology of the real dirt sample was measured by a scanning electron microscope (SEM) at an accelerating voltage of 200 kV (JSM 6700 Scanning Electron Microscope; JEOL Ltd). Powder samples were deposited on a double sided carbon tape attached to the substrate. The result indicated that the real dirt contained particles of different sizes and shapes, as shown in **Figure 5-2**.

Figure 5-2 SEM image of sifted real dirt

Spectra of ^1H nuclear magnetic resonance (NMR) were recorded at room temperature by a NMR spectrophotometer (Nanobay 400 MHz; Bruker Co.). The sample was dissolved in

deuterated solvents and the spectra were referenced to the solvent line (CDCl_3 : ^1H , 7.26 ppm) relative to Tetramethylsilane (TMS). The result revealed the existence of a wide range of mixture of hydrocarbon in the real dirt, as shown in **Figure 5-3**.

Figure 5-3 NMR analysis result of real dirt

Inductively coupled plasma mass spectroscopy (ICP-MS) measurements were performed on an ICP-OES spectrophotometer (Vista-MPX CCD Simultaneous ICP-OES; Varian Inc.). Compounds were digested in concentrated nitric/hydrochloric acids and diluted with deionized water. Internal standards (2–5 mL, consist of deionized water and nitric/hydrochloric acid) were added with 500 μL of samples in a sample tube and mixed well before injection. In the ICP-MS, five main elements were measured, as shown in **Figure 5-4**.

Figure 5-4 ICP-MS analysis result of real dirt

Thermal stability of the dirt was characterised by the thermogravimetric analysis (TGA) of dirt sample both under N₂ and air atmosphere at a heating rate of 10 °C/min using a TGA instrument (SDT-2960T; TA instruments). Degradation of dirt was observed in multistep process due to the multicomponent nature of the dirt including initial desorption of moisture (about 13%) followed by the degradation of different organic components (about 21%). Final residue at 800°C signified the presence of non-degradable inorganic components (about 66%). The results are shown in **Figure 5-5**.

Figure 5-5 TGA overlay plots of real dirt

5.2.2 Carbon micropowder

Carbon is one component in real dirt. It is strong radiation-absorbing and is suggested as the most significant factor in real dirt that contributes to the solar reflectance loss of soiled coating [123]. Therefore, carbon micropowder was chosen as the other soiling agent for this soiling study. The carbon micropowder (Carbon black $\geq 99.9\%$, Acetylene, 50% compressed, ALFA39724-30; VWR International Pte Ltd) with a spherical powder size range between 0.4–12 μm was used in this study. The SEM result of carbon micropowder is shown in **Figure 5-6**. It was observed both the carbon micropowder and the real dirt particles displayed random particle shapes and sizes.

Figure 5-6 SEM image of carbon micropowder

5.2.3 Similarity between the two soiling agents in decreasing the solar reflectance

The two soiling agents would be used to decrease the solar reflectance of cool coating in the experiments. A test was conducted to evaluate their effect and efficiency.

Two cool coating samples were soiled by real dirt (RD) and carbon micropowder (CM) respectively to the same level of solar reflectance (however, the amounts of these two soiling agents used to achieve this solar reflectance were different). The spectral reflectance of the two soiled samples and one reference sample (clean cool coating) is shown in **Figure 5-7**. The figure revealed a remarkable similarity between the spectral reflectance of these two soiled samples throughout the full spectrum. That is, the two soiling agents' effects on decreasing solar reflectance are highly similar.

Figure 5-7 Spectral reflectance of clean and soiled cool coating samples

In spite of the similarity of the effects, the efficiency of the two soiling agent are different. In this test, the concentration of real dirt used on the cool coating sample was 740 mg/m^2 , while the concentration of carbon micropowder on the other sample was 14.7 mg/m^2 . The concentration of the former was about 50 times as high as that latter, which means carbon micropowder is 50 times as efficient as real dirt in decreasing the solar reflectance of cool coating. This test result indicats that carbon micropowder is a potential candidate for replacing real dirt for some solar reflectance experimental studies.

5.2.4 Cool coatings

The Coating 1 was used in the natural ageing study, as introduced in Section 4.3 . Since then, prototypes of new cool coating paints had been proposed by the company, based on the Coating 1. In the following experiments, not only the Coating 1, but also two new coating prototypes (marked as Coating 1-2 and Coating 1-3) would be used as the test cool coatings. The major difference between the new prototypes and the Coating 1 is that novel fluorinated

core-shell nanoparticle additives are added in the prototypes. Some surface properties of the new prototypes were measured and presented below.

The solar reflectance, thermal emittance, and spectral reflectance of the two new prototypes and Coating 1 were measured by reflectometer, emissometer, and spectrophotometer. The results are shown in **Table 5-1** and **Figure 5-8**. It could be observed that the new prototypes have the initial solar reflectance higher than Coating 1, and the thermal emittance no lower than Coating 1.

Table 5-1 Solar reflectance and thermal emittance of Coating 1, Coating 1-2, and Coating 1-3

Coating	Solar reflectance	Thermal emittance
Coating 1	0.80	0.88
Coating 1-2	0.84	0.90
Coating 1-3	0.84	0.89

Figure 5-8 Spectrum reflectance of Coating 1, Coating 1-2, and Coating 1-3

The new prototypes have much lower contact angle than Coating 1, as shown in

Table 5-2. It could be observed that after annealing at 40°C for seven days, the water and hexadecane contact angles of Coating 1-2 and Coating 1-3 became much higher than Coating 1, which indicated the enhanced hydrophobicity and oleophobicity of the new prototypes. This could be explained by the concept that the added fluorinated nanoparticles would move to top of the surface and increase higher surface fluorine content. As the characteristic of the nanoparticles is omniphobic, the surface omniphobic properties of the coating would be enhanced. Then the dirt removal efficiency might be increased, which would be tested in this chapter.

Table 5-2 Contact angles of Coating 1, Coating 1-2, and Coating 1-3

Coating	Contact angle (°) after 7 days of annealing at 40°C	
	Water (hydrophobicity)	Hexadecane (oleophobicity)
Coating 1	94	1
Coating 1-2	127	17
Coating 1-3	135	86

Surface profile of the cool coating was measured by a three-dimension (3D) scanning profilometer (TalyScan 150; Taylor Hobson Ltd), with scan rate of 1000 $\mu\text{m/s}$, x -axis spacing of 0.5 μm , and y -axis spacing of 5 μm . The image of the profilometer is shown in **Figure 5-9**. The 3D surface profiles of three coating are shown in **Figure 5-10**. The amplitude measurements are summarised in **Table 5-3**, based on the results of at least three samples for each coating. It could be observed that the new prototypes have smoother surface than

Coating 1. One reason is that the nanoparticles migrate towards the top of the coating surface and fills up the gaps between the microsphere and pigment molecules.

Figure 5-9 3D scanning profilometer

Figure 5-10 3D surface profile of cool coating samples: (a) Coating 1; (b) Coating 1-2; (3) Coating 1-3.

Table 5-3 Surface amplitude parameters of Coating 1, Coating 1-2, and Coating 1-3

Coating	Surface amplitude parameters (μm)		
	S_a (arithmetical mean height)	S_q (root mean square height)	S_t (maximum height)
Coating 1	12.05	15.10	100
Coating 1-2	3.79	5.00	43
Coating 1-3	3.13	4.30	34

5.3 Methodology: dry deposition

Dry deposition is the process when soiling particles settle down on surfaces without water. Laboratory-based experiments were designed to mimic the dry deposition, and evaluate how it would decrease the solar reflectance of cool coating, and thereafter how the cleaning process would restore the lost solar reflectance.

5.3.1 Sample preparation and measuring instruments

In this dry deposition study, not only Coating 1, but also Coating 1-2 and Coating 1-3 were used as the test coating. The samples preparation procedures were the same as introduced in Section 4.3 .

Real dirt was used as soiling agent in the experiments. Since the particle size of the real dirt ranged from nanometre to micrometre (refer to **Figure 5-2**), non-uniform distribution of the particles might occur when the particles deposit onto the surface of samples. For this reason, ball milling was carried out on the real dirt prior to the experiment to narrow down the particles size distribution, using the planetary ball mill system (PM 400; RETSCH ltd). The real dirt was milled in the stainless steel jar for 12 hours at a speed of 250 rpm with 30 pieces

of agate balls with the diameter of 10 mm and weight of 4.0 g each, followed by being mortared with a stone pestle for 30 minutes.

A reflectometer, as introduced in Section 3.3 , was used for measuring the solar reflectance.

An electronic scale (Analytical balance XA 110/X; RADWAG Balances and Scales; Radom, Poland) was used for measuring the weight. The balance is shown in **Figure 5-11**.

Figure 5-11 Analytical balance

5.3.2 Apparatus and experiment procedures

Natural dry deposition was mimicked inside a customised chamber (as shown in **Figure 5-12**) by letting the real dirt particles deposit freely onto the cool coating samples. The chamber is made of stainless steel with the dimensions of 60 cm (W) × 60 cm (H) × 60 cm (L). Four mixing fans (Paps, Series 8000N; ebm-papst Group), each providing an airflow rate of 50 m³/h, are installed on the interior walls of the chamber to provide gentle air stirring, for the purpose of uniform suspension of real dirt particles inside the chamber. There is an inlet port

at the centre of the ceiling through which real dirt particles can be introduced into the chamber.

Figure 5-12 Schematic drawing and image of dry deposition chamber

A standard operation procedure (SOP) was developed in this study for the laboratory-based dry deposition, as described in **Table 5-4**. This SOP provided a controllable method to repeat the experiment.

Table 5-4 SOP for laboratory-based dry deposition experiment

Step	Detailed procedures
1	<p>The solar reflectance of each sample was measured before the dry deposition, ρ_0.</p> <p>The weight of each sample, M_0, was measured with the analytical balance.</p>
2	<p>Four samples, in two by two arrangements, were put on the centre of the floor of the deposition chamber. The door of the chamber was then closed, and the mixing fans in the chamber were turned on.</p>
3	<p>After 5 minutes, the real dirt particle was loaded into the chamber through the inlet port via a fine sieve (opening size 100 μm), by gently sifting the real dirt particles over a time frame of 5 minutes to let the particles pass through slowly. The mixing fans remained on for another 5 minutes after the particle loading process to ensure ensures adequate mixing in the chamber.</p>
4	<p>The chamber was closed for one day to allow adequate settlement of real dirt particles.</p>
5	<p>The samples were retrieved, and their weight was measured again with the balance, mark as M_1. Then the weight of the particles on the sample could be calculated as $M_1 - M_0$. The solar reflectances of the samples, ρ_1, were measured again as well.</p>
6	<p>If the solar reflectance has not decreased to the desired level (e.g., 0.50), Steps 2-5 would be repeated, and the amount of particles in Step 3 would be adjusted accordingly.</p>

5.3.3 Results

Figure 5-13 shows some of the cool coating samples after dry deposition. It could be observed that the real dirt spread relatively uniformly on the surface. Measurements indicated that about 40 mg of real dirt particles on each samples (that surface concentration is 9.5 g/m^2) were needed to decrease the solar reflectance of the sample from the original level to 0.50 ± 0.02 .

Figure 5-13 Dry deposition of real dirt

It could be observed that the real dirt particles aggregated during the dry deposition, which happened when the particles suspended inside the chamber. It was also noticed that the dry-deposited particles did not firmly adhere onto the sample surface. Some of the deposited particles could be removed by wind blowing or shaking, as shown in **Figure 5-14**.

Figure 5-14 Detachment of particles when the sample was inclined

5.4 Methodology: wet deposition

Wet deposition is common in real world, as introduced in Section 2.4.2 . In Singapore, it happens mostly in the form of precipitation. The droplets absorb the soiling particles, and then impact on the building envelope. After the droplets evaporate, the particles would be left to the surface. Laboratory-based experiments were conducted to reproduce the wet deposition process of soiling particles.

5.4.1 Sample preparation and measuring instruments

Coating 1, Coating 1-2, and Coating 1-3 coatings were used in this wet deposition experiment, and both real dirt and carbon micropowder were used as soiling agents, to evaluate their effects and efficiency of decreasing the solar reflectance of cool coating. The samples preparation procedures were the same as introduced in Section 4.3 .

The solar reflectance of the samples was measured by the reflectometer, as introduced in section 3.3 .

5.4.2 Apparatus and experiment procedures

The wet deposition procedures consist of dispersion of soiling agents in water to form an aqueous suspension, loading the aqueous suspension onto cool coating samples, and drying the samples in the oven. This methodology enables loading the exact amount of soiling agent on the sample surface, and decreasing the solar reflectance to a desired level. The SOP is described in detail in **Figure 5-15** and **Table 5-5**.

Figure 5-15 Steps of wet deposition: (a) bordering the sample with silicon sealant; (b) weighing soiling particles; (c) making particle mixture; (d) ultrasonic bathing of particle mixture; (e) drying in oven; (f) soiled samples.

Table 5-5 SOP for laboratory-based wet deposition experiment

Step	Detailed procedures
1	The solar reflectance of each sample was measured before the wet deposition, mark as ρ_0 .
2	The cool coating samples were sealed on the edges by silicone sealant, fencing its surface with a 2 mm high sealant barrier. Then the samples were conditioned under room temperature for 2 hours for the sealant to dry.
3	Soiling agent (real dirt or carbon micropowder) was weighted, and transported into a test tube, along with deionized water, forming a soiling mixture with a designed concentration.
4	The tube was capped, sealed, and then sonicated in an ultrasonic bath for 30 minutes for creating uniformly dispersed mixture.
5	A designed amount of the mixture was dipped onto the surface of the cool coating sample by a clean pipette.
6	The sample was put in an oven at 50°C for 4 hours, evaporating the water and leaving only the soiling agent on the sample surface.
7	The solar reflectance of the sample was measured again, mark as ρ_1 .
8	If the solar reflectance has not decreased to the desired level (e.g., 0.50), Steps 3-7 would be repeated, and the amount of soiling agents in Step 3 would be adjusted accordingly.

5.4.3 Results

Batches of samples were wet deposited by this method to lower their solar reflectance to different levels. The solar reflectance of each sample, as well as the amount of soiling agent used on the sample, was recorded. Linear regression models were built based on the results,

as shown in **Figure 5-16** and **Figure 5-17**. The reflectance ratios in the figures are calculated by (Eq. 5-1).

Figure 5-16 Solar reflectance change with the increase of real dirt concentration (with error bars representing one standard deviation)

Figure 5-17 Solar reflectance change with the increase of carbon micropowder concentration
(with error bars representing one standard deviation)

Reflectance ratio

$$\begin{aligned}
 &= \frac{\text{Solar reflectance after deposition}}{\text{Solar reflectance before deposition}} \times 100\% \\
 &= \frac{\rho_1}{\rho_0} \times 100\%
 \end{aligned}
 \tag{Eq. 5-1}$$

Based on the measurement results, linear relationships were proposed between the reflectance ratio and the surface concentration of the soiling agents, as in (Eq. 5-2) and (Eq. 5-3). The high R^2 value indicated good fitting of these two models.

$$y = -0.2327x + 1 \tag{Eq. 5-2}$$

This model (**Eq. 5-2**) is applicable to the samples soiled by real dirt, where $y = \frac{\rho_1}{\rho_0}$ is the reflectance ratio, and x is the surface concentration of real dirt (g/m²). The coefficient of determination R^2 is 0.9457, indicating the surface concentration of real dirt explains 94.6% of the variation of reflectance ratio.

$$y = -0.0116x + 1 \quad (\text{Eq. 5-3})$$

This model (**Eq. 5-3**) is applicable to the samples soiled by carbon micropowder, where y is the reflectance ratio, and x is the surface concentration of carbon micropowder (mg/m²). The coefficient of determination R^2 is 0.9507, indicating the surface concentration of real dirt explains 95.1% of the variation of reflectance ratio.

The two models are linear and the constants in the two equations are the same, which suggests that the two soiling agents caused similar decreasing trends on the reflectance ratio of the cool coating samples. However, the coefficients before x are different (-0.2327 m²/g and -0.0116 m²/mg, respectively), which suggests that the two soiling agents have different efficiencies in decreasing the reflectance ratio. By comparing the two coefficients, it could be calculated that the carbon micropowder is about 50 times as efficient as the real dirt in decreasing the reflectance ratio. These findings concurred with the results in Section 5.2.3 .

The two equations could be converted to (**Eq. 5-4**) and (**Eq. 5-5**).

$$\rho_{soiled}^{RD} = \rho_0 - 0.2327\rho_0 \cdot x \quad (\text{Eq. 5-4})$$

where ρ_{soiled}^{RD} is the solar reflectance of cool coating soiled by real dirt.

$$\rho_{soiled}^{CM} = \rho_0 - 0.0116\rho_0 \cdot x \quad (\text{Eq. 5-5})$$

where ρ_{soiled}^{CM} is the solar reflectance of cool coating soiled by carbon micropowder.

5.5 Methodology: wind blowing

Wind blowing could partly remove the soiling particles from soiled cool coating, restoring solar reflectance. This process was mimicked by laboratory-based experiments. A wind tunnel from the Thermal & Fluids Lab of School of Mechanical and Aerospace Engineering (MAE), NTU, was used in the experiments. Soiled cool coating samples were exposed to wind blowing in wind tunnel. The solar reflectance of the cool coating samples was measured before and after the wind blowing, to quantify the restored solar reflectance. The weight of the samples was monitored as well, to quantify the loss of soiling particles. In this way, the effects and efficiency of wind blowing as a solar-reflectance-restoring method could be evaluated.

5.5.1 Sample preparation and measuring instruments

Cool coating samples were prepared with Coating 1, Coating 1-2, and Coating 1-3 coatings, and were soiled with real dirt by dry and wet deposition methods to decrease their solar reflectance to about 0.50. The samples list for the wind tunnel experiments are introduced in **Table 5-6**. A reflectometer, as introduced in Section 3.3 , was used for measuring the solar reflectance of the cool coating samples. An electronic scale, as introduced in Section 5.3 , was used for weighing the samples.

Table 5-6 List of cool coating samples for wind blowing experiment

Coating	Number of samples	
	Dry deposited	Wet deposited
Coating 1	3	6
Coating 1-2	3	6
Coating 1-3	3	6

5.5.2 Apparatus and experiment procedures

The wind tunnel consists of a flow straightener, a contraction cone, a test section, a Pitot tube, a diffuser, a fan, and a frequency inverter, as illustrated in **Figure 5-18**. The dimensions of the test section are 200 mm (W) $\times$ 200 mm (H) $\times$ 1000 mm (L). A 1300 mm (W) $\times$ 40 mm (H) $\times$ 150 mm (L) supportive substrate base for mounting the test samples was fixed in the centre of its floor. A 10° wedge was placed in front of the supportive base for smoothing the direction change of airflow. The speed of fan (Kruger Engineering Pte Ltd, FSA200/CM), i.e., the free stream velocity, was controlled by a frequency inverter. The maximum static pressure achievable by the fan is 850 Pa. The wind speed was measured by the Pitot tube. The wind tunnel was calibrated before the experiment, and it could generate the required wind speeds. The image of the wind tunnel is shown in **Figure 5-19**.

Figure 5-18 Schematic drawing of the wind tunnel

Figure 5-19 Image of the wind tunnel

According to Meteorological Service Singapore, winds in Singapore are generally mild, with the mean surface speed normally lower than 2.5 m/s. High wind speed was observed during the presence of a Northeast Monsoon surge, when the mean speed could be up to 10 m/s [181]. In this experiment, wind speed of 3 m/s, 6 m/s, 10 m/s, and 14 m/s were used. The SOP for the wind blowing experiment is summarised in **Table 5-7**. All the prepared dry deposited and wet deposited samples underwent the wind blowing.

Table 5-7 SOP for laboratory-based wind blowing experiment

No.	Detailed procedures
1	The cool roof samples were prepared with Coating 1, Coating 1-2, and Coating 1-3. Their initial solar reflectance (R_0) and weight (M_0) were measured and recorded.
2	The solar reflectance of the samples was decreased to 0.50 ± 0.02 . Then their solar reflectance (mark as R_1) and weight (marked as M_1) were measured and recorded again. Then the weight of the soiling particles on the samples could be calculated as $M_1 - M_0$.
3	The wind tunnel was turned on, and the wind speed was adjusted to 3 m/s and maintained for 10 mins to ensure the wind tunnel works properly.
4	The wind tunnel was turned off, and one sample was mounted onto the centre of the supportive substrate base inside the tunnel.
5	The wind tunnel was turned on and maintained for 1 hour.
6	The wind tunnel was turned off. The sample was retrieved, and its solar reflectance (mark as R_2) and weight (mark as M_2) were measured and recorded again. Then the weight of the soiling particles on the sample could be calculated as $M_2 - M_1$. Then the lost weight of particles could be calculated as $(M_2 - M_1) - (M_1 - M_0)$.
7	The other samples were tested by the same steps 3-6.
8	After that, steps 3-7 were repeated with all the samples, but the wind speed was adjusted to 6 m/s. The solar reflectance after this turn was marked as R_3 , and the weight after this turn was marked as M_3 .
9	After that, steps 3-7 were repeated with all the samples, but the wind speed was adjusted to 10 m/s. The solar reflectance after this turn was marked as R_4 , and the weight after this turn was marked as M_4 .

After that, steps 3-7 were repeated with all the samples, but the wind speed was
10 adjusted to 14 m/s. The solar reflectance after this turn was marked as R_5 , and the
weight after this turn was marked as M_5 .

5.5.3 Results

For the dry deposited samples, loss of soiling particles was observed during the wind blowing, as shown in **Figure 5-20**.

Figure 5-20 Loss of soiling particles during wind blowing

The solar reflectances of the samples were measured before the deposition, after the deposition, and after wind blowing of each speed. The “solar reflectance restoration over the loss” after each turn of washing could be calculated based on the measurement results, as by (Eq. 5-6). It describes how much of the lost solar reflectance could be restored by the cleaning method. The weights of the samples were measured as well, and the weight of the real dirt particles on the samples was calculated accordingly. The results of the dry deposited samples are presented in **Table 5-8** and **Figure 5-21**.

Solar reflectance restoration over loss

$$= \frac{\text{Solar reflectance after deposition}}{\text{Solar reflectance before deposition}} \times 100\% \quad (\text{Eq. 5-6})$$

$$= \frac{R_{2,3,4,5} - R_1}{R_0 - R_1} \times 100\%$$

Table 5-8 Solar reflectance of samples and weight of real dirt particles during the wind blowing experiment

Solar reflectance (mean)					Real dirt weight (mean)		
Coating	Before loading	After loading	After all the blowing	Restoration over loss (%)	After loading (mg)	After all the blowing (mg)	Weight loss (%)
Coating 1	0.80	0.49	0.53	11	40	21	47
Coating 1-2	0.83	0.50	0.58	24	38	9	77
Coating 1-3	0.85	0.50	0.59	24	41	10	75

Figure 5-21 Restoration of solar reflectance and loss of soiling particles of dry deposited samples during wind blowing (with error bars representing one standard deviation)

It could be observed that wind blowing could remove the particles and restore the solar reflectance. And the effects became more and more significant as the wind speed increased. When the wind speed is 3 m/s, which is even higher than the mean surface speed in Singapore, the removal of soiling particle and the restoration of lost solar reflectance was much less than the results after the wind blowing of 14 m/s.

At the end of the experiment, the Coating 1 samples totally lost 47% of the real dirt particles in weight, and restored 11% of the lost solar reflectance. The Coating 1-2 samples totally lost 77% of the real dirt particles in weight, and restored 24% of the lost solar reflectance. The Coating 1-3 samples totally lost 75% of the real dirt particles in weight, and restored 24% of

the lost solar reflectance. The new prototypes (Coating 1-2 and Coating 1-3) restored more lost solar reflectance than Coating 1. One reason would be the reduced surface roughness.

The results also showed that the weight loss percentage of the soiling particles were much higher than the solar reflectance restoration percentage. It indicated that a large part (i.e., the removed part) of particles contributed to a disproportionate small part of the lost solar reflectance. Contrarily, a small part (i.e., the remaining part) of the particles contributed to a large part of the solar reflectance loss. In other words, the wind tend to remove the large size particles which account for a large part of the total weight, while the small size particles are more likely to stay on the surface and they are the main contributors for the solar reflectance loss. The small particles might be trapped by the surface elements. That could explain why Coating 1-2 and Coating 1-3 samples which have smoother surface experienced more removal of real dirt particles than Coating 1 samples. The small spheres have higher surface-area-to-weight ratio than the large ones (taking the density as constant), hence they could absorb more radiation when given the same weight.

The above introduced the wind blowing results of the dry deposited samples. For the wet deposited samples, on the other hand, results showed little removal of real dirt and little restoration of solar reflectance, as shown in **Table 5-9**. The explanation would be that the attachment between the particles and the sample surfaces are stronger for the wet deposited samples than the dry deposited ones, therefore the wind blowing could not remove them. However, the particles of wet deposited samples could be partly removed by another cleaning method, rain washing, as would be introduced in the following section.

Table 5-9 Solar reflectance of wet deposited samples during the wind blowing experiment

Solar reflectance (mean)					
Coating	Before	After	After all the	Restoration	
	loading	loading	blowing	over	loss
				(%)	
Coating 1	0.80	0.49	0.49	0	
Coating 1-2	0.83	0.50	0.50	0	
Coating 1-3	0.85	0.50	0.50	0	

5.6 Methodology: rain washing

Rain could wash off the accumulated particles on the cool coating and restore its solar reflectance. In this study, this washing process was mimicked in laboratory. Soiled cool coating samples were exposed to artificial rain washing, and the change of solar reflectance was measured. In this way, the effects of rain washing on restoring the solar reflectance could be evaluated.

5.6.1 Sample preparation and measuring instruments

The soiled cool coating samples, prepared by the dry deposition and wet deposition methods as introduced in the previous sections, were used in the rain washing experiments. The coatings included Coating 1, Coating 1-2, and Coating 1-3. The soiling agents was real dirt. The number of the test samples are shown in **Table 5-10**. The solar reflectance of the cool coating samples were measured by a reflectometer, as introduced in Section 3.3 .

Table 5-10 List of cool coating samples for rain washing experiment

Coating	Number of samples	
	Dry deposited	Wet deposited
Coating 1	3	6
Coating 1-2	3	6
Coating 1-3	3	6

5.6.2 Apparatus and experiment procedures

A customised spraying chamber was used for the rain washing experiment, as shown in **Figure 5-22**. It is a 550 mm (L) × 450 mm (W) × 500 mm (H) acrylic chamber with a fine spray hydraulic atomizing nozzle (1/4M-316SS6 Nozzle; Spraying System Co. (S) Pte Ltd) that is able to deliver a water flow rate of up to 31 L/h with at 75° spray angle at 5 bar pressure.

Figure 5-22 Schematic drawing and image of the spraying chamber

For this apparatus, a pressure of 2 bar was set for the water tank to produce a flow rate of 200 mL/min with a spraying area of 0.145 m². This would translate into a rainfall intensity of 82.8 mm/h, which could present the extreme rainfall occasions in Singapore. The soiled samples would undergo the intense rain washing, to reproduce the cleaning effects it would experience in natural environment. The daily average rainfall was 6 mm/day in Singapore, based on the historical data of 2009, 2010, and 2011 [182]. The highest hourly rainfall during the three years was 89.6 mm/h in June 2011 [183]. These data justified the setting of the rainfall intensity in the spraying chamber.

The samples were exposed to water spraying for 180 minutes. This amount of precipitation was equivalent to about 41 days' rainfall in local climate, based on the daily average rainfall in Singapore during 2009 to 2011. The operation procedures for the rain washing experiment are summarised in **Table 5-11**.

Table 5-11 SOP for laboratory-based rain washing experiment

No.	Detailed procedures
1	The cool roof samples were prepared with Coating 1, Coating 1-2, and Coating 1-3 coating. Their initial solar reflectance was measured.
2	The solar reflectance of the samples was decreased to 0.50 ± 0.02 . Their solar reflectance was measured again.
3	The tank of the spraying chamber was filled with deionized water.
4	The compressed air for the tank was turned on, and the pressure was adjusted to 2 bar to ensure the tank and the nozzle work properly. The flow rate was measured with a timer and a beaker. The flow rate at 2 bar should be about 200 ml/min.
5	The samples were put inside the spraying chamber, under the nozzle. Close the chamber.
6	The compressed air was turned off after 30 mins, and the samples were retrieved.
7	The solar reflectance of the samples was measured after they got dry.
8	After that, steps 4-7 were repeated for another 5 cycles. Then the total spraying duration would be 180 mins.
9	The compressed air was turned off, and the samples were retrieved.

5.6.3 Results

For wet deposited samples, the changes of solar reflectance and the restoration over loss are shown in **Table 5-12** and **Figure 5-23**.

Table 5-12 Solar reflectance and restoration over loss of wet deposited samples during rain washing experiment

Coating	Solar reflectance (mean)			Solar restoration over loss (mean)
	Before loading	After loading	After all the washing	After all the washing (%)
Coating 1	0.80	0.51	0.52	6
Coating 1-2	0.84	0.51	0.60	28
Coating 1-3	0.85	0.51	0.57	18

Figure 5-23 Solar reflectance and restoration over loss of wet deposited samples during rain washing (with error bars representing one standard deviation)

It could also be noticed that for Coating 1-2 and Coating 1-3 samples, most of the restoration was achieved after the first 30 mins of washing. The restored solar reflectance achieved in the later 150 mins was less significant than that in the first 30 mins. While for the Coating 1 samples, the restoration kept increasing as the washing duration increased, and the increasing slowed down only after 150 mins of washing. At the end of the experiment, after all steps of rain washing, the Coating 1 samples restored 6% of the lost solar reflectance, the Coating 1-2 samples restored 28% of the lost solar reflectance, and the Coating 1-3 samples restored 18% of the lost solar reflectance.

The results suggested that the new prototypes (Coating 1-2 and Coating 1-3) outperformed the original coating in rain-washing-cleaning ability. They restored more lost solar reflectance and restored more quickly, due mainly to their reduced surface roughness and improved omniphobic properties, as introduced in section 5.2.4

The above introduced the results of the wet deposited samples. For dry deposited samples, the results are shown in **Table 5-13**. These restorations were all achieved after the first 30 mins of washing, and changed little in the later 150 mins.

Table 5-13 Solar reflectance and restoration over loss of dry deposited samples during rain washing experiment

Solar reflectance (mean)			Solar restoration over loss (mean)
Coating	Before loading	After loading	After all the washing (%)
Coating 1	0.80	0.50	62
Coating 1-2	0.83	0.49	99
Coating 1-3	0.85	0.50	100

These results again demonstrated that Coating 1-2 and Coating 1-3 have enhanced ability of regaining the lost solar reflectance by washing. These results also suggested that the dry deposited particles were more loosely attached to the sample surface when compared to the wet deposited particles. Therefore they were removed more easily by the washing.

5.7 Summary

This chapter introduced the studies on two important factors in the ageing process of cool coating: soiling and cleaning. Two types of soiling mechanisms namely wet deposition and dry deposition, as well as two types of cleaning mechanisms namely wind blowing and rain washing, were simulated and investigated in this chapter. The experiments mimicked in laboratory would not be exactly the same as the natural phenomenon. But these laboratory-based experiments provided a repeated and controllable approach for investigating the effects of individual environmental factor. Standard Operation Procedure (SOP) was developed for controllable and repeatable laboratory-based experiments.

The main soiling agent used in the studies was real dirt, which was collected from the fresh air intake filter of the air-conditioning units on the rooftop of the building. It could represent the natural soiling particles in the environment of Singapore. Another soiling agent used in this study was carbon micropowder, which is strong radiation-absorbing. Experimental results show that it has similar effects (but much higher efficiency) of reducing the solar reflectance of cool coating with the real dirt. It is a potential candidate for replacing real dirt for some solar reflectance experiments.

Besides Coating 1, two new prototypes of cool coating were also tested in the studies. The experimental results indicate that they, compared to Coating 1, have improved self-cleaning ability when exposed to wind blowing and rain washing, due to the smoother surface and enhanced omniphobic properties.

The dry deposition experiments show that it takes about 9.5 g/m^2 of real dirt particles to decrease the solar reflectance of the sample from the original level (0.80) to 0.50 ± 0.02 . The dry deposited particles are relatively loosely attached on the cool coating surface, and could be removed by even gentle shakings. The wet deposited particles, somehow, have stronger attachment with the cool coating surface. And it takes only 1.6 g/m^2 of real dirt particles to decrease the solar reflectance of the sample from the original level (0.80) to 0.50 ± 0.02 . The wind blowing experiments show that wind blowing could remove part of the dry deposited particles, but could hardly remove the wet deposited particles. The rain washing experiments show that rain washing has more effective cleaning effects than the wind blowing. Therefore, the soiling accumulation in natural environment, would be predominantly determined by the wet deposition and water washing, especially in a climate with abundant precipitation such as Singapore. The wet deposited and then washed cool coating samples should be good replicates of the naturally aged cool coatings.

Mathematical models were built based on the results of wet deposition experiments, which show that the solar reflectance ratio of cool coating decreases linearly with the increase of the surface concentration of soiling particles (real dirt or carbon micropowder). Rain washing could restore part of the lost solar reflectance, but even extreme rainfall (82.8 mm/h lasting for three hours) could not remove all the soiling particles and restore all the lost solar reflectance. For Coating 1, rain washing could restore 6% of the lost solar reflectance caused by wet deposition, and restore 62% of the lost solar reflectance caused by dry deposition.

Chapter 6. Studies on Ageing Factors: UV (ultraviolet)

6.1 Introduction

As introduced in Chapter 2, UV is believed to be one factor for the ageing of cool coating [38, 74, 115]. It can deteriorate the cool coating by the UV degradation effects [141]. Many studies have been conducted about the changes of some chemical and mechanical properties, such as yellowing and chalking. However the effects of UV on the loss of solar reflectance of cool coating have been rarely explored.

Another unexplored topic is that whether the effects of UV would be affected by the soiling on cool coating. This question raises from the fact that some components of the soiling, such as black carbon [184], would absorb UV and might then mitigate the UV degradation on cool coating [185]. Therefore the loss of solar reflectance caused by UV might be different when the cool coating is soiled. Furthermore, different soiling agents might have different impacts. Part of this chapter is published in the reference *Effects of UV on radiation properties of cool coating* [186], which covered the study methodology, sample preparation, experiments, and results analysis.

6.2 Methodology

To fill the research gap, this study investigated the effects of UV on the change of solar reflectance and thermal emittance of cool coating through an accelerated UV ageing method. The cool coating samples were prepared and exposed to the artificial UV radiation in the UV chamber, and the changes of their radiative properties were monitored.

Some of the cool coating samples were clean when put into the UV chamber, while the other samples were pre-soiled by two types of soiling agent, real dirt and carbon micropowder,

before the UV radiation. After the UV ageing, by comparing the radiative properties of the unsoiled samples with the soiled ones, it would be able to evaluate the impact of soiling on the solar reflectance loss caused by UV.

6.3 Sample preparation

A total of 21 Coating 1 cool coating samples were prepared, by the same method introduced in Section 4.3 . Of these Coating 1 samples, seven were soiled by real dirt and seven were soiled by carbon micropowder, by the wet deposition method introduced in section 5.4 . The solar reflectance was decreased to around 0.50. The other seven Coating 1 samples were unsoiled, with the initial reflectance about 0.80. Besides, three Coating 1-2 coating samples and three Coating 1-3 samples were prepared as well. The number of the samples are summarised in **Table 6-1**.

Table 6-1 List of cool coating samples for wind blowing experiment

Group	Coating	Solar reflectance before UV exposure	Soiling agent	No. of samples
1	Coating 1	0.80 ± 0.02	Nil	7
2	Coating 1	0.50 ± 0.02	Real dirt	7
3	Coating 1	0.50 ± 0.02	Carbon micropowder	7
4	Coating 1-2	0.85 ± 0.03	Nil	3
5	Coating 1-3	0.82 ± 0.03	Nil	3

When preparing the soiled samples, the solar reflectance of the samples were measured after the wet deposition. Then the samples underwent an artificial washing process. The washing process was the same as the laboratory-based rain washing described in Section 5.6 ,

conducted in the spraying chamber. This process removed the loosely attached soiling agents on the samples, which ensured that the no soiling agent would be washed off in later UV testing which consists of condensation cycling. Therefore all the change of solar reflectance of the soiled samples would be caused only by UV rather than by the washing off of soiling agents. When washing finished and the samples were dry, the solar reflectance was measured again. If the solar reflectance of the samples did not fall into the designed range, they would be soiled, washed and measured again. This cycle was repeated until all the samples had the solar reflectance within the designed range.

6.4 Instruments, apparatus, and procedures

The solar reflectance of the samples was measured by the reflectometer, as introduced in Section 3.3 . The spectral solar reflectance was measured by the spectrophotometer, as introduced in Section 4.4 . The thermal emittance of each sample was measured by an emissometer, as introduced in Section 3.3 .

The cool coating samples underwent the accelerated UV ageing in a QUV test chamber (Q-Lab Corp.; Westlake, OH), as shown in **Figure 6-1**. The chamber exposes the samples to repetitive cycles of UV radiation and moisture under controlled environmental conditions, in compliance with ASTM G151-10 (Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources) [187] and ASTM G154-12 (Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials) [188]. The UV radiation (UVA, peak wavelength at 340 nm) is generated by fluorescent lamps in the chamber, which mimics the UV part of natural sunlight but with higher intensity. The moist environment is mimicked inside the chamber by periodically condensation of hot vapour of deionized water.

Figure 6-1 Schematic drawing and image of the QUV test chamber

The UV ageing experiment was conducted for eight weeks, following ASTM G154-12 cycle 6, as shown in **Table 6-2**. The total UV exposure dosage for the samples during this period of experiment was 536 MJ/m^2 , which is equivalent to that of 22 months' natural exposure in the climate of Singapore [189].

Table 6-2 UV exposure condition

Lamp	Typical Radiance	Exposure cycle
UVA-340	$1.55 \text{ W/m}^2/\text{nm}$	(1) 8 hours UV at $60 \pm 3 \text{ }^\circ\text{C}$ black panel temperature
		(2) 4 hours condensation at $50 \pm 3 \text{ }^\circ\text{C}$ black panel temperature.

6.5 Results

6.5.1 Effects of UV on the loss of solar reflectance

The solar reflectance of all the Coating 1 samples were measured before and after UV exposure. For each sample, five spots (centre and four corners) were measured and the mean was obtained. The results are summarised in **Figure 6-2**. Each black dot in the figure represents the measurement result of a sample, its x -axis reading is its solar reflectance before UV exposure, and its y -axis reading is its solar reflectance after UV exposure. The figure shows that all the Coating 1 samples had their solar reflectance after UV exposure lower than that before UV exposure.

Figure 6-2 Solar reflectance of Coating 1 samples before and after UV exposure

Paired t-test was conducted on “solar reflectance before UV exposure” and “solar reflectance after UV exposure”. The analysis results are summarised in **Table 6-3**. The P value (Sig., in

the last cell of the third table) is almost 0, much smaller than 0.05, indicating the difference between “solar reflectance before UV exposure” and “solar reflectance after UV exposure” is statistically significant. This suggests that UV does reduce the solar reflectance of cool coating.

The average solar reflectance loss of all the Coating 1 samples was 0.012. This was caused by the artificial UV ageing whose dosage is equivalent to that of 22 months’ natural exposure. Based on the natural ageing results of Coating 1 samples, as introduced in Chapter 4, the loss of solar reflectance after 22 months would be about 0.15. The comparison between these two figures (0.012 vs. 0.15) suggests that the solar reflectance loss caused by UV is even lower than 10% (just 8%) of the loss in the natural environment.

Table 6-3 Paired t-test for means of “solar reflectance before UV exposure” and “solar reflectance after UV exposure” of cool coating samples

(1) Paired Samples Statistics

	Mean	N	Std. Deviation	Std. Error Mean
Pair 1 solar reflectance before UV exposure	.6038095	21	.15255464	.03329015
solar reflectance after UV exposure	.5918667	21	.15018131	.03277225

(2) Paired Samples Correlations

	N	Correlation	Sig.
Pair 1 solar reflectance before UV exposure & solar reflectance after UV exposure	21	0.999	.000

(3) Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
1 Pairsolar reflectance before UV exposure - solar reflectance after UV exposure	.011943	.004358	.000951	.009959	.013927	12.558	20	.000

Solar reflectance of unsoiled Coating 1 samples (Group 1) were measured weekly. The results are presented in **Figure 6-3**.

Figure 6-3 Changes of solar reflectance of unsoiled Coating 1 samples, with error bars representing one standard deviation

It could be observed that the solar reflectance of the samples decreased linearly as the UV ageing weeks increased. The correlations are strong and negative (as analysed in Appendix E.1). An equation (**Eq. 6-1**) was proposed for the relationship between the solar reflectance and the UV ageing weeks.

$$y = -0.0027x + 1 \quad (\text{Eq. 6-1})$$

where y is the solar reflectance ratio, and x is the UV ageing weeks in QUV chamber. The coefficient of determination R^2 is 0.9260, indicating the UV ageing weeks explains 92.6% of the variation seen in solar reflectance.

6.5.2 Impacts of soiling agents on the loss of solar reflectance caused by UV

The solar reflectance loss of Group 1, 2, and 3 (as listed in **Table 6-1**) is presented separately in **Table 6-4**, **Table 6-5**, and **Figure 6-4**. Therefore it would be able to evaluate the whether the solar reflectance loss would be different when the samples are soiled by different soiling agents. It could be observed that the solar reflectance loss of the soiled samples (Group 2 and Group 3) are similar, but are both less than that of the unsoiled samples (Group 1). The solar reflectance loss (mean of the seven samples in each group) was 0.015, 0.010, and 0.010, respectively, for Group 1 (the unsoiled group), Group 2 (real dirt soiled group), and Group 3 (carbon micropowder soiled group).

Table 6-4 Solar reflectance loss (absolute value) of each sample

Group	Solar reflectance loss of each sample of the group						
Unsoiled	0.0150	0.0156	0.0146	0.0138	0.0122	0.0160	0.0200
RD soiled	0.0124	0.0066	0.0102	0.0096	0.0128	0.0024	0.0166
CM soiled	0.0064	0.0052	0.0086	0.0098	0.0132	0.0136	0.0162

Table 6-5 Solar reflectance loss (percentage) of each sample

Group	Solar reflectance loss of each sample						
Unsoiled	1.88%	1.96%	1.84%	1.72%	1.52%	2.00%	2.51%
RD soiled	2.58%	1.36%	2.13%	1.98%	2.65%	0.49%	3.47%
CM soiled	1.27%	1.02%	1.75%	1.99%	2.69%	2.82%	3.35%

Figure 6-4 Solar reflectance loss of soiled and unsoiled cool coating samples, with error bars representing one standard deviation

Similar to the statistical analysis in Section 6.5.1 , the relationship between the soiling agents and the solar reflectance loss were investigated. The results suggested statistically significant difference between the solar reflectance of Group 1 and Group 2, as well as between Group 1 and Group 3 (see Appendix E.2). But no statistically significant difference could be concluded between that of Group 2 and Group 3 (see Appendix E.3).

In other words, the soiling agents could reduce the solar reflectance loss caused by UV. One possible reason is that the soiling agents on the sample surface would absorb UV and mitigate the degradation. Another finding is that real dirt and carbon micropowder have similar effects on the reduction of solar reflectance loss caused by UV, which could be explained by the results in Section 5.2 , that they have highly similar absorbing effects of solar irradiation.

6.5.3 Effects of UV and soiling on thermal emittance

The thermal emittance of the cool coating samples were monitored before and after UV exposure. The results are summarised in

Table 6-6. It could be observed that the thermal emittance of all the three groups of samples changed little after the UV ageing. Actually, similar to the statistical analysis in Section 6.5.1 , the changes of the thermal emittance of the three groups were analysed by independent-sample t test (see Appendix E.4). The results suggested that there was no statistically significant change after the UV ageing, for each group.

Table 6-6 Thermal emittance of the Coating 1 samples before and after UV ageing

(1) Thermal emittance of the seven unsoiled samples (Group 1)							
Before UV ageing	0.88	0.86	0.85	0.86	0.85	0.84	0.85
After UV ageing	0.87	0.85	0.85	0.87	0.84	0.87	0.87
(2) Thermal emittance of the seven real dirt soiled samples (Group 2)							
Before UV ageing	0.87	0.87	0.84	0.88	0.85	0.85	0.88
After UV ageing	0.86	0.87	0.85	0.86	0.85	0.86	0.87
(3) Thermal emittance of the seven carbon micropowder soiled samples (Group 3)							
Before UV ageing	0.86	0.88	0.89	0.85	0.86	0.85	0.89
After UV ageing	0.87	0.88	0.86	0.86	0.86	0.86	0.89

The measurement results and statistical analysis indicated that no significant change of thermal emittance was caused by the UV ageing, no matter whether the cool coating were unsoiled or soiled by real dirt or carbon micropowder. Actually in the natural ageing experiment, as introduced in Chapter 4, no significant change of thermal emittance was

observed as well. And this concurred with the findings from some other studies which also noticed no significant change of thermal emittance during the natural ageing [73, 190].

6.5.4 Coating 1-2 and Coating 1-3 results of solar reflectance loss

As introduced in Section 6.3 , Coating 1-2 samples (Group 4) and Coating 1-3 coating samples (Group 5) were prepared for this UV ageing experiment. They also underwent 8 weeks' UV ageing in the QUV chamber, and their solar reflectance were measured. The results are presented in **Figure 6-5**. At the end of 8 weeks' UV ageing, the solar reflectance loss (mean of each group samples) was 0.015, 0.014, and 0.013, respectively, for unsoiled Coating 1 samples (Group 1), Coating 1-2 samples (Group 4), and Coating 1-3 samples (Group 5). It indicated that Coating 1-2 and Coating 1-3 had less solar reflectance than the Coating 1, probably due to the UV radiation protection from their added core-shell particles which moved to top of the coating surface. However, this difference is not much, and no statistical conclusions could be drawn due to the limitation of the small sample size of Coating 1-2 and Coating 1-3.

Figure 6-5 Solar reflectance loss of Coating 1, Coating 1-2, and Coating 1-3 samples after 8 weeks' UV ageing, with error bars representing one standard deviation

6.6 Summary

In this study, the accelerated UV ageing experiments were conducted to evaluate the effects of UV on the changes of radiative properties of cool coating. Besides unsoiled cool coating samples, samples soiled with different soiling agents were used in the experiments as well, to investigate how the surface soiling would affect the solar reflectance loss caused by UV.

The results show that UV does reduce the solar reflectance of cool coating, regardless of whether they are soiled or not. The solar reflectance generally decreased linearly with the increase of UV ageing time. By the end of eight weeks' artificial UV ageing, during which the UV dosage is equivalent to that of 22 months' natural exposure in tropical climate, the solar reflectance (mean of the 7 samples in each group) was 0.015, 0.010, and 0.010 respectively for the unsoiled Coating 1 samples, real dirt soiled Coating 1 samples, and carbon micropowder soiled Coating 1 samples. The average solar reflectance loss of all the samples was 0.012. This solar reflectance is statistically significant. However, their absolute value is not very high, and is only 8% of the solar reflectance loss of the samples aged for 22 months in natural environment. This indicates that UV is not the dominant factor among all the environmental factors that lead to the solar reflectance loss of cool coating.

The results also show that soiling on the surface of samples would mitigate the solar reflectance caused by UV degradation. A possible reason is that these soiling particles partially absorb the UV and protect the cool coating beneath them. Two soiling agents, real dirt and carbon micropowder, were used in the study. The experimental results suggest that their effects on mitigating the solar reflectance loss of cool coating were highly similar, with

no significant difference. This finding again highlights that carbon micropowder could be a potential alternative of real dirt in solar reflectance experimental studies.

Thermal emittance of the cool coating samples were measured before and after the UV ageing, and no significant change was observed, no matter whether the samples are unsoiled, real dirt soiled, or carbon micropowder soiled.

The new prototypes of cool coating, Coating 1-2 and Coating 1-3, showed less loss of solar reflectance after UV ageing than Coating 1. But this difference is no more than 0.002, and no statistical conclusions were obtained.

Chapter 7. Studies on the Change of Solar Reflectance during the Ageing Process

7.1 Introduction

This thesis by far has investigated the effects of ageing process and several environmental factors on the changes of solar reflectance and thermal emittance of cool coatings in the context of Singapore. Natural ageing experiments and laboratory-based experiments have been conducted. Results have been obtained from observation and measurement. In this chapter, models would be built based on the results, to describe how the radiative properties of cool coatings would change during ageing process in local climate. As thermal emittance changes little during the ageing process, this chapter would mainly focus on solar reflectance.

A generalised heat transfer model for cool coated roof was proposed by Zingre et al. [25] based on the spectral approximation method. The model was verified against the Conduction Transfer Function (CTF) method and experimental results. It is able to predict surface temperatures of the building envelope, indoor air temperatures, and heat transfer. This model is easy to use and can handle transient indoor and outdoor boundary conditions.

Like other Cool Roof Heat Transfer (CRHT) models, this model treats the solar reflectance of cool coating as constant. However, it has been demonstrated in this thesis that the solar reflectance would decrease as the ageing time increase. After embedding this change of solar reflectance into existing CRHT models, more accurate predictions of the thermal performance of cool coating could be achieved. In this chapter a new CRHT model would be proposed based on the existing one. Long-term thermal performance of cool coating would be predicted by the new model, and compared with the results from existing model to highlight the improvement.

7.2 A model for solar reflectance change during ageing

Cool coating has high solar reflectance when it is fresh. But during the ageing process, soiling and cleaning could significantly change the solar reflectance, as indicated by the study results in Chapter 5. UV is another factor that reduce the solar reflectance, though it accounts for only a small part of the total solar reflectance loss, as indicated by the results in Chapter 6. The solar reflectance of aged cool coating is mainly determined by these three parameters, as illustrated by (Eq. 7-1).

$$\rho_{aged} = \rho_{initial} + \Delta\rho_{soiling\ and\ cleaning} + \Delta\rho_{UV} \quad (\text{Eq. 7-1})$$

where ρ_{aged} is the solar reflectance after ageing, $\rho_{initial}$ is the initial reflectance before ageing, $\Delta\rho_{soiling\ and\ cleaning}$ is the solar reflectance change caused by soiling and ageing, and $\Delta\rho_{UV}$ is the solar reflectance change caused by UV.

Soiling includes dry deposition and wet deposition of airborne pollutant particles originating from pollution sources in the local environment. The particles accumulation would increase with time. From the long-term natural ageing experiment, it was observed that the solar reflectance decreased approximately linearly with the ageing time. In the wet deposition experiment, it was also observed that the solar reflectance decreased linearly with the surface accumulation of real dirt. Therefore, it could be assumed that the accumulation rate of the soiling particles are constant, when the environment and pollutant sources are relatively constant during the long-term ageing. And the accumulation would lead to decrease of solar reflectance that is linear with ageing time.

$$C_{dry\ deposition} = V_{dry\ deposition} \times t \quad (\text{Eq. 7-2})$$

$$C_{wet\ deposition} = V_{wet\ deposition} \times t \quad (\text{Eq. 7-3})$$

where $C_{dry\ deposition}$ (g/m^2) and $C_{wet\ deposition}$ (g/m^2) are the surface concentrations of dry deposition and wet deposited soiling particles respectively on cool coating, $V_{dry\ deposition}$ ($\text{g/m}^2/\text{s}$) and $V_{wet\ deposition}$ ($\text{g/m}^2/\text{s}$) are the accumulation rates of the dry deposition and wet deposition particles respectively, and t (s) is time.

Then the deposited particles would undergo two cleaning mechanisms, wind blowing and rain washing, in the natural environment. Study results in Section 5.5 and Section 5.6 showed that rain washing is more efficient than wind blowing in removing the soiling particles and restoring the solar reflectance. Washing could furtherly restore reflectance from blown samples, while blowing could not restore any reflectance from the washed samples. In other words, the cleaning effects are finally determined by rain washing. And by then, all the remaining particles after washing would become wet deposited, due to the aqueous condition brought by the washing. This phenomenon is reflected in (Eq. 7-4).

$$\begin{aligned} C_{wet\ deposition}^{total} &= C_{dry\ deposition} \times \eta + C_{wet\ deposition} \\ &= (V_{dry\ deposition} \times \eta + V_{wet\ deposition}) \times t \end{aligned} \quad (\text{Eq. 7-4})$$

where $C_{wet\ deposition}^{total}$ (g/m^2) is the surface concentration of total wet deposited particles, η is the converting efficiency indicating how much of the dry deposited particles would be changed to wet deposited when exposed to aqueous condition.

The cleaning could not restore all the lost reflectance. The restoration percentage would come to its maximum after a period of cleaning. In the rain washing experiment, as introduced in Section 5.6 , no more solar reflectance was restored for Coating 1 samples after 150 min of washing, which is equivalent to a month's precipitation in Singapore. In the long-term natural ageing, it could be assumed that the restoration percentage is always at the maximum level. Study results in section 5.4 show a linear relationship between the solar reflectance loss and the surface concentration of the soiling particles. Therefore, (Eq. 7-5) and (Eq. 7-6) could be obtained.

$$\Delta\rho_{soiling} = C_{wet\ deposition}^{total} \times k_{concentration}^{wet} \quad (\text{Eq. 7-5})$$

$$\Delta\rho_{soiling\ and\ cleaning} = \Delta\rho_{soiling} \times (1 - f_{rain}^{for\ wet}) \quad (\text{Eq. 7-6})$$

where $\Delta\rho_{soiling}$ is the solar reflectance change caused by soiling, $C_{wet\ deposition}^{total}$ (g/m²) is the surface concentration of total wet deposited particles, $k_{concentration}^{wet}$ (m²/g) is the coefficient linking the surface concentration of wet deposited particles and the reflectance change, $\Delta\rho_{soiling\ and\ cleaning}$ is the solar reflectance change after soiling and cleaning, and $f_{cleaning}^{for\ wet}$ is the solar restoration percent by rain washing on wet deposited cool coatings.

Solar reflectance loss caused by UV, as indicated by the results in Section 6.5.1 , increases linearly with the UV ageing time. Hence (Eq. 7-7) could be proposed.

$$\Delta\rho_{UV} = k_{UV} \times t \quad (\text{Eq. 7-7})$$

where k_{UV} (s⁻¹) is the coefficient linking the UV ageing time and the reflectance change.

Summarising (Eq. 7-1), (Eq. 7-2), (Eq. 7-3), (Eq. 7-4), (Eq. 7-5), (Eq. 7-6), and (Eq. 7-7) results in (Eq. 7-8), which then could be converted to (Eq. 7-9) after introducing two parameters.

$$\begin{aligned} \rho_{aged} = & \rho_{initial} \\ & + (V_{dry\ deposition} \times \eta + V_{wet\ deposition}) \times t \\ & \times k_{concentration}^{wet} \times (1 - f_{rain}^{for\ wet}) + k_{UV} \times t \end{aligned} \quad (\text{Eq. 7-8})$$

$$\Delta\rho = \rho_{aged} - \rho_{initial} = (V_{dry+wet}^{equivalent} \times k_{concentration}^{wet} \times F_{rain}^{for\ wet} + k_{UV}) \times t \quad (\text{Eq. 7-9})$$

where $V_{dry+wet}^{equivalent} = V_{dry\ deposition} \times \eta + V_{wet\ deposition}$ (g/m²/s) is the equivalent accumulation rate for the combination of the dry deposition and wet deposition after exposing to aqueous condition, and $F_{rain}^{for\ wet} = 1 - f_{rain}^{for\ wet}$ is the percent of the unrestored solar reflectance after rain washing on wet deposited cool coatings.

Based on (Eq. 7-9), it could be observed that the change of solar reflectance is determined by several variables. $k_{concentration}^{wet}$ reflects the absorption efficiency of the wet deposited particles. $V_{dry\ deposition}$ and $V_{wet\ deposition}$ are mainly determined by the pollutant source, local weather, and the dirt pick-up ability of cool coating. η and $f_{rain}^{for\ wet}$ mainly reflect the self-cleaning ability of cool coating. k_{UV} indicates the coating's resistance to UV. And the last variable t means the change of solar reflectance is ageing-time dependent.

If the cool coating properties, pollutant sources, and local climate are consistent (e.g., a certain cool coating used under a certain climate), the above variables (except t) could be assumed as constant. Then the change of solar reflectance would become linear with the ageing time.

Taking Coating 1 as one example, its surface properties is consistent and can be treated as constants. The climate in Singapore is also stable and consistent. In most months of the year, the wind speed and precipitation are abundant. When there is no haze or building construction project near the test site, the airborne pollutant concentration remains low. This suggests the solar reflectance loss of Coating 1 is probably linear with ageing time.

Based on the measurement results and mathematical models built in this thesis, the value of some parameters are obtained and listed in **Table 7-1**.

Table 7-1 Values of some parameters for Coating 1 during ageing in the climate of Singapore

Parameter	Value
$\rho_{initial}$	0.80
η	40%
$k_{concentration}^{wet}$	-1.86 cm ² /mg
$f_{rain}^{for wet}$	6%
k_{UV}	-7×10^{-4} /month

Substituting these values into (Eq. 7-9), it becomes (Eq. 7-10).

$$\Delta\rho = -(1.75 V_{dry+wet}^{equivalent} cm^2/mg + 7 \times 10^{-4}/month) \times t \quad (\text{Eq. 7-10})$$

where $V_{dry+wet}^{equivalent} = 0.4V_{dry deposition} + V_{wet deposition}$ (unit: mg/cm²/month).

In the three-year natural ageing experiment, Coating 1 and the other four cool coatings were tested. The total sola reflectance loss after three years was 0.25 for Coating 1. The total loss of the other four coatings was 0.19, 0.22, 0.27, and 0.28, respectively. Based on the results,

the ordinary solar reflectance loss after three years in ordinary conditions of Singapore would be about 0.19-0.28.

For Coating 1, as the solar reflectance loss is assumed to be linear with the ageing time, it could be calculated that the average solar reflectance is 0.007/month. Compare this to (Eq. 7-10), it could get $V_{dry+wet}^{equivalent} = 0.45 \text{ mg/cm}^2/\text{month}$. The meaning of this figure is explained below:

During natural ageing, some soiling particles accumulate on cool coating by dry deposition and some by wet deposition. Usually the wet deposited particles adhere firmly to the coating and could not be removed by wind, while the dry deposited particles would be partially removed by wind. $V_{dry+wet}^{equivalent}$ is the accumulation rate of the wet deposited particles plus the dry deposited particles that withstand wind blowing. For Coating 1, averagely this kind of accumulation rate is 0.45 mg/cm^2 per month.

7.3 Existing CRHT model and improved CRHT model

As introduced, the CRHT model was developed and the heat transfer equation through roof is shown in (Eq. 7-11). The problem formulation and boundary conditions are presented in Section 2.2.3 ,

$$q = U(1 + Bi) \left\{ T_{sol-air}^{simulated} - \left[T_i \left(1 - \frac{U}{h_i} \right) + \frac{U}{h_i} T_{sol-air}^{Mean} \right] \right\} \quad (\text{Eq. 7-11})$$

where $Bi = h_i L/k$ is the Biot number, $T_{sol-air}^{Mean}$ is the mean of $T_{sol-air}$, $T_{sol-air}^{simulated}$ is a function of outdoor conditions (solar irradiation, outdoor air temperature, and wind speed). It could be calculated based on (Eq. 7-12).

$$T_{sol-air} = T_{air} + (\alpha I / h_{outside}) \quad (\text{Eq. 7-12})$$

where $h_{outside}$ (W/m²·K) is the outside total heat transfer coefficient between building envelope and ambient air, it contains the emissive radiation to the sky, and T_{air} (K) is the outdoor ambient air temperature.

This CRHT model was validated against experiment results, as introduced in Reference [25]. The experiment was carried out on the top storey of a high-rise residential building in Singapore in February 2012. The roof of the building is a 100 mm thick concrete slab plus 10 mm thick plaster. Two identical, side-by-side unoccupied apartments of the top storey were selected in the experiment. One coated with a 5 mm thick cool coating, while the other uncoated. Solar radiation, roof and ceiling surface temperatures, indoor and outdoor air temperatures, and some other parameters were monitored during the experiment. The CRHT model predications were compared with the experiment results, and acceptable matching could be observed. The difference between CRHT model predications of roof surface temperatures were within $\pm 1.1^\circ\text{C}$ from those of the experiments. The difference of ceiling surface temperature was within $\pm 1.5^\circ\text{C}$.

This CRHT model was demonstrated to be valid for the short term heat transfer of cool coating. However, from (Eq. 7-11) and (Eq. 7-12) it could be observed that the heat flux q depends on $T_{sol-air}$, while $T_{sol-air}$ depends on $\alpha = 1 - \rho$. As the solar reflectance ρ changes during ageing process, the heat transfer through would be different, which is not reflected in current CRHT model.

Based on the findings in this thesis, it could be assumed that the solar reflectance, when exposed to a consistent climate and pollutant sources, decreases linear with the ageing time, as shown in (Eq. 7-13). Then (Eq. 7-12) could be improved by embedding the changes of solar reflectance, as shown in (Eq. 7-14).

$$\rho_{aged} = \rho_{initial} - k_{solar\ reflectance} \times t \quad (\text{Eq. 7-13})$$

$$T_{sol-air} = T_a + \left((\rho_{initial} - k_{solar\ reflectance} \times t) I / h_o \right) \quad (\text{Eq. 7-14})$$

For Coating 1 that used in this thesis, $\rho_{initial}$ is 0.80, $k_{solar\ reflectance}$ is 0.007/month. For some other cool coating tested in Section 4.6, $k_{solar\ reflectance}$ is 0.006-0.008/month. Based on the several months' natural ageing experiment as introduced in Appendix D, the rate of solar reflectance loss of Coating 1-2 is approximately 1/3 or that of Coating 1, probably due to the improved surface properties. In this thesis it would be assumed that the reflectance loss rate of Coating 1-2 would be 0.0023/month (1/3 of that of Coating 1), though this figure needs to be validated by further long-term experiment.

7.4 Heat transfer prediction based on existing and improved CRHT model

Based on this model, the heat gain through the roof could be calculated. The building for the study of energy saving performance of cool coating, as introduced in Chapter 3, was used again as the test building for the heat transfer calculation based on the existing CRHT model. Some information about the field experiment is presented in Section 3.3. Below are more information for the calculation from mathematical model, as shown in **Table 7-2**. The information are from the manufacturer and the material dataset.

Table 7-2 Thermal and physical properties of the test building

Building material	Thermal conductivity (W/m·K)	Thickness (mm)	Conduction resistance (m²·K/W)	Density (kg/m³)	Specific heat capacity (J/kg·K)
Air	0.0262	-	-	1.23	1008
Concrete	0.65	1100	0.15	2450	840
Cool coating (Coating 1)	0.05	0.5	0.01	1053	0 (assumed)
Glazing	0.7	3.5	0.01	-	-
Plastered	1.10	125	0.12	800	920
Plaster	0.25	10	0.04	850	1000

The cool coating used in this prediction is Coating 1. The thermal resistance of the roof (R value) could be calculated according, which is $0.48 \text{ m}^2 \cdot \text{K/W}$. Based on the existing model (**Eq. 7-11**), the annual heat transfer could be calculated. Not only the inward heat transfer (heat gain) was calculated, but also the outward heat transfer (heat loss, which mainly occurs when the indoor is warmer than the outdoor, e.g., during night) and net heat gain (by subtracting heat loss from heat gain). The results are shown in **Table 7-3**. The preset temperature for the air-conditioner inside the test building was $24 \text{ }^\circ\text{C}$. Typical Meteorological Year (TMY) weather data file (including weather data on an hourly basis) for the Changi airport weather station in Singapore were used for the calculation [191].

Table 7-3 Annual heat gain, heat loss, and net heat gain of roofs with different thermal resistance, based on the existing CRHT model

Thermal resistance of roof ($\text{m}^2 \cdot \text{K/W}$)	Annual Heat gain (kWh/m^2)	Annual Heat loss (kWh/m^2)	Annual Net heat gain (kWh/m^2)	Total net heat gain for 3 years (kWh/m^2)
0.48 (test building)	90.6	49.3	41.3	123.8

It could be observed that based on the existing CRHT model, for the test building on NTU campus in Singapore, the annual heat gain would be 90.6 kWh/m^2 , the annual heat loss would be 49.3 kWh/m^2 , then the annual net heat gain would be 41.3 kWh/m^2 . As the solar reflectance was taken as constant in the model, the heat gain for every year would be the same, given the same typical weather, the net heat gain for three years would be 123.9 kWh/m^2 .

After taking the changes of solar reflectance of solar reflectance into consideration, the long term heat gain predictions became different, based on the improved CRHT model, as shown in **Table 7-4**.

Table 7-4 Heat gain, heat loss, and net heat gain of three years of roofs with different thermal resistance, based on the improved CRHT model

Thermal resistance of roof ($\text{m}^2 \cdot \text{K/W}$)	1 st year net heat gain (kWh/m^2)	2 nd year net heat loss (kWh/m^2)	3 rd year net heat gain (kWh/m^2)	Total net heat gain for 3 years (kWh/m^2)
0.48 (test building)	51.2	73.7	96.1	221.0

It can be seen that the heat gains calculated by the improved CRHT model are higher than those obtained based on the existing CRHT model. For the test building (with thermal resistance of $0.48 \text{ m}^2 \cdot \text{K/W}$), the net heat gain for the first year increased by 24% from 41.3 kWh/m^2 to 51.2 kWh/m^2 , for the second year increased by 78% to 73.7 kWh/m^2 , for the third year increased by 133% to 96.1 kWh/m^2 . And the total net heat gain for three years was increased by 78% from 123.8 kWh/m^2 to 221.0 kWh/m^2 .

The heat gain prediction were then run for Coating 1-2 coating and uncoated roof. The net heat gains of each month in three years of the three kinds of roofs (i.e., uncoated, coated with Coating 1, and coated with Coating 1-2) are shown in **Figure 7-1**, assuming the cool coating was applied in January of the first year.

7.5 Summary

Mathematical models are proposed in this chapter for solar reflectance loss of cool coating during ageing. Study results and analysis suggest that the solar reflectance is linear with the ageing time, for a cool coating exposed in an environment with consistent weather condition and pollutant source. Thermal emittance of cool coating, however, changes little during the ageing process. The thermal emittance could be taken as constant.

Based on the 3-year natural ageing experiment, the average solar reflectance loss of Coating 1 was 0.007 per month. This figure becomes 0.006-0.008 per month for the other four cool coating tested in the natural ageing experiment. However, this figure could be different when the cool coatings have improve surface omiphobic properties, or when exposed to pollutant sources more intense than usual. Based on a several-month ageing experiment, the average solar reflectance loss of Coating 1-2 was approximately 1/3 of that of Coating 1. Further study is needed to investigate whether this still holds in the long-term ageing.

An improved model was proposed by incorporating solar reflectance changes into the existing CRHT model, based on the study results in this thesis. The improved model incorporates the change of solar reflectance of cool coating during ageing, and therefore could produce more accurate prediction. It was used to simulate the heat gain of a test building in Singapore, and to compare the results with those obtained from the existing model. Differences could be observed between the results from the two models, and the difference increases as the ageing time increases. For a three-year simulation of the test building coated by Coating 1, the total net heat gain was 123.8 kWh/m² based on the existing model, while it became 221.0 kWh/m² based on the improved model. This model is generalised, and can be applied to all the climates, not only the climate of Singapore. But the parameters for the local environment and cool coating needs to be obtained before the calculation.

Chapter 8. Conclusions and Recommendations

8.1 Conclusions

A field experiment in Singapore demonstrated the cooling performance and energy saving benefits of cool coating, with fills the research gap with experimental monitoring data.

The natural ageing experiments found that for Coating 1, its solar reflectance would decrease by 0.25 after three years' ageing, from 0.80 to 0.55. For other four coatings, the reflectance loss was 0.19-0.28 after three years. The reflectance loss decreased approximately linearly with the increase of ageing time. This finding is not like that concluded by some overseas studies that most solar reflectance loss happens in the first year. Two coatings (Coating 1-2 and Coating 1-3) were found to have less loss of solar reflectance, compared to Coating 1, probably due to their improved surface properties such as roughness and omniphobicity.

Carbon micropowder was found to have an effect of reducing the spectral reflectance that is highly similar to real dirt. It could be a substitute for real dirt in experiments related with soiling. What's more, "real dirt" is localised, but carbon micropowder is a standard product and thus could reproduce experiments in different countries.

Soiling was found to be efficient in decreasing the solar reflectance of cool coating. The decrease is linear with the surface concentration of the soiling agents. For dry deposition, it requires 40 mg of real dirt particles to decrease the solar reflectance from 0.80 to 0.50. For wet deposition, it requires about 1.6 g/m² of real dirt or 32 mg/m² of carbon micropowder to decrease the solar reflectance from 0.80 to 0.50. In this respect, wet deposition is more efficient than dry deposition in reducing the solar reflectance of cool coatings. Wind blowing could remove part of the dry deposited soiling particles on cool coating samples, and restore part of the lost solar reflectance. But rain washing was found to be more efficient in restoring the lost solar reflectance.

Accelerated UV ageing experiment results indicated that UV indeed decreases the solar reflectance of cool coatings. But this decrease accounts for only a small part of the whole decrease in ageing process. The decrease was linear with the UV ageing time. Soiling particles on surface of cool coating were found to be able to mitigate the reflectance loss caused by UV. One reasonable explanation is that the soiling particles absorb UV, and reduce the UV that reaches the coating beneath.

Mathematical models were developed for the change of solar reflectance of cool coating during ageing process in the climate of Singapore. The solar reflectance loss is predicted to be linear with the ageing time. The models for the changes of solar reflectance were then incorporated into an existing cool roof heat transfer model, which had been validated by experiment data. Then the improved model would have higher accuracy for predicting the heat transfer for cool coating during ageing process. It shows that for the net heat gain of a test building for three years, the difference between the results from the two models could be up to 78%. This model is generalised, and can be applied to all the climates, not only the climate of Singapore. But the parameters for the local environment and cool coating needs to be obtained before the calculation.

8.2 Recommendations for future work

Despite the work accomplished as above, more research efforts are still needed to better understand the effects of ageing on the performance of cool coatings in the local climate. Below some topics are recommended for future work.

8.2.1 Soiling accumulation experiment

One work that remains to be done is the investigation of soiling accumulation rate on the roof. Though some studies have been conducted overseas, Singapore has a different climate and the accumulation rate would be different.

The dirt accumulation rate is affected by both the pollutant source and the surface properties (e.g., dirt pick-up ability and self-cleaning ability). Field experiments are needed to record the accumulation rates on different surfaces, at different locations.

8.2.2 Comparison between cool coatings and other passive cooling techniques

Some studies compare the thermal performance of cool coating and other passive cooling techniques, e.g., thermal insulation and green roof. But the solar reflectance of cool coating is always taken as constant during the comparisons, which made the results might be inaccurate especially for long term simulation. The new model developed in this these could be applied for this kind of comparison.

8.2.3 Development of new additives for cool coating

Two new models of cool coating, Coating 1-2 and Coating 1-3, were tested in this thesis. They exhibit high initial solar reflectance and slow decrease rate of solar reflectance, which render these new coatings as beneficial for energy saving. The improved surface properties are believed to be the reasons. This was achieved by the addition of extra core-shell nanoparticles. In future, new kinds of additives could be developed, and the thermal performance of cool coatings could be further improved.

References

1. S. Bilgen. (2014). Structure and environmental impact of global energy consumption. *Renewable and Sustainable Energy Reviews*, 38, 890-902. doi:<http://dx.doi.org/10.1016/j.rser.2014.07.004>
2. Hooi Hooi Lean and Russell Smyth. (2010). CO₂ emissions, electricity consumption and output in ASEAN. *Applied Energy*, 87(6), 1858-1864. doi:<http://dx.doi.org/10.1016/j.apenergy.2010.02.003>
3. Gert Spaargaren and Bas Van Vliet. (2000). Lifestyles, consumption and the environment: The ecological modernization of domestic consumption. *Environmental Politics*, 9(1), 50-76. doi:10.1080/09644010008414512
4. Zhongren Zhou, Wenliang Wu, Xiaohua Wang, Qun Chen, and Ou Wang. (2009). Analysis of changes in the structure of rural household energy consumption in northern China: A case study. *Renewable and Sustainable Energy Reviews*, 13(1), 187-193. doi:<http://dx.doi.org/10.1016/j.rser.2007.05.006>
5. Steve Sorrell. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, 47, 74-82. doi:<http://dx.doi.org/10.1016/j.rser.2015.03.002>
6. US EIA. (2013). International energy outlook 2013. *US Energy Information Administration (EIA)*.
7. US EIA. (2004). International energy outlook 2004. *US Energy Information Administration (EIA)*.
8. Luis Pérez-Lombard, José Ortiz, and Christine Pout. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394-398. doi:<http://dx.doi.org/10.1016/j.enbuild.2007.03.007>
9. Mark Z Jacobson. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, 2(2), 148-173.
10. Bimal K Bose. (2010). Global warming: Energy, environmental pollution, and the impact of power electronics. *IEEE Industrial Electronics Magazine*, 4(1), 6-17.
11. A. Synnefa, M. Santamouris, and H. Akbari. (2007). Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings*, 39(11), 1167-1174. doi:10.1016/j.enbuild.2007.01.004
12. Hai-xiang Zhao and Frédéric Magoulès. (2012). A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews*, 16(6), 3586-3592. doi:<http://dx.doi.org/10.1016/j.rser.2012.02.049>
13. Luis Pérez-Lombard, José Ortiz, Juan F. Coronel, and Ismael R. Maestre. (2011). A review of HVAC systems requirements in building energy regulations. *Energy and Buildings*, 43(2-3), 255-268. doi:10.1016/j.enbuild.2010.10.025
14. D. J. Sailor and A. A. Pavlova. (2003). Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. *Energy*, 28(9), 941-951. doi:[http://dx.doi.org/10.1016/S0360-5442\(03\)00033-1](http://dx.doi.org/10.1016/S0360-5442(03)00033-1)
15. M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, and D. N. Assimakopoulos. (2001). On the impact of urban climate on the energy consumption of buildings. *Solar Energy*, 70(3), 201-216. doi:[http://dx.doi.org/10.1016/S0038-092X\(00\)00095-5](http://dx.doi.org/10.1016/S0038-092X(00)00095-5)
16. R. Giridharan, S. Ganesan, and S. S. Y. Lau. (2004). Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. *Energy and Buildings*, 36(6), 525-534. doi:<http://dx.doi.org/10.1016/j.enbuild.2003.12.016>

17. K. J. Chua, S. K. Chou, W. M. Yang, and J. Yan. (2013). Achieving better energy-efficient air conditioning – A review of technologies and strategies. *Applied Energy*, 104, 87-104. doi:<https://doi.org/10.1016/j.apenergy.2012.10.037>
18. National Climate Change Secretariat Building and Construction Authority. (2014). Building Energy Efficiency R&D Roadmap.
19. JC Lam and ALS Chan. *Energy audits and surveys of air-conditioned buildings*. in *Proceeding of Australian and New Zealand Architectural Science Association Conference*. 1995.
20. Joseph C Lam. (1998). Climatic and economic influences on residential electricity consumption. *Energy Conversion and Management*, 39(7), 623-629.
21. K. J. Chua and S. K. Chou. (2010). Energy performance of residential buildings in Singapore. *Energy*, 35(2), 667-678. doi:<http://dx.doi.org/10.1016/j.energy.2009.10.039>
22. C. Romeo and M. Zinzi. (2013). Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy and Buildings*, 67, 647-657.
23. A. Synnefa, M. Santamouris, and K. Apostolakis. (2007). On the development, optical properties and thermal performance of cool colored coatings for the urban environment. *Solar Energy*, 81(4), 488-497. doi:10.1016/j.solener.2006.08.005
24. Michael F Modest. Radiative heat transfer. 2003. *Amsterdam: Academic*.
25. Kishor T. Zingre, Man Pun Wan, Shanshan Tong, Hua Li, Victor W. C. Chang, Swee Khian Wong, Winston Boo Thian Toh, and Irene Yen Leng Lee. (2015). Modeling of cool roof heat transfer in tropical climate. *Renewable Energy*, 75, 210-223. doi:<http://dx.doi.org/10.1016/j.renene.2014.09.045>
26. A. Synnefa, M. Santamouris, and I. Livada. (2006). A study of the thermal performance of reflective coatings for the urban environment. *Solar Energy*, 80(8), 968-981. doi:<http://dx.doi.org/10.1016/j.solener.2005.08.005>
27. A. Synnefa and M. Santamouris. (2012). Advances on technical, policy and market aspects of cool roof technology in Europe: The Cool Roofs project. *Energy and Buildings*, 55, 35-41. doi:<http://dx.doi.org/10.1016/j.enbuild.2011.11.051>
28. M. Santamouris, K. Pavlou, A. Synnefa, K. Niachou, and D. Kolokotsa. (2007). Recent progress on passive cooling techniques: Advanced technological developments to improve survivability levels in low-income households. *Energy and Buildings*, 39(7), 859-866. doi:<http://dx.doi.org/10.1016/j.enbuild.2007.02.008>
29. Hashem Akbari. (2011). Using cool roofs to reduce energy use, greenhouse gas emissions, and urban heat-island effects: Findings from an India experiment. *Lawrence Berkeley National Laboratory*.
30. Kai L. Uemoto, Neide M. N. Sato, and Vanderley M. John. (2010). Estimating thermal performance of cool colored paints. *Energy and Buildings*, 42(1), 17-22. doi:10.1016/j.enbuild.2009.07.026
31. S Konopacki, L Gartland, H Akbari, and L Rainer. (1998). Demonstration of energy savings of cool roofs: Lawrence Berkeley National Lab., Environmental Energy Technologies Div., CA (United States).
32. Hashem Akbari, Sarah Bretz, Dan M. Kurn, and James Hanford. (1997). Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings*, 25(2), 117-226.
33. Ronnen Levinson, Hashem Akbari, Steve Konopacki, and Sarah Bretz. (2005). Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. *Energy Policy*, 33(2), 151-170. doi:10.1016/s0301-4215(03)00206-4

34. Parker, D., Sherwin, J., Sonne, and J. (1998). Measured performance of a reflective roofing system in a Florida commercial building. *AASHRAE Technical Data Bulletin*, 14(2), 7-12.
35. Michelle van Tijen and Rebecca Cohen. (2008). Features and Benefits of Cool Roofs: The Cool Roof Rating Council Program. *Journal of Green Building*, 3(2), 13-19. doi:doi:10.3992/jgb.3.2.13
36. Hashem Akbari and Ronnen Levinson. (2008). Evolution of cool-roof standards in the US. *Advances in building energy research*, 2(1), 1-32.
37. Rich Brown, Carrie Webber, and Jonathan G Koomey. (2002). Status and future directions of the ENERGY STAR program. *Energy*, 27(5), 505-520.
38. Paul Berdahl, Hashem Akbari, Ronnen Levinson, and William A. Miller. (2008). Weathering of roofing materials – An overview. *Construction and Building Materials*, 22(4), 423-433.
39. M Santamouris, A Synnefa, D Kolokotsa, V Dimitriou, and K Apostolakis. (2008). Passive cooling of the built environment–use of innovative reflective materials to fight heat islands and decrease cooling needs. *International Journal of Low-Carbon Technologies*, 3(2), 71-82.
40. Sarah E. Bretz and Hashem Akbari. (1997). Long-term performance of high-albedo roof coatings. *Energy and Buildings*, 25(2), 159-167. doi:[http://dx.doi.org/10.1016/S0378-7788\(96\)01005-5](http://dx.doi.org/10.1016/S0378-7788(96)01005-5)
41. H. Akbari, A. Berhe, Levinson Ronnen, S. Graveline, K. Foley, A. H. Delgado, and Ralph M. Paroli. (2005). Aging and weathering of cool roofing membranes. Lawrence Berkeley National Laboratory.
42. California Energy Commission. (2008). Building Energy Efficiency Standards for Residential and Nonresidential Buildings. *Title 24, Part 6*.
43. Ben Richard Hughes, Hassam Nasarullah Chaudhry, and Saud Abdul Ghani. (2011). A review of sustainable cooling technologies in buildings. *Renewable and Sustainable Energy Reviews*, 15(6), 3112-3120. doi:<http://dx.doi.org/10.1016/j.rser.2011.03.032>
44. Suresh B. Sadineni, Srikanth Madala, and Robert F. Boehm. (2011). Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews*, 15(8), 3617-3631. doi:<http://dx.doi.org/10.1016/j.rser.2011.07.014>
45. ASHRAE Handbook. (2001). Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta*, 111.
46. Dr Mohammad S. Al-Homoud. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, 40(3), 353-366. doi:<http://dx.doi.org/10.1016/j.buildenv.2004.05.013>
47. Mehmet Azmi Aktacir, Orhan Büyükalaca, and Tuncay Yılmaz. (2010). A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions. *Applied Energy*, 87(2), 599-607. doi:<http://dx.doi.org/10.1016/j.apenergy.2009.05.008>
48. Mousa S. Mohsen and Bilal A. Akash. (2001). Some prospects of energy savings in buildings. *Energy Conversion and Management*, 42(11), 1307-1315. doi:[http://dx.doi.org/10.1016/S0196-8904\(00\)00140-0](http://dx.doi.org/10.1016/S0196-8904(00)00140-0)
49. Fabrizio Ascione, Nicola Bianco, Filippo de' Rossi, Gianluca Turni, and Giuseppe Peter Vanoli. (2013). Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? *Applied Energy*, 104, 845-859. doi:<http://dx.doi.org/10.1016/j.apenergy.2012.11.068>
50. Jeroen Mentens, Dirk Raes, and Martin Hermy. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and*

51. Issa Jaffal, Salah-Eddine Ouldboukhitine, and Rafik Belarbi. (2012). A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy*, 43, 157-164. doi:<http://dx.doi.org/10.1016/j.renene.2011.12.004>
52. M. Zinzi and S. Agnoli. (2012). Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. *Energy and Buildings*, 55, 66-76. doi:<http://dx.doi.org/10.1016/j.enbuild.2011.09.024>
53. Salah-Eddine Ouldboukhitine, Rafik Belarbi, Issa Jaffal, and Abdelkrim Trabelsi. (2011). Assessment of green roof thermal behavior: A coupled heat and mass transfer model. *Building and Environment*, 46(12), 2624-2631. doi:<http://dx.doi.org/10.1016/j.buildenv.2011.06.021>
54. Karen Liu and John Minor. (2005). Performance evaluation of an extensive green roof. *Presentation at Green Rooftops for Sustainable Communities, Washington DC*, 1-11.
55. S. Parizotto and R. Lamberts. (2011). Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. *Energy and Buildings*, 43(7), 1712-1722. doi:<http://dx.doi.org/10.1016/j.enbuild.2011.03.014>
56. Paulo Cesar Tabares-Velasco and Jelena Srebric. (2009). The role of plants in the reduction of heat flux through green roofs: laboratory experiments. *ASHRAE transactions*, 115(2), 793-802.
57. Stuart Gaffin, Cynthia Rosenzweig, Lily Parshall, David Beattie, Robert Berghage, Greg O'Keeffe, and Dan Braman. (2010). Energy balance modeling applied to a comparison of white and green roof cooling efficiency. *Green Roofs in the New York Metropolitan Region Research Report*, 7.
58. Wong Nyuk Hien, Tan Puay Yok, and Chen Yu. (2007). Study of thermal performance of extensive rooftop greenery systems in the tropical climate. *Building and Environment*, 42(1), 25-54. doi:<http://dx.doi.org/10.1016/j.buildenv.2005.07.030>
59. M Santamouris. (2014). Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, 103, 682-703.
60. R. Kannan, K. C. Leong, R. Osman, and H. K. Ho. (2007). Life cycle energy, emissions and cost inventory of power generation technologies in Singapore. *Renewable and Sustainable Energy Reviews*, 11(4), 702-715. doi:10.1016/j.rser.2005.05.004
61. N. H. Wong and S. Li. (2007). A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore. *Building and Environment*, 42(3), 1395-1405. doi:10.1016/j.buildenv.2005.11.032
62. N. H. Wong, H. Feriadi, P. Y. Lim, K. W. Tham, C. Sekhar, and K. W. Cheong. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment*, 37(12), 1267-1277. doi:[http://dx.doi.org/10.1016/S0360-1323\(01\)00103-2](http://dx.doi.org/10.1016/S0360-1323(01)00103-2)
63. GAISMA. (2013). Singapore - solar energy and surface meteorology. Retrieved from <http://www.gaisma.com/en/location/singapore.html>
64. Siew Eang Lee and Priyadarsini Rajagopalan. (2008). Building energy efficiency labeling programme in Singapore. *Energy Policy*, 36(10), 3982-3992. doi:10.1016/j.enpol.2008.07.014
65. Department of Statistics. (2009). Report on the Household Expenditure Survey 2007/2008.

66. Department of Statistics. (2005). Report on the Household Expenditure Survey 2002/2003.
67. Bing Dong, Siew Eang Lee, and Majid Haji Sapor. (2005). A holistic utility bill analysis method for baselining whole commercial building energy consumption in Singapore. *Energy and Buildings*, 37(2), 167-174. doi:<http://dx.doi.org/10.1016/j.enbuild.2004.06.011>
68. National Environment Agency. (2010). Singapore's Second National Communication: Under the United Nations Framework Convention on Climate Change, National Environmental.
69. Energy Market Authority. (2012). Singapore Energy Statistics 2012.
70. Steven J. Konopacki and Hashem Akbari. (2001). Measured energy saving and demand reduction from a reflective roof membrane on a large retail store in Austin. *Lawrence Berkeley National Laboratory*.
71. Hashem Akbari, Ronnen Levinson, and Leo Rainer. (2005). Monitoring the energy-use effects of cool roofs on California commercial buildings. *Energy and Buildings*, 37(10), 1007-1016. doi:10.1016/j.enbuild.2004.11.013
72. Zhiyang Shi and Xiong Zhang. (2011). Analyzing the effect of the longwave emissivity and solar reflectance of building envelopes on energy-saving in buildings in various climates. *Solar Energy*, 85(1), 28-37. doi:<http://dx.doi.org/10.1016/j.solener.2010.11.009>
73. Meng-Dawn Cheng, William Miller, Joshua New, and Paul Berdahl. (2012). Understanding the long-term effects of environmental exposure on roof reflectance in California. *Construction and Building Materials*, 26(1), 516-526.
74. Mohamad Sleiman, Thomas W. Kirchstetter, and Haley E. Gilbert. (2012). Accelerated aging method to mimic changes in solar reflectance of roofing materials. *International Roof Coatings Conference*.
75. R. Levinson, P. Berdahl, A. A. Berhe, and H. Akbari. (2005). Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. *Atmospheric Environment*, 39(40), 7807-7824.
76. R. N. Butlin. (1990). Effects of air pollutants on buildings and materials. *Proceedings of the Royal Society of Edinburgh Section B: Biology*, 97, 255-272.
77. DL Loveday and AH Taki. (1996). Convective heat transfer coefficients at a plane surface on a full-scale building facade. *International Journal of Heat and Mass Transfer*, 39(8), 1729-1742.
78. D. Kolokotsa, M. Santamouris, and S. C. Zerefos. (2013). Green and cool roofs' urban heat island mitigation potential in European climates for office buildings under free floating conditions. *Solar Energy*, 95, 118-130. doi:<http://dx.doi.org/10.1016/j.solener.2013.06.001>
79. Haider Taha. (2001). Potential impacts of climate change on tropospheric ozone in California: a preliminary episodic modeling assessment of the Los Angeles Basin and the Sacramento Valley: Lawrence Berkeley National Lab., CA (US).
80. M. Santamouris, A. Synnefa, and T. Karlessi. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, 85(12), 3085-3102. doi:10.1016/j.solener.2010.12.023
81. Hashem Akbari, Melvin Pomerantz, and Haider Taha. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar energy*, 70(3), 295-310.
82. Arthur H. Rosenfeld, Hashem Akbari, Sarah Bretz, Beth L. Fishman, Dan M. Kurn, David Sailor, and Haider Taha. (1995). Mitigation of urban heat islands: materials,

- utility programs, updates. *Energy and Buildings*, 22(3), 255-265. doi:[http://dx.doi.org/10.1016/0378-7788\(95\)00927-P](http://dx.doi.org/10.1016/0378-7788(95)00927-P)
83. Arthur H. Rosenfeld, Hashem Akbari, Joseph J. Romm, and Melvin Pomerantz. (1998). Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings*, 28(1), 51-62. doi:[http://dx.doi.org/10.1016/S0378-7788\(97\)00063-7](http://dx.doi.org/10.1016/S0378-7788(97)00063-7)
 84. H. Akbari, L. M. Gartland, and S. Konopacki. (1998). Measured energy savings of light-colored roofs: results from three California demonstration sites *1998 ACEEE Summer Study on Energy Efficiency in Buildings* (Vol. 3).
 85. S. Konopacki, L. Gartland, H. Akbari, and L. Rainer. (1998). Demonstration of energy savings of cool roofs *Other Information: PBD: Jun 1998* (pp. Medium: ED; Size: 116 p.).
 86. E. Bozonnet, M. Doya, and F. Allard. (2011). Cool roofs impact on building thermal response: A French case study. *Energy and Buildings*, 43(11), 3006-3012. doi:<http://dx.doi.org/10.1016/j.enbuild.2011.07.017>
 87. Anna Laura Pisello, Ansgar Thiemann, Mattheos Santamouris, and Franco Cotana. *Analysis of a Cool Roof System for Reducing Cooling Loads and Improving Cooling System Efficiency*. in *Proceedings of CLIMA2013 International Conf. Prague*. 2013.
 88. M. Kolokotroni, B. L. Gowreesunker, and R. Giridharan. (2013). Cool roof technology in London: An experimental and modelling study. *Energy and Buildings*, 67, 658-667. doi:<http://dx.doi.org/10.1016/j.enbuild.2011.07.011>
 89. Marwa Dabaieh, Omar Wanas, Mohamed Amer Hegazy, and Erik Johansson. (2015). Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. *Energy and Buildings*, 89, 142-152. doi:<http://dx.doi.org/10.1016/j.enbuild.2014.12.034>
 90. Aviruch Bhatia, Jyotirmay Mathur, and Vishal Garg. (2011). Calibrated simulation for estimating energy savings by the use of cool roof in five Indian climatic zones. *Journal of Renewable and Sustainable Energy*, 3(2), 023108.
 91. H. Akbari, S. Konopacki, and M. Pomerantz. (1999). Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy*, 24(5), 391-407. doi:[http://dx.doi.org/10.1016/S0360-5442\(98\)00105-4](http://dx.doi.org/10.1016/S0360-5442(98)00105-4)
 92. Serdar Celik, Susan Morgan, William Retzlaff, and Orcun Once. (2011). Thermal Insulation Performance of Green Roof Systems. *The Masterbuilder (May 2013)*, 186-190.
 93. Yunus A Cengel. (2007). *Heat & mass transfer: a practical approach*: Tata McGraw-Hill Education.
 94. L. Adelard, F. Pignolet-Tardan, T. Mara, P. Lauret, F. Garde, and H. Boyer. (1998). Sky temperature modelisation and applications in building simulation. *Renewable Energy*, 15(1), 418-430. doi:[https://doi.org/10.1016/S0960-1481\(98\)00198-0](https://doi.org/10.1016/S0960-1481(98)00198-0)
 95. AH Maghrabi. (2012). Modification of the IR sky temperature under different atmospheric conditions in an arid region in central Saudi Arabia: Experimental and theoretical justification. *Journal of Geophysical Research: Atmospheres*, 117(D19).
 96. Shanyou Zhu, Huade Guan, John Bennett, Roger Clay, Caecilia Ewenz, Simon Benger, Abdullrahman Maghrabi, and Andrew C. Millington. (2013). Influence of sky temperature distribution on sky view factor and its applications in urban heat island. *International Journal of Climatology*, 33(7), 1837-1843. doi:10.1002/joc.3660
 97. Simos Yannas, Evyatar Erell, and Jose Luis Molina. (2006). *Roof cooling techniques: a design handbook*: Earthscan.

98. Dhirendra K. Pandey, Robert B. Lee, and Jack Paden. (1995). Effects of atmospheric emissivity on clear sky temperatures. *Atmospheric Environment*, 29(16), 2201-2204. doi:[https://doi.org/10.1016/1352-2310\(94\)00243-E](https://doi.org/10.1016/1352-2310(94)00243-E)
99. Jing-Ming Chen and Ren-Hua Zhang. (1989). Studies on the measurements of crop emissivity and sky temperature. *Agricultural and Forest Meteorology*, 49(1), 23-34. doi:[https://doi.org/10.1016/0168-1923\(89\)90059-2](https://doi.org/10.1016/0168-1923(89)90059-2)
100. Thijs Defraeye, Bert Blocken, and Jan Carmeliet. (2011). Convective heat transfer coefficients for exterior building surfaces: Existing correlations and CFD modelling. *Energy Conversion and Management*, 52(1), 512-522. doi:<https://doi.org/10.1016/j.enconman.2010.07.026>
101. Fernando Pacheco-Torgal, Joao Labrincha, Luisa Cabeza, and Claes Goeran Granqvist. (2015). *Eco-efficient Materials for Mitigating Building Cooling Needs: Design, Properties and Applications*: Woodhead Publishing.
102. P. W. O'Callaghan and S. D. Probert. (1977). Sol-air temperature. *Applied Energy*, 3(4), 307-311. doi:[https://doi.org/10.1016/0306-2619\(77\)90017-4](https://doi.org/10.1016/0306-2619(77)90017-4)
103. Y. Tham and T. Muneer. (2011). Sol-air temperature and daylight illuminance profiles for the UKCP09 data sets. *Building and Environment*, 46(6), 1243-1250. doi:<https://doi.org/10.1016/j.buildenv.2010.11.014>
104. William J. Parton and Jesse A. Logan. (1981). A model for diurnal variation in soil and air temperature. *Agricultural Meteorology*, 23, 205-216. doi:[https://doi.org/10.1016/0002-1571\(81\)90105-9](https://doi.org/10.1016/0002-1571(81)90105-9)
105. Ibrahim Atmaca, Omer Kaynakli, and Abdulvahap Yigit. (2007). Effects of radiant temperature on thermal comfort. *Building and Environment*, 42(9), 3210-3220. doi:<https://doi.org/10.1016/j.buildenv.2006.08.009>
106. ASHRAE Handbook. (1989). Fundamentals volume. *American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga*, 2.
107. Harry Suehrcke, Eric L. Peterson, and Neville Selby. (2008). Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Buildings*, 40(12), 2224-2235. doi:10.1016/j.enbuild.2008.06.015
108. Xia Fang, Jon Winkler, and Dane Christensen. (2011). Using EnergyPlus to perform dehumidification analysis on Building America homes. *HVAC&R Research*, 17(3), 268-283. doi:10.1080/10789669.2011.564260
109. James J Hirsch. (2010). eQUEST: Introductory tutorial, version 3.63. *Camarillo, CA*.
110. University of Wisconsin--Madison. Solar Energy Laboratory and Sanford A Klein. (1979). *TRNSYS, a transient system simulation program*: Solar Energy Laboratory, University of Wisconsin--Madison.
111. Saulo P Oliveira and Juarez S Azevedo. (2014). Spectral element approximation of Fredholm integral eigenvalue problems. *Journal of Computational and Applied Mathematics*, 257, 46-56.
112. Irene M Gamba and Jeffrey R Haack. (2014). A conservative spectral method for the Boltzmann equation with anisotropic scattering and the grazing collisions limit. *Journal of Computational Physics*, 270, 40-57.
113. Naouel Daouas, Zaineb Hassen, and Habib Ben Aissia. (2010). Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. *Applied Thermal Engineering*, 30(4), 319-326. doi:<http://dx.doi.org/10.1016/j.applthermaleng.2009.09.009>
114. George Wypych. (1999). Weathering of Plastics: testing to mirror real life performance. *William Andrew*.
115. L. F. E. Jacques. (2000). Accelerated and outdoor/natural exposure testing of coatings. *Progress in Polymer Science*, 25(9), 1337-1362.

116. Aaron R. Byerley and Jeffrey E. Christian. (1994). the long term thermal performance of radiation control coatings. *Proc ACEEE 1994 Summer study on Energy Efficiency in Buildings, Vol. 5*(American Council for an Eney Efficiency Economy, Berkeley, CA), 5.59 -5.71.
117. Masayuki Ichinose, Takashi Inoue, and Yoshihito Sakamoto. (2009). Long-term performance of high-reflectivity exterior panels. *Building and Environment*, 44(8), 1601-1608. doi:10.1016/j.buildenv.2008.10.003
118. Mohamad Sleiman, George Ban-Weiss, Haley E. Gilbert, David François, Paul Berdahl, Thomas W. Kirchstetter, Hugo Destailats, and Ronnen Levinson. (2011). Soiling of building envelope surfaces and its effect on solar reflectance—Part I: Analysis of roofing product databases. *Solar Energy Materials and Solar Cells*, 95(12), 3385-3399. doi:10.1016/j.solmat.2011.08.002
119. WA Miller, A Desjarlais, DS Parker, and S Kriner. *Cool Metal Roofing Tested for Energy Efficiency and Sustainability*. in *Proceedings of CIB World Building Congress, Toronto, Ontario*. 2004.
120. Kenneth E Wilkes, Thomas W Petrie, Jerald A Atchley, and Phillip W Childs. *Roof heating and cooling loads in various climates for the range of solar reflectances and infrared emittances observed for weathered coatings*. in *Proceedings 2000 ACEEE Summer Study on Energy Efficiency in Buildings*. 2000.
121. Sherwood B Idso and Ray D Jackson. (1969). Comparison of Two Methods for Determinlug Infrared Emittances of Bare Soils. *Journal of Applied Meteorology*, 8(1), 168-169.
122. C. H. M. van Bavel and D. I. Hillel. (1976). Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. *Agricultural Meteorology*, 17(6), 453-476. doi:[https://doi.org/10.1016/0002-1571\(76\)90022-4](https://doi.org/10.1016/0002-1571(76)90022-4)
123. Paul Berdahl, Hashem Akbari, and Leanna S. Rose. (2002). Aging of reflective Roofs: soot Deposition. *Appl. Opt.*, 41(12), 2355-2360.
124. Chuanmin Hu, Frank E. Muller-Karger, and Richard G. Zepp. (2002). Absorbance, absorption coefficient, and apparent quantum yield: A comment on common ambiguity in the use of these optical concepts. *Limnology and Oceanography*, 47(4), 1261-1267. doi:10.4319/lo.2002.47.4.1261
125. Lars Hengren, Ashantha Goonetilleke, and Godwin A Ayoko. (2005). Understanding heavy metal and suspended solids relationships in urban stormwater using simulated rainfall. *Journal of Environmental Management*, 76(2), 149-158.
126. J. Roed. (1987). Dry Deposition in Rural and in Urban Areas in Denmark. *Radiation Protection Dosimetry*, 21(1-3), 33-36.
127. G-P Hu and R Balasubramanian. (2003). Wet deposition of trace metals in Singapore. *Water, air, and soil pollution*, 144(1-4), 285-300.
128. G. P. Hu, R. Balasubramanian, and C. D. Wu. (2003). Chemical characterization of rainwater at Singapore. *Chemosphere*, 51(8), 747-755. doi:10.1016/s0045-6535(03)00028-6
129. Ź Polkowska, T Górecki, and J Namieśnik. (2011). Determination of atmospheric pollutants in wet deposition. *Environmental Reviews*, 19(NA), 185-213.
130. O. Clus, P. Ortega, M. Muselli, I. Milimouk, and D. Beysens. (2008). Study of dew water collection in humid tropical islands. *Journal of Hydrology*, 361(1), 159-171. doi:<https://doi.org/10.1016/j.jhydrol.2008.07.038>
131. Jiang He, Akio Okumura, Akira Hoyano, and Kohichi Asano. (2001). A solar cooling project for hot and humid climates. *Solar Energy*, 71(2), 135-145. doi:[https://doi.org/10.1016/S0038-092X\(01\)00022-6](https://doi.org/10.1016/S0038-092X(01)00022-6)

132. Singapore National Environment Agency. (2017). Records of Climate Station Mean (Climatological Reference Period: 1981-2010).
133. Climatemps. (2017). Relative Humidity in Singapore. Retrieved from <http://www.singapore.climatemps.com/humidity.php>
134. P. Pesava, R. Aksu, S. Toprak, H. Horvath, and S. Seidl. (1999). Dry deposition of particles to building surfaces and soiling. *Science of The Total Environment*, 235(1-3), 25-35. doi:[http://dx.doi.org/10.1016/S0048-9697\(99\)00187-4](http://dx.doi.org/10.1016/S0048-9697(99)00187-4)
135. R. Levinson, P. Berdahl, A. Asefawberhe, and H. Akbari. (2005). Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. *Atmospheric Environment*, 39(40), 7807-7824. doi:10.1016/j.atmosenv.2005.08.037
136. P. Egodawatta, E. Thomas, and A. Goonetilleke. (2007). Mathematical interpretation of pollutant wash-off from urban road surfaces using simulated rainfall. *Water Res*, 41(13), 3025-31. doi:10.1016/j.watres.2007.03.037
137. Prasanna Egodawatta and Ashantha Goonetilleke. (2008). Understanding road surface pollutant wash-off and underlying physical processes using simulated rainfall. *Water science and technology: a journal of the International Association on Water Pollution Research*, 57(8), 1241.
138. P. Egodawatta, E. Thomas, and A. Goonetilleke. (2009). Understanding the physical processes of pollutant build-up and wash-off on roof surfaces. *Sci Total Environ*, 407(6), 1834-41. doi:10.1016/j.scitotenv.2008.12.027
139. W Tobiska and A Nusinov. *ISO 21348-Process for determining solar irradiances*. in *36th COSPAR Scientific Assembly*. 2006.
140. Ronnen Levinson, Paul Berdahl, and Hashem Akbari. (2005). Solar spectral optical properties of pigments—Part I: model for deriving scattering and absorption coefficients from transmittance and reflectance measurements. *Solar Energy Materials and Solar Cells*, 89(4), 319-349. doi:10.1016/j.solmat.2004.11.012
141. A. Ammala, A. J. Hill, P. Meakin, S. J. Pas, and T. W. Turney. (2002). Degradation Studies of Polyolefins Incorporating Transparent Nanoparticulate Zinc Oxide UV Stabilizers. *Journal of Nanoparticle Research*, 4(1-2), 167-174.
142. R. P. Singh, Namrata S. Tomer, and S. Veera Bhadraiah. (2001). Photo-oxidation studies on polyurethane coating: effect of additives on yellowing of polyurethane. *Polymer Degradation and Stability*, 73(3), 443-446.
143. D. Santos, M. R. Costa, and M. T. Santos. (2007). Performance of polyester and modified polyester coil coatings exposed in different environments with high UV radiation. *Progress in Organic Coatings*, 58(4), 296-302.
144. R. Asmatulu, G. A. Mahmud, C. Hille, and H. E. Misak. (2011). Effects of UV degradation on surface hydrophobicity, crack, and thickness of MWCNT-based nanocomposite coatings. *Progress in Organic Coatings*, 72(3), 553-561.
145. Mundel Lufitha. (2001). Effect of substrate temperature on coating adhesion: National Library of Canada= Bibliothèque nationale du Canada.
146. A. Dubosc, G. Escadeillas, and P. J. Blanc. (2001). Characterization of biological stains on external concrete walls and influence of concrete as underlying material. *Cement and Concrete Research*, 31(11), 1613-1617. doi:[http://dx.doi.org/10.1016/S0008-8846\(01\)00613-5](http://dx.doi.org/10.1016/S0008-8846(01)00613-5)
147. Solvig Görs, Rhena Schumann, Norbert Häubner, and Ulf Karsten. (2007). Fungal and algal biomass in biofilms on artificial surfaces quantified by ergosterol and chlorophyll a as biomarkers. *International Biodeterioration & Biodegradation*, 60(1), 50-59. doi:10.1016/j.ibiod.2006.10.003

148. Ji-Dong Gu, Tim E. Ford, Neal S. Berke, and Ralph Mitchell. (1998). Biodeterioration of concrete by the fungus *Fusarium*. *International Biodeterioration & Biodegradation*, 41(2), 101-109. doi:[http://dx.doi.org/10.1016/S0964-8305\(98\)00034-1](http://dx.doi.org/10.1016/S0964-8305(98)00034-1)
149. Christine C. Gaylarde and L. H. Glyn Morton. (1999). Deteriogenic biofilms on buildings and their control: A review. *Biofouling*, 14(1), 59-74. doi:10.1080/08927019909378397
150. Gilles Escadeillas, Alexandra Bertron, Erick Ringot, Philippe J. Blanc, and Arnaud Dubosc. (2008). Accelerated testing of biological stain growth on external concrete walls. Part 2: Quantification of growths. *Materials and Structures*, 42(7), 937-945. doi:10.1617/s11527-008-9433-3
151. Gilles Escadeillas, Alexandra Bertron, Philippe Blanc, and Arnaud Dubosc. (2006). Accelerated testing of biological stain growth on external concrete walls. Part 1: Development of the growth tests. *Materials and Structures*, 40(10), 1061-1071. doi:10.1617/s11527-006-9205-x
152. YC Wee and KB Lee. (1980). Proliferation of algae on surfaces of buildings in Singapore. *International Biodeterioration Bulletin*, 16(4), 113-117.
153. YC Wee and G Lim. (1988). Biological growths on building surfaces. *Control of the External Environment of Buildings: Selected Papers on the Protection of the External Surfaces of Buildings in Warm Humid Climate*, 47.
154. Clive Briffitt. (1995). *Building maintenance technology in tropical climates*: NUS Press.
155. Meng-Dawn Cheng, Susan M. Pfiffner, William A. Miller, and Paul Berdahl. (2011). Chemical and microbial effects of atmospheric particles on the performance of steep-slope roofing materials. *Building and Environment*, 46(5), 999-1010. doi:10.1016/j.buildenv.2010.10.025
156. Rhena Schumann, Norbert Häubner, Steffi Klausch, and Ulf Karsten. (2005). Chlorophyll extraction methods for the quantification of green microalgae colonizing building facades. *International Biodeterioration & Biodegradation*, 55(3), 213-222. doi:<http://dx.doi.org/10.1016/j.ibiod.2004.12.002>
157. K. V. Thomas and S. Brooks. (2010). The environmental fate and effects of antifouling paint biocides. *Biofouling*, 26(1), 73-88. doi:10.1080/08927010903216564
158. Rajagopalan Priyadarsini, Wong Nyuk Hien, and Cheong Kok Wai David. (2008). Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. *Solar Energy*, 82(8), 727-745. doi:10.1016/j.solener.2008.02.008
159. ASTM. (2016). ASTM E1918-16, Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field, ASTM International, West Conshohocken, PA, 2016, www.astm.org. doi:10.1520/E1918-16
160. ASTM. (2014). ASTM C1549-09(2014), Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer, ASTM International, West Conshohocken, PA, 2014, www.astm.org. doi:10.1520/C1549-09R14
161. Ronnen Levinson, Hashem Akbari, and Paul Berdahl. (2010). Measuring solar reflectance—Part I: Defining a metric that accurately predicts solar heat gain. *Solar Energy*, 84(9), 1717-1744. doi:<https://doi.org/10.1016/j.solener.2010.04.018>
162. Ronnen Levinson, Hashem Akbari, and Paul Berdahl. (2010). Measuring solar reflectance—Part II: Review of practical methods. *Solar Energy*, 84(9), 1745-1759. doi:<https://doi.org/10.1016/j.solener.2010.04.017>
163. ASTM. (2010). ASTM C1371-04a(2010)e1, Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers,

- ASTM International, West Conshohocken, PA, 2010, www.astm.org. doi:10.1520/C1371-04AR10E01
164. ASTM. (2013). ASTM D7091-13, Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals, ASTM International, West Conshohocken, PA, 2013, www.astm.org. doi:10.1520/D7091
165. ASTM. (2014). ASTM B499-09(2014), Standard Test Method for Measurement of Coating Thicknesses by the Magnetic Method: Nonmagnetic Coatings on Magnetic Basis Metals, ASTM International, West Conshohocken, PA, 2014, www.astm.org. doi:10.1520/B0499-09R14
166. Kishor T Zingre, Man Pun Wan, and Xingguo Yang. *An Investigation of Microclimatic Impact of Cool Coating for Buildings in Low-Latitude and Tropical Climate*. in *ASME 2014 International Mechanical Engineering Congress and Exposition*. 2014. American Society of Mechanical Engineers.
167. Paul SH Poh and Jundong Chen. (1998). The Singapore buildable design appraisal system: a preliminary review of the relationship between buildability, site productivity and cost. *Construction Management & Economics*, 16(6), 681-692.
168. Shanshan Tong, Hua Li, Kishor T. Zingre, Man Pun Wan, Victor W. C. Chang, Swee Khian Wong, Winston Boo Thian Toh, and Irene Yen Leng Lee. (2014). Thermal performance of concrete-based roofs in tropical climate. *Energy and Buildings*, 76, 392-401. doi:<http://dx.doi.org/10.1016/j.enbuild.2014.02.076>
169. ASTM. (2007). ASTM D3276-07, Standard Guide for Painting Inspectors (Metal Substrates), ASTM International, West Conshohocken, PA, 2007, www.astm.org. doi:10.1520/D3276-07
170. ASTM. (2009). ASTM D6237-09, Standard Guide for Painting Inspectors (Concrete and Masonry Substrates), ASTM International, West Conshohocken, PA, 2009, www.astm.org. doi:10.1520/D6237-09
171. ASTM. (2014). ASTM D1730-09(2014), Standard Practices for Preparation of Aluminum and Aluminum-Alloy Surfaces for Painting, ASTM International, West Conshohocken, PA, 2014, www.astm.org. doi:10.1520/D1730-09R14
172. ASTM. (2009). ASTM G147-09, Standard Practice for Conditioning and Handling of Nonmetallic Materials for Natural and Artificial Weathering Tests, ASTM International, West Conshohocken, PA, 2009, www.astm.org. doi:10.1520/G0147-09
173. Steve Davidson. (2004). SkyCool - extraordinary paint on a hot tin roof. *Ecos*, 2004(119), 12-12.
174. John Pockett and Martin Belusko. (2010). A Review of Heat-reflective Paints *Conference: Solar2010*. Canberra, ACT, Australia.
175. C.S. Wojtysiak. (2009). Radiative cooling surface coatings: Google Patents.
176. Spring Singapore. (2003). Singapore standard ss 5 B10: 2003(2013) Methods of test for paints, varnishes and related materials.
177. ASTM. (2012). ASTM E903-12, Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres, ASTM International, West Conshohocken, PA, 2012, www.astm.org. doi:10.1520/E0903-12
178. ASTM. (2012). G173-03(2012), Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, ASTM International, West Conshohocken, PA, 2012, www.astm.org. doi:10.1520/G0173-03R12
179. Casimiro A Pio, Maria M Ramos, and Armando C Duarte. (1998). Atmospheric aerosol and soiling of external surfaces in an urban environment. *Atmospheric Environment*, 32(11), 1979-1989.

180. H. Saaroni, A. Chudnovsky, and E. Ben-Dor. (2010). Reflectance spectroscopy is an effective tool for monitoring soot pollution in an urban suburb. *Sci Total Environ*, 408(5), 1102-10. doi:10.1016/j.scitotenv.2009.10.052
181. Meteorological Service Singapore. (2017). Climate of Singapore.
182. National Environment Agency. (2011). Rainfall - Monthly Total.
183. National Environment Agency. (2011). Annual Weather Review 2011.
184. Olivier Favez, Hélène Cachier, Anne Chabas, Patrick Ausset, and Roger Lefevre. (2006). Crossed optical and chemical evaluations of modern glass soiling in various European urban environments. *Atmospheric Environment*, 40(37), 7192-7204.
185. G. J. M. Fechine, M. S. Rabello, and R. M. Souto-Maior. (2002). The effect of ultraviolet stabilizers on the photodegradation of poly(ethylene terephthalate). *Polymer Degradation and Stability*, 75(1), 153-159.
186. Xingguo Yang, Kishor T Zingre, and Man Pun Wan. (2016). Effects of UV on radiation properties of cool coating *7th International Conference on Energy and Environment of Residential Buildings*. Brisbane, Australia.
187. ASTM. (2010). ASTM G151-10, Standard Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources, ASTM International, West Conshohocken, PA, 2010, www.astm.org. doi:10.1520/G0151-10
188. ASTM. (2012). ASTM G154-12a, Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials, ASTM International, West Conshohocken, PA, 2012, www.astm.org. doi:10.1520/G0154-12A
189. Keng Jee Tan and Thong Ngee Goh. (1977). Solar insolation in an equatorial region (Singapore). *Solar Energy*, 19(1), 101-103.
190. Sami A. Al-Sanea. (2002). Thermal performance of building roof elements. *Building and Environment*, 37(7), 665-675.
191. Charles S Barnaby and Drury B Crawley. (2011). Weather data for building performance simulation. *Building Performance Simulation for Design and Operation*, 37-55.
192. Spring Singapore. (1999). Singapore Standard SS 345 : 1990.
193. Petr Beckmann and Andre Spizzichino. (1987). The scattering of electromagnetic waves from rough surfaces. *Norwood, MA, Artech House, Inc., 1987, 511 p.*
194. Gilbert M Masters. (2013). *Renewable and efficient electric power systems*: John Wiley & Sons.

Appendix A Algal Resistance Test on Cool Coating Samples

A.1 Methodology

The algal resistance test was conducted on Coating 1, Coating 1-2, and Coating 1-3 in triplicate samples, under two standards which are the Singapore Standard SS 345: 1990 (Algae resistant emulsion paint for decorative purposes) [192] and the ASTM standard G154-12a (Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials) [188]. Based on the standards, *Trentepohlia Odorata* species was the recommended microbial for this test as it was found to be one of the common biofouling species to colonize most of the building surface in Singapore. The samples were prepared by applying two layers of the coating the surface of petridis, prior to 72 hours of standing at room temperature. Then the samples were pre-aged by undergoing cycles of UV exposure for 168 hours, with exposure cycle of UV light on at 55°C for 8 hours followed by light off and condensation on at 45°C for four hours. Then after a cool down period at room temperature of 24 hours, the samples were inoculated with algae culture, and then exposed to fluorescent lighting at room temperature for eight weeks immediately, with the lighting cycle of 12 hours on followed by 12 hours off.

A.2 Results

Coating 1 samples (labelled as 132a1, 132a2, and 132a3), Coating 1-2 samples (132b1, 132b2, and 132b3), and Coating 1-3 samples (132c1, 132c2, and 132c3) were tested by TUV SUD PSB Pte Ltd on the anti-microbial growth resistance, following the standards and methods above. The images of the samples are shown in **Figure A-1**.

Figure A-1 Algal resistance test results: (a) Coating 1 samples; (b) Coating 1-3 samples; (c) Coating 1-2 samples; (d) Control samples.

The results indicated that there was no sign of microbial growth on all the samples after eight weeks of incubation. The control samples (empty petri dishes without coating) went through the same test procedures and severe microbial growth could be seen. The results suggest that all the tested cool coatings (Coating 1, Coating 1-2, and Coating 1-3) have excellent anti-microbial growth performance. It would be reasonable to assume that no microorganism would grow on cool coatings and change the solar reflectance.

Appendix B Spectral Reflectance of Cool Coating

The reflection from a surface (e.g., cool coating) includes the specular reflection part and the diffuse reflection part [193]. When the specular reflection is the dominant part of the total reflection, the surface could be termed as “specular”. When the diffuse reflection becomes the dominant part, the surface could be termed as “diffuse”. To quantify the specular part and the diffuse part of the reflection from the cool coating (Coating 1) surface, the total reflectance and diffusive reflectance was measured by the spectrophotometer introduced in Section 4.4 , as shown in **Figure B-1**. The angle of incidence and the angle of reflection is 8° . The total reflectance and diffusive reflectance of a mirror was also presented in the figure as a reference. The specular reflection could be calculated by subtracting the diffusive part from the total reflection.

Figure B-1 Total spectral reflectance and diffusive reflectance of cool coating and mirror (with the angle of incidence and the angle of reflection of 8°).

It could be observed from the figure that the total reflectance of the mirror is relatively high through the spectrum, while its diffusive reflectance is almost zero. This means that the reflection of the mirror is dominated by the specular part, and the mirror could be regarded as specular. For the cool coating, it could be observed that the total reflectance and the diffusive reflectance are almost the same through the spectrum, which means the reflection of the cool coating is dominated by the diffuse part, and the cool coating could be regarded as diffuse.

Appendix C Calculation Methods for Heat Flux and Energy Consumption

C.1 Fourier's Law of Conduction

In this experiment, the thermal loadings of the test building were determined by tabulating the amount of heat flux transferred across the roof slab to the interior ceiling surface, by the Fourier's law of conduction [24] as shown in (Eq. C-1).

$$q = \frac{Q}{A} = k \times \frac{\Delta T}{d} = U \times \Delta T = \frac{\Delta T}{R} \quad (\text{Eq. C-1})$$

where q (W/m²) is the heat flux, Q (W) is the heat flow through the wall, A (m²) is the envelope surface area, k (W/m·K) is the thermal conductivity, d (m) is the thickness of the envelope, ΔT (°C) = $T_{\text{External}} - T_{\text{Internal}}$ is the temperature difference of external and internal surfaces of the envelope, U (W/m²·K) is the thermal transmittance of the building envelope, and R (m²·K/W) = $1/U$ is the thermal resistance.

C.2 Electrical Power

The electrical power is the rate of electric energy transferred by a circuit, powered by electricity. The electrical energy consumption of the air-conditioning system was calculated based on the measurement results in the study, based on the Ohm's law of power [194], as shown in (Eq. C-2).

$$P = I \times V \quad (\text{Eq. C-2})$$

where P (W) is the power, I (A) is the current, and V (V) is the voltage.

With a known standard electricity supply of 230 volts at 50 hertz in Singapore, power consumption of the air-conditioner in watts was calculated by multiplying the current (in ampere) data obtained by the power meter with the standard electricity supply of 230 volts.

Appendix D Natural Ageing Study of Cool Coatings (Coating 1, Coating 1-2, and Coating 1-3)

D.1 Change of solar reflectance

A short term natural ageing experiment was conducted with Coating 1, Coating 1-2, and Coating 1-3 coatings. The instruments, exposure racks, and test site are the same as the first natural ageing experiment. The sample information is presented in **Table D-1**. Group 1 samples were aged during 19th October 2015 to 23rd March 2016. Groups 2, 3, and 4 samples were aged during 25th January 2016 to 23rd March 2016. The image of the samples is shown in **Figure D-1**.

Table D-1 Information of tested cool coating samples

Group	Coating	Ageing period	Solar reflectance (mean of 5 samples)	
			Before ageing	After ageing
1	Coating 1	5 months	0.80	0.53
2	Coating 1	2 months	0.80	0.68
3	Coating 1-2	2 months	0.84	0.80
4	Coating 1-3	2 months	0.84	0.79

Figure D-1 Coating 1, Coating 1-2, and Coating 1-3 samples for natural ageing experiment

It could be observed that Group 1 samples lost solar reflectance of 0.27 after five months' ageing. Group 2 samples lost 0.12 after two months. These losses of solar reflectance were much higher than those in the first natural ageing experiment introduced in Section 4.5 . The reason should be some new construction projects near the testing site during that period of time, as shown in **Figure D-2**. Therefore the concentration of the airborne particles was much higher than normal, which led to fast soiling accumulation on the samples during this ageing period.

It was also observed that the solar reflectance loss of Group 3 and Group 4 samples was much lower than Group 1 and Group 2. This is because of the smoother surface and improved omniphobic properties of the two new coatings. The solar reflectance of Group 3 (Coating 1-2) was just 1/3 of that of Group 2 (Coating 1). Hence it could be assumed that in long term ageing, the reflectance decreasing rate of Coating 1-2 is still 1/3 of that of Coating 1.

Figure D-2 Locations of the construction projects on NTU campus: (a) construction at location 1; (b) construction at location 2; (c) construction at location 3

D.2 Images of cool coating samples during natural ageing

Images of Group 1 samples were taken during the ageing period, as shown in **Figure D-3**.

The soiling accumulation could be observed on the surface of the samples.

Figure D-3 Images of cool coating (Coating 1) samples during 5 months' natural ageing: (a) before ageing; (b) after 10 days; (c) after 36 days; (d) after 50 days; (e) after 71 days; (f) after 92 days; (g) after 115 days; (h) after 157 days.

Appendix E Statistical Analysis of Experiment Data of Accelerated UV Ageing Study

E.1 Bivariate Pearson correlation analysis between solar reflectance loss and UV ageing weeks

Bivariate Pearson correlation test was conducted to evaluate whether the solar reflectance loss of Coating 1 samples was correlated with the UV ageing time. The measurement results are summarised in **Table E-1**. The P value (Sig. (2-tailed)) is almost 0.000, lower than 0.05, indicating a statistically significant linear relationship between the solar reflectance of Coating 1 samples and the UV ageing weeks.

Table E-1 Bivariate Pearson correlation test for solar reflectance of Coating 1 samples and the UV ageing weeks

Correlations

		UV ageing weeks	Solar reflectance of Coating 1 samples
UV ageing weeks	Pearson Correlation	1	-.794**
	Sig. (2-tailed)		.000
	N	63	63
Solar reflectance of Coating 1 samples	Pearson Correlation	-.794**	1
	Sig. (2-tailed)	.000	
	N	63	63

** . Correlation is significant at the 0.01 level (2-tailed).

E.2 Independent t-test for the impacts of “whether soiled by RD or CM” on the solar reflectance loss

Independent sample t-test was conducted to evaluate whether the solar reflectance loss would be significantly changed when the cool coating samples are soiled by real dirt. The measurement results are summarised in **Table E-2**. The P value (Sig. (2-tailed), in the second table) is 0.021, lower than 0.05, indicating a significant difference in mean solar reflectance loss between unsoiled and RD soiled samples. This suggests that soiling of real dirt did reduce the solar reflectance loss of cool coating.

Table E-2 Independent t-test for means of solar reflectance of unsoiled and RD soiled cool coating samples

(1) Group Statistics

	Whether soiled by CM	N	Mean	Std. Deviation	Std. Error Mean
Solar Reflectance Loss	Unsoiled	7	.015314	.0024190	.0009143
	RD soiled	7	.010086	.0045940	.0017364

(2) Independent Samples Test

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Solar Reflectance Loss	Equal variances assumed	1.876	.196	2.664	12	.021	.0052286	.0019624	.0009529	.0095042
	Equal variances not assumed			2.664	9.090	.026	.0052286	.0019624	.0007960	.0096611

Another independent sample t-test was conducted to evaluate whether the solar reflectance loss would be significantly changed when the cool coating samples are soiled by carbon micropowder. The measurement results are summarised in **Table E-3**. The P value (Sig. (2-tailed), in the second table) is 0.018, lower than 0.05, indicating a significant difference in mean solar reflectance loss between unsoiled and CM soiled samples. This suggests that soiling of carbon micropowder did reduce the solar reflectance loss of cool coating.

Table E-3 Independent t-test for means of solar reflectance of unsoiled and CM soiled cool coating samples

(1) Group Statistics

	Whether soiled by RD	N	Mean	Std. Deviation	Std. Error Mean
Solar Reflectance Loss	Unsoiled	7	.015314	.0024190	.0009143
	CM Soiled	7	.010429	.0040488	.0015303

(2) Independent Samples Test

	Levene's Test for Equality of Variances	t-test for Equality of Means							
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference
									Lower Upper
Solar Reflectance Loss	Equal variances assumed	3.422	.089	2.741	12	.018	.0048857	.0017826	.0010017 .0087697
	Equal variances not assumed			2.741	9.799	.021	.0048857	.0017826	.0009028 .0088687

E.3 Independent t-test for the impacts of soiling agents on the solar reflectance loss

Independent sample t-test was conducted to evaluate whether the solar reflectance loss would be significantly changed when the samples are soiled by different soiling agents. The measurement results are summarised in **Table E-4**. The P value (Sig. (2-tailed), in the second table) is 0.885, higher than 0.05, indicating no significant difference in mean solar reflectance loss between RD soiled and CM soiled samples. This suggests that the impacts of real dirt and carbon micropowder were highly similar on mitigating the solar reflectance caused by UV.

Table E-4 Independent t-test for means of solar reflectance of RD soiled and CM soiled cool coating samples

(1) Group Statistics

	Soiling agents	N	Mean	Std. Deviation	Std. Error Mean
Solar Reflectance Loss	RD soiled	7	.0104	.00405	.00153
	CM soiled	7	.0101	.00459	.00174

(2) Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Solar Reflectance Loss	Equal variances assumed	.000	.990	.148	12	.885	.00034	.00231	-.00470	.00539
	Equal variances not assumed			.148	11.813	.885	.00034	.00231	-.00471	.00539

E.4 Paired t-test for the change of thermal emittance after UV ageing

Paired t-test was conducted to evaluate whether the thermal emittance of unsoiled cool coating samples would be significantly changed after the UV ageing. The measurement results are summarised in **Table E-5**. The P value (Sig. (2-tailed), in the third table) is 0.510, higher than 0.05, indicating no significant difference in mean thermal emittance of unsoiled cool coating samples before and after UV ageing. This suggests that UV ageing did not change thermal emittance of unsoiled samples.

Table E-5 Paired t-test for means of thermal emittance of unsoiled cool coating samples
before and after UV ageing

(1) Paired Samples Statistics

	Mean	N	Std. Deviation	Std. Error Mean
Before_UV	.85577	7	.01272	.00481
Unsoiled After_UV	.86007	7	.01291	.00488

(2) Paired Samples Correlations

	N	Correlation	Sig.
Unsoiled Before_UV & After_UV	7	.203	.663

(3) Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Before_UV - Unsoiled After_UV	-.00429	.01618	.00612	-.01925	.01068	-.701	6	.510

A second paired t-test was conducted to evaluate whether the thermal emittance of real dirt soiled cool coating samples would be significantly changed after the UV ageing. The measurement results are summarised in **Table E-6**. The P value (Sig. (2-tailed), in 3rd table) is 0.522, higher than 0.05, indicating no significant difference in mean thermal emittance of

RD soiled cool coating samples before and after UV ageing. This suggests that UV ageing did not change thermal emittance of real dirt soiled samples.

Table E-6 Paired t-test for means of thermal emittance of real dirt soiled cool coating samples before and after UV ageing

(1) Paired Samples Statistics

	Mean	N	Std. Deviation	Std. Error Mean
Before_UV	.8629	7	.01604	.00606
After_UV	.8600	7	.00816	.00309

(2) Paired Samples Correlations

	N	Correlation	Sig.
Before_UV & After_UV	7	.764	.046

(3) Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
RD soiled	Before_UV - After_UV	.00286	.01113	.00421	-.00743	.01315	.679	6	.522

A third paired t-test was conducted to evaluate whether the thermal emittance of carbon micropowder soiled cool coating samples would be significantly changed after the UV ageing. The measurement results are summarised in **Table E-7**. The P value (Sig. (2-tailed), in the third table) is 1.000, higher than 0.05, indicating no significant difference in mean thermal emittance of CM soiled cool coating samples before and after UV ageing. This suggests that UV ageing did not change thermal emittance of carbon micropowder soiled samples.

Table E-7 Paired t-test for means of thermal emittance of carbon micropowder soiled cool coating samples before and after UV ageing

(1) Paired Samples Statistics

	Mean	N	Std. Deviation	Std. Error Mean
Before_UV	.86867	7	.01773	.00670
CM soiled After_UV	.86867	7	.01215	.00459

(2) Paired Samples Correlations

	N	Correlation	Sig.
CM soiled Before_UV & After_UV	7	.608	.148

(3) Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
CM Before_UV - soiled After_UV		.00000	.01414	.00535	-.01308	.01308	.000	6	1.000