Frontiers of Architectural Research (2014) **3**, 283–297

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Frontiers of Architectural Research

REVIEW

Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review

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Received 14 October 2013; received in revised form 4 June 2014; accepted 5 June 2014

KEYWORDS
Passive cooling;
Reflective roof;
Radiative roof;
Southeast Asia;
Tropical houses

Abstract

Cooling is one of the major concerns in building tropical houses. This problem is exacerbated by the heat gain of the roof, which constitutes 70% of the total heat gain. The passive cooling technique is one of the innovative practices and technologies that provide buildings with comfortable conditions through natural means. Reflective and radiative processes are the methods used to decrease heat gain by facilitating the elimination of excess heat in a building's interior to maintain a comfortable environment. Given that the potential of these techniques vary from region to region, their application in the tropics should be examined.

Exploring these approaches in detail allows us to rethink how to effectively adapt these techniques to overcome the build-up of heat in modern tropical houses in Southeast Asia. This study reviews the physical characteristics of these approaches to guide architects and building designers. Results indicate a great reduction in operational cost. However, the significant differences in the performance of colour and material properties should be considered, given that the selected approach strongly affects the required thermal conditions of a building.

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Peer review under responsibility of Southeast University.

http://dx.doi.org/10.1016/j.foar.2014.06.002

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1. Introduction

The tropical zone is the part of the earth that lies between the Tropic of Cancer (23°27′N) and the Tropic of Capricorn (23°27′S) (Ayoade, 1983). Atkinson (1954) and Edmonds and Greenup (2002) report that the equatorial zone has a hot and humid climate from 10° to 15° (north and south) of the equator, such as Southeast Asia, as shown in Figure 1. The tropical region is an uncomfortable climate zone that receives a large amount of solar radiation, high temperature, high level of relative humidity, and long periods of sunny days throughout the year.

Recently, this region has undergone increased urbanisation, particularly developed countries such as Singapore, Malaysia, and Indonesia, because of the rapid growth of the urban population, as shown in Figure 2. This development further increased the intensity of urban heat island (UHI) (Wong et al., 2011). This effect is associated with the increase in energy consumption, specifically the cooling issue, which is the primary concern of this region.

Studies conducted by the Building and Construction Authority (BCA) indicate that the buildings in Singapore, the world's fourth leading financial centre, accounts for about 57% of the country's entire electricity consumption (Dong et al., 2005). In addition, the results show that the country's total household electricity consumption increased from 6514 GWh in 2009 to 6560 GWh in 2011 (The Energy Market Authority, 2011). The Handbook of Energy and Economic Statistics of 2011 indicate that energy consumption in Indonesia increased by 15% from 2009 to 2010. The country's energy consumption climbed from 446.49 million BOE in 2000 to 998.52 million BOE in 2011, given that 51% of the energy is still derived from fossil sources (Handbook of Energy and Economic Statistics of Indonesia, 2011; Ministry of Mineral Resources, 2011). The Energy Commission (2010) of Malaysia indicated that the electricity demand increased from 14,245 MW in 2009 to 15,072 MW in 2010, reaching 15,476 MW in 2011. The residential sector consumes about 20% of the energy supply. Approximately 21% of this portion is used to power air-conditioning and 2% to power other mechanical fans (IEA, 2009). Chan (2004) showed that in 1999, the total number of air-conditioning units in residential buildings owned by Malaysians was 493,082. This figure

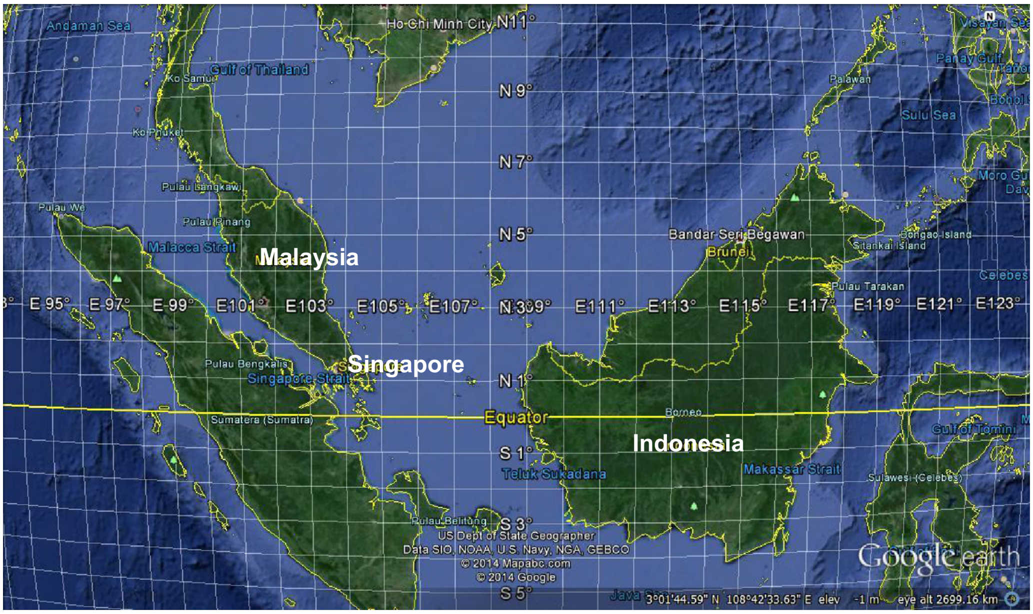

Figure 1 Map of tropical countries in Southeast Asia (Google Earth).

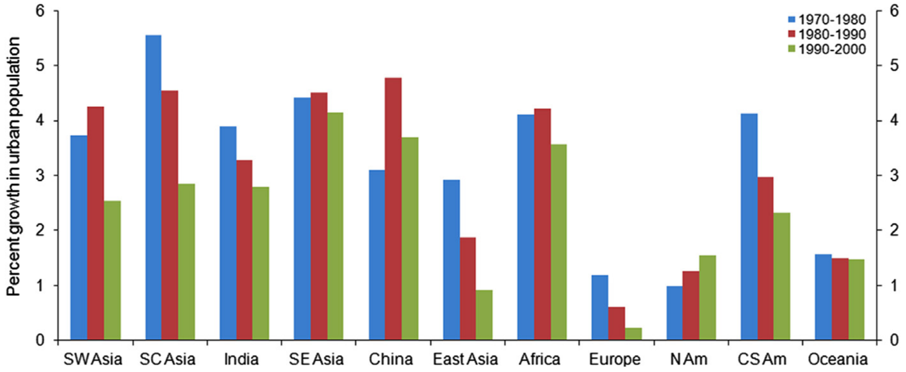

Figure 2 Annual rates of the change in urban population measures by region and by decade (Seto et al., 2011).

increased by 6.7% (528,792 units) in 2000 and by roughly 42% (907,670 units) in 2009 (Saidur et al., 2007). Al Yacouby et al. (2011) showed that about 75% of Malaysians rely on air-condoning to maintain a comfortable environment.

In a study on tropical architecture, particularly on building materials, Lauber (2005) wrote that the most commonly used materials in the tropics include clay, wood, and bamboo. However, these materials are rejected by most new cities, which prefer to use concrete, steel, glass, and shiny metals. Rahman et al. (2013) indicated that affordable houses in Malaysia suffer from a high level of heat build-up, which has to be controlled to overcome the effects of global warming. Most of the cooling energy demands in the tropics are directly related to building materials, particularly the roofing area. Vijaykumar et al. (2007) indicated that the roofing system represents 70% of the total heat gain. For example, Allen et al. (2008) investigated roof materials used in Malaysian houses: in semi-detached houses (concrete tiles 20% and clay tiles 2.5%), in terrace apartments (concrete tiles 45% and clay tiles 2.5%), and in bungalows (concrete tiles 17.5%, clay tiles 5%, and metal deck 5%). These materials permit the high transmission of solar radiation that induces a sauna effect, which creates an uncomfortable environment.

One of the sustainable approaches to cooling buildings by natural means is the passive cooling strategy (Kamal, 2012). This strategy involves a controller that limits the total effect of the heat gain to provide the interior a temperature lower than that of the natural surroundings (Givoni, 1994). In general, the flow of energy in a passive design is based on natural means, such as radiation, convection, or conduction (Kamal, 2012; Al-Obaidi et al., 2013b, 2014a). Passive cooling systems do not eliminate the use of a fan or a pump, when their application boosts performance (Givoni, 1994). In fact, several studies on the tropics such as Al-Obaidi et al. (2014b, 2014c) enhance passive cooling through the use of hybrid systems.

Passive cooling strategies generally consist of all the preventive measures against overheating in the interior of buildings (Asimakopoulos, 1996). Such cooling strategies should cover three levels:

(1) Passive cooling strategies should prevent heat gains inside the building. The parameters that should be considered include the envelope's insulation, the solar shading of the facade, and surface properties, such as the colour of the external surfaces (Asimakopoulos, 1996).
(2) Heat gains should be modulated by effective solar control to achieve a balance between controlling solar gain and admitting sufficient daylight, while ensuring the architectural and structural requirements of the building envelope. Moreover, a comfortable level of heat load should be permitted by modulating the required temperatures for the different uses of internal spaces during the design phase (Mumovic and Santamouris, 2009).
(3) The heat in the building's interior should be reduced by heat sinks (natural or hybrid cooling) through air infiltration (Al-Obaidi et al., 2014b, 2014c), surface properties, such as the colour of the internal surfaces and energy-efficient equipment that can considerably reduce internal heat gains (Mumovic and Santamouris, 2009).

The first two approaches reduce the heat gains and air temperature inside the building, whereas the third approach reduces the interior air temperature (Asimakopoulos, 1996). To activate these strategies effectively and to prevent the entry or eliminate the heat entering the building, two factors are required: a heat sink whose temperature is lower than that of the interior air, and an improved mechanism for heat transfer towards the heat sink. These conditions can be achieved through environmental heat sinks, which are divided into four types (Givoni, 1994; Asimakopoulos, 1996; Kamal, 2012):

- Ambient air, which transfers heat by convection.
- Sky (upper atmosphere), which transfers heat by long-wave radiation through building surfaces, such as the roof.
- Water, which transfers heat by evaporation inside and/or outside the building fabric.
- Ground (beneath the surface soil), which transfers heat by conduction through the building fabric.

Each of these cooling sources can be utilised in different ways and build various systems. The rejection of heat into these heat sinks can be achieved through the natural methods of heat transfer (natural cooling)—radiation, convection, conduction and evaporation—or through mechanical boosting using small power fans or pumps (hybrid cooling) (Asimakopoulos, 1996).

Cavelius et al. (2007) classified the common passive cooling systems into comfort ventilation, nocturnal ventilation cooling, radiant cooling, evaporative cooling, and using the earth as a

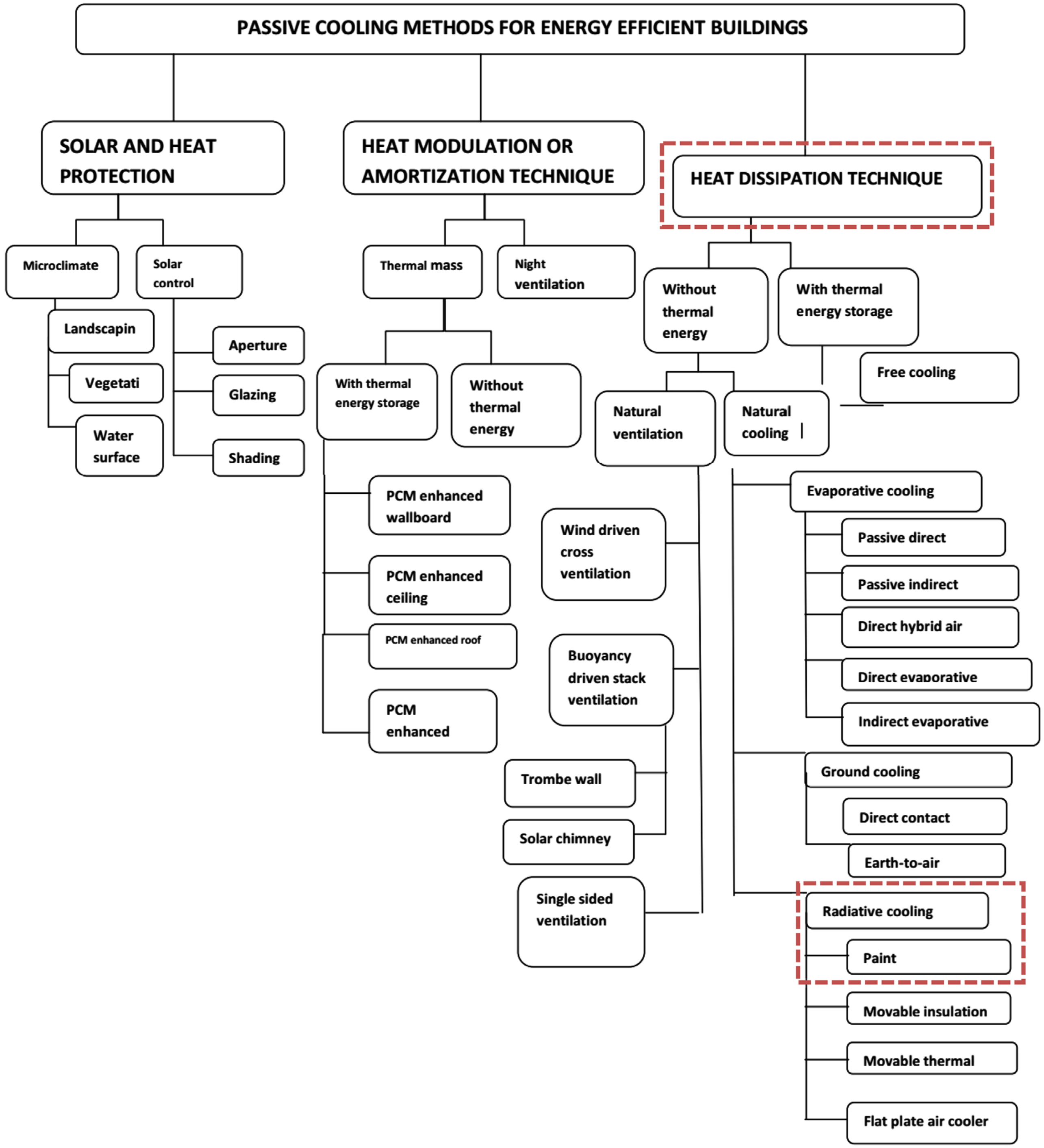

Figure 3 Classification of passive cooling approaches in energy-efficient buildings (Geetha and Velraj, 2012), red dashed lines represent the selected approach.

cooling source. Likewise, Kamal (2012) listed the most important techniques for passive cooling, which include solar shading, insulation, induced ventilation techniques, radiative cooling, evaporative cooling, earth coupling, and desiccant cooling. Moreover, Geetha and Velraj (2012) developed a very clear framework for the strategies of passive cooling, which generally fall into three categories: (i) heat prevention/reduction, (decreasing heat gains), (ii) thermal moderation (modifying heat gains), and (iii) heat dissipation (removing internal heat). The approaches that have been adopted and classified in literature are shown in Figure 3.

The present study does not intend to cover all these techniques, but focuses on the roof elements that adopt heat dissipation techniques, which have been discussed by Geetha and Velraj (2012). The study also selects the reflective and radiative approaches of the paint method, as listed in Figure 3. Finally, this study targets the relationship between the fundamental physical principles and

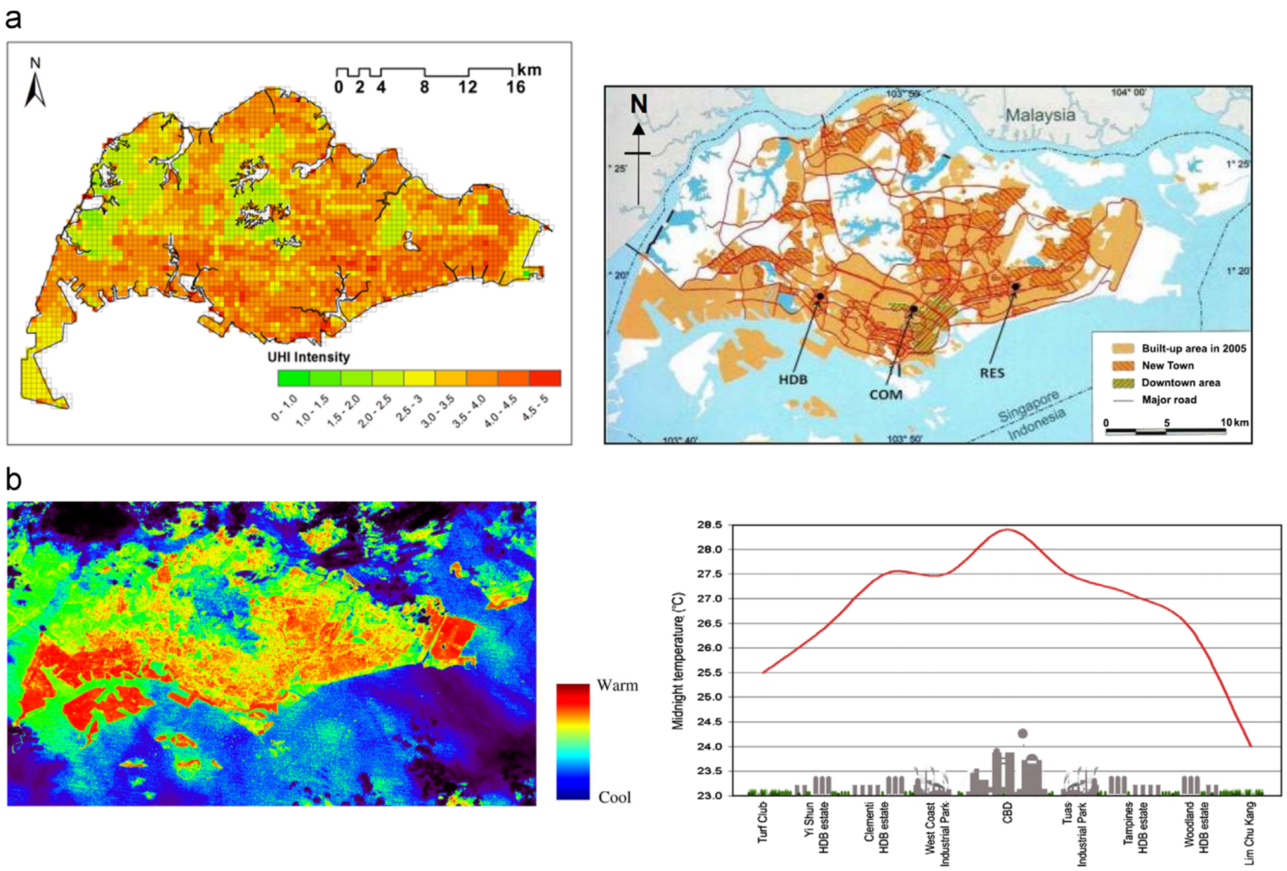

Figure 4 (a) UHI intensity map of Singapore (De Koninck et al., 2008) and (b) UHI profile of Singapore (Priyadarsini et al., 2008).

building roof design, which are classified as follows:

(1) Slowing down the heat transfer into a building (reflective cooling technique).

(2) Removing unwanted heat from a building (radiative cooling technique).

2. Reflective roof strategy (slowing down the heat transfer into a building)

Studies estimate that about 60% of urban areas are covered by roofs and pavements (Akbari et al., 2008). This figure continues to increase, given that 50% of the world's population are currently found in urban regions. This figure is expected to increase to 70% by the end of 2040. Such an increase has been clearly reflected in the behaviour of UHI. Wong et al. (2011) showed that the heat island intensity may increase by up to 10 °C, as had happened in India. As shown in Figure 4, the effect of urban development in Singapore is reflected by the quality of the city environment. De Koninck et al. (2008) reported that the surface air temperature of urban areas is very high, reaching up to 40–50 °C.

Priyadarsini et al. (2008) showed that downtown areas maintain their temperature at midnight, with the air temperature reaching as high as 28.5 °C. In contrast, other places in rural areas, whose air temperature reach below 4 °C, as shown in Figure 4(b). Wong et al. (2011) suggested that the UHI in Singapore indicates a potential increase of urban air temperature by 1 °C. Tso (1994) showed that if such trend continues, the energy consumption required to cool down the whole island will increase by 33 GWh per year within 50 years.

With a population of over 238 million, Indonesia is the world's fourth most populous country. This country consists of 34 provinces, with Bandung, the capital of the province of West Java, as the second largest metropolitan area. The urban areas of Bandung significantly suffer from high urban density, as shown in Figure 5. Tursilowati (2007) suggested that the surface temperature of the city will tremendously increase in less than ten years because of the construction of more roofs and pavements that come along with urban expansion.

These findings show that an increase in urban population translates to the relentless use more energy , and therefore an increase in the level of greenhouse gas emissions and UHI. Therefore, energy-efficient methods, such as the reflective colour strategy, are necessary to reduce such emissions and mitigate the rising cost of energy.

The colour of external surfaces (such that of the roof) has a remarkable counter-effect on the impact of solar radiation on buildings and the indoor temperature of buildings without air-conditioning systems. This technique is widely implemented in hot regions, but its application in the tropics remains imperfect. Concerning the issue on a small scale, Al Yacouby et al. (2011) showed that the colour of the majority of roof tiles in Malaysia is dark, as shown in Table 1.

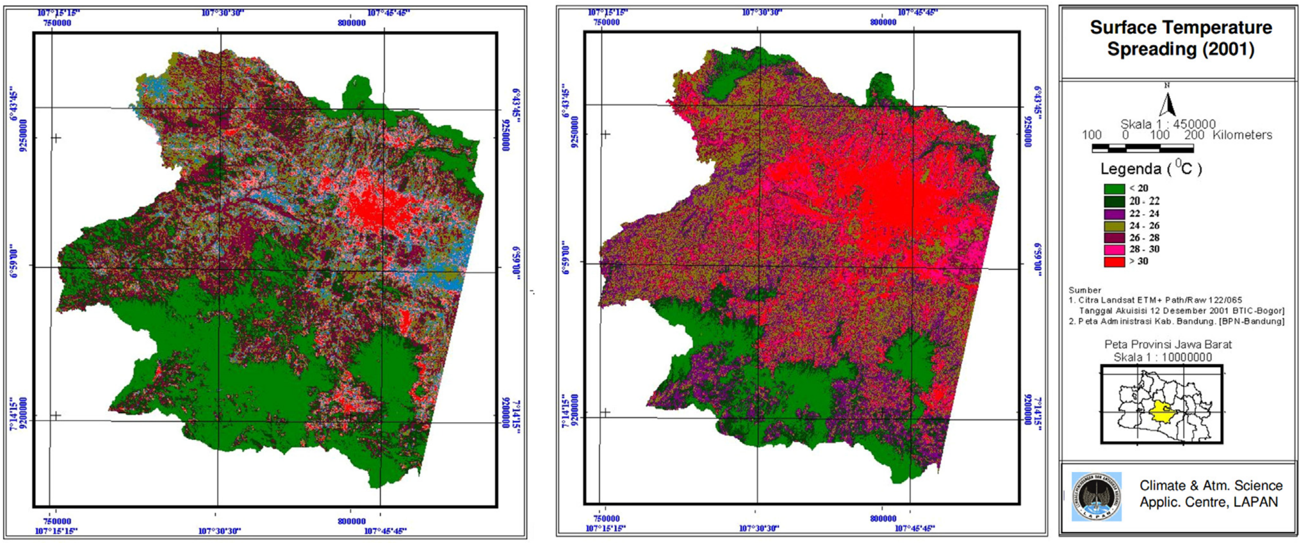

Figure 5 Surface temperature of Bandung spreading to the left (1994) and to the right (2001) (Tursilowati, 2007).

Table 1 Colour of roof tiles in Malaysia (Al Yacouby et al., 2011).

Roof colour	Percentage (%)
Red	38
Brown	25.9
White	9.5
Beige and Blue	7.8
Black	4.9
Grey	2.9

In fact, this review found that not one of the developed countries in Southeast Asia employs the reflective roof strategy. In Singapore, Building & Construction Authority launched the BCA Green Mark in 2005 to encourage the construction of energy-efficient buildings. However, no specific standard provided for the use of the cool roof technology. In Malaysia, the Ministry of Energy, Green Technology and Water specified energy efficiency standards in the building code such as Green Building Index. However, this standard does not include the use of cool roofs in Malaysia. In Indonesia, the Greenship asgreen building rating system was established in 2010 to introduce a standard for green initiatives and Overall Thermal Transfer Value (OTTV) calculation. However, no specific policy measure pertained to the use of cool roofs (Building System & Diagnostics Pte Ltd., 2011).

The study of Al Yacouby et al. (2011) on Malaysia showed that 27.9% of the survey respondents prefer red as the colour for the roof tiles of their new houses, 19.6% brown, 19.2% blue, 11.1% green, 9.6% grey, and 4.8% yellow. However, 68.8% of the respondents did not object to changing the colour of their tiles to white, if only to reduce the costs of air conditioning. Given this incipient interest on reflective roofing, this approach should be fully explained to both occupants and designers.

Givoni (1994) has been studying the effect of the colour of roofs since 1968 at the Technion in Haifa. His first study revealed that lightweight roofs made of a type of concrete called Ytong, which is 7, 12 and 20 cm thick and painted grey, investigated with a maximum external air temperature of approximately 31 °C, generate an average maximum external surface temperature of about 69 °C. The maximum ceiling temperatures are likewise significantly affected by the thickness of the roof: 45 °C, 39 °C, and 33 °C, respectively. Conversely, when the roof was painted white and investigated with maximum air temperature about 27 °C, the average external maximum surface temperature was about 27.5 °C. The maximum temperature of the ceiling was about 25.5 °C for all roofs.

These results showed that the intensities of solar radiation incidence on the roof varied depending on the colour and thermo-physical properties of the roof. Givoni (1994) showed that the the difference in the maximum external surface temperature between a black and white roof in the desert during summer can be between 30 °C–40 °C, a difference that can be considered huge and significant.

2.1. Characteristics of the reflective approach

Reflective roof is a design concept that aims to reduce the effect of heat gain on building roofs during sunny days (Akbari et al., 2006). This design consists of a single or multiple layers comprising different materials. The physical properties of the material surfaces are the major factors that affect roof behaviour, particularly if it is cool or not. Several reasons support the use of cool roofs:

- Enhance indoor thermal comfort of spaces without air-conditioning.
- Extend the service life of a roof by reducing roof operating temperature.
- Reduce energy consumption.
- Reduce the trapped heat in the atmosphere by

reflecting solar rays back into the sky, which can delay climate change.

Given that most of the light that is derived from the sun is visible, the concept of the reflective roof works with surface properties as a reflector of invisible electromagnetic radiation (short-wave and long-wave) and as a very good emitter of heat (infrared radiation), unlike dark or hot roofs that absorb huge amounts of solar energy (Urban and Roth, 2010). Urban and Roth (2010) showed that during hot days, the temperature of normal dark roofs reaches 66 °C or higher. By contrast, a reflective roof under a similar environmental condition maintains its temperature at about 28 °C.

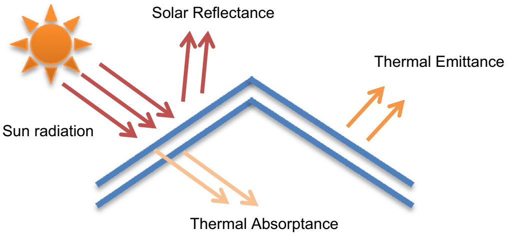

Figure 6 Behaviour of incident rays on roof surfaces.

Two key factors identified with the roof temperature are clearly related to the properties of the material surface, as shown in Figure 6.

(1) **Solar reflectance:** also known as albedo, this feature refers to the reflection of solar energy after it comes into contact with the surface material.
(2) **Thermal emittance:** this feature refers to the radiant emittance of heat of a specific object in the form of infrared or thermal radiation and pertains to how efficiently a surface cools itself.

Targeting the solar reflectance and thermal emittance of roof surfaces can lower the indoor air temperature and reduce the need for air conditioning in buildings, as shown in Figures. 7 and 8, respectively. Akbari et al. (2006) showed that replacing conventional surface colours with light colours significantly reduces the infrared radiation and heat absorption. For example, raising the solar reflectance of a typical residential dark roof from 0.10 to 0.35 can lessen the building's cooling energy use by 7–15%.

Various colours can function as a reflective component. Urban and Roth (2010) suggested that any coloured surface that can reflect more of the invisible solar rays is considered a cool dark colour or cool colour. For example, a light-

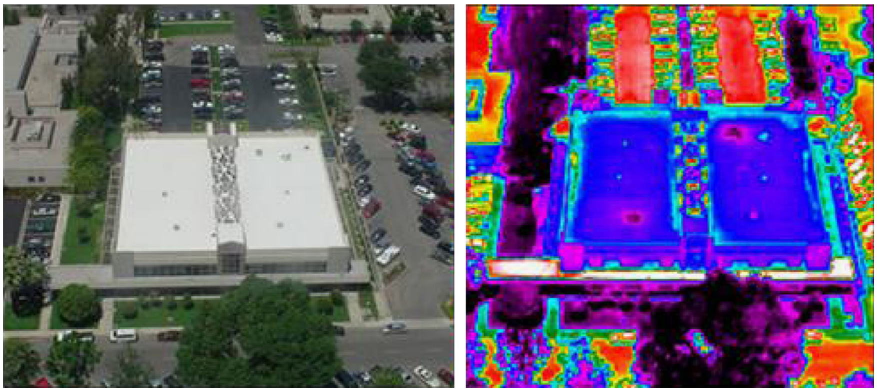

Figure 7 Dark vs. cool roof surface (IR). (Commercial Single Ply, INC., 2013).

Figure 8 Dark vs. cool roof surface. temperatures. (Urban and Roth, 2010).

coloured surface reflects 80%, a reflective dark-coloured surface reflects 40%, and a normal dark-coloured surface reflects 20% of the incoming sunlight.

2.2. Types of reflective roofs

Urban and Roth (2010) identified the different types of reflective roofs, which are as follows:

Types	Description
*** Flat roof**	
Cool Roof Coatings	Painted in white or special pigments that can reflect more sunlight. Such paints are very thick, thus preserving the roof surface from UV and chemical damages. This common type of coating is used in different roof systems.
*** Low-sloped roofs**	
Single-ply membranes	Consist of pre-fabricated sheets installed above the rooftop, fastened by mechanical fasteners and attached by ballast or chemical adhesives.
Built-up roofs	Composed of a base sheet, fabric reinforcement layers, and normally, a dark preservative surface layer. The sheet layer employs various methods to achieve the cooling options.
Modified bitumen sheet membranes	Consist of one or more layers of plastic support or rubber material supported with reinforcing fabrics and covered with a smooth finish or mineral granules.
Spray polyurethane foam roofs	Consist of a mixture of two liquid chemicals that together produce a strong chemical sprayed on the roof.
*** Steep-sloped roofs**	
Shingled roofs	Made from any type of material and composed of overlapping panels. Fiberglass asphalt shingles is one of the common types used in residential homes.
Tile roofs	Produced from concrete or simple natural materials, such as a clay or slate. Depending on their properties, clay and slate tiles naturally have a variety of colours. However, some of them have their own reflective cooling properties, whereas others do not meet the standards.
*** Low- and steep-sloped roofs**	
Metal roofs	Commonly obtainable through different types of finishing granular coated surfaces, natural metallic finishes or oven-baked paint finishes. In general, unpainted metals are low thermal emitters but adequate solar reflectors. The application of paint can enhance their solar reflectance and thermal emittance.

Cool roofs are typically white, and can be divided into single ply or liquid applied (Mac Cracken, 2009). Typically liquid applied products include white paints, acrylic coatings, polyurethane, or elastomeric. Santamouris et al. (2011) presented a recent study of the common liquid applied materials used in reflective roofs. The first-generation materials employed in cool roofs consist of natural materials with a relatively high albedo which is rarely higher than 0.75 (Doulos et al., 2004). The second generation was based on artificial white materials with values close or higher than 0.85 (Santamouris et al., 2008; Kolokotsa et al., 2012). The third phase of development, coloured high reflective materials have been proposed to have a high reflectivity value in the infrared spectrum (Levinson et al., 2005; Synnefa et al., 2007). The specific materials had a much higher global reflectivity compared with the conventional of the same colour. Recently, fourth-generation reflective materials based on nanotechnological additives have been developed, such as thermochromic paints and tiles (Karlessi et al., 2009) or PCM-doped cool materials (Pasupathy et al., 2008; Karlessi et al., 2011).

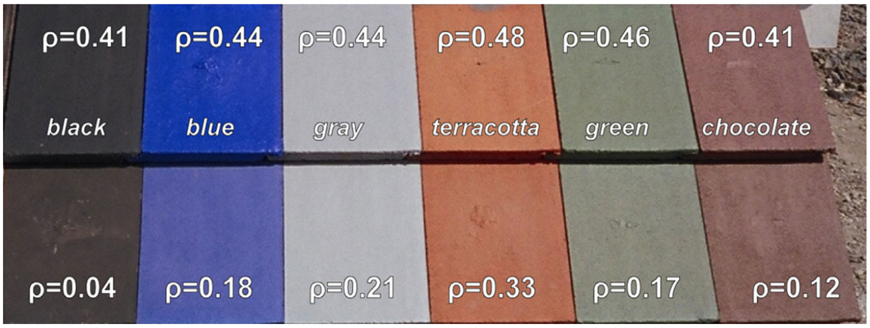

Figure 9 Cool dark colour roofs.
(*Source*: American Roof tile Coatings and Lawrence Berkeley National Laboratory).

Figure 10 Reflective white roof paint (Cool Roof Hawaii, 2013).

These materials are likely to be used for future cool roof applications.

Recently, many companies began to provide solar reflective pigmented colours to decrease household energy demand given that conventional coloured coat tends to absorb more than half of the power in sunlight. The new coloured pigments significantly reduce surface temperature, which consequently reduce the necessity for cooling energy in buildings with and without air-conditioning systems, as shown in Figures 9 and 10, respectively.

Akbari et al. (2006), showed that the application of new cool colours on roofs in residential sites as compared with the energy performance revealed that the attic air temperature under a cool chocolate brown concrete tile roof (solar reflectance 0.41) ranged from 3 K to 5 K (5.4–9 °F) cooler compared with that underneath at the same colour and type of conventional roof (solar reflectance 0.10). In addition, under the cool brown metal roof (solar reflectance 0.31); the attic air temperature was 5 to 7 K (9–12.6 °F) cooler than a similar colour and conventional roof type (solar reflectance 0.08).

Using cool colours on roofs are widely practiced to curb the increase in urban air temperatures. This method results in reduced demand for cooling needs. Rosenfeld et al. (1998) reported that in Los Angeles, each 1 K (1.8 °F) less in the diurnal maximum temperature drops peak demand for electric power by 2% to 4% and each 1 K (1.8 °F) decrease down to 21 °C (70 °F). If such reduction reaches 3 K (5.4 °F), the lower air temperature can likewise reduce the peak power needs by 200 MW, provide cooling energy savings worth $21 M/year, and yield a 12% reduction in ozone worth $104 M/year.

Recently, the use of reflective roofs for residential, commercial, and industrial buildings has aroused interest (Akbari et al., 2009; Olsen et al., 2010), given that it is one of the inexpensive solutions to mitigate global warming and reduce greenhouse gases. Many studies reported the capability of reflective roofs to control indoor temperature. According to Akbari et al. (1999) and Parker et al. (2002), nine homes in Florida, USA showed that the use of reflective roof coatings reduced the need for space cooling by about 20% to 70%. Similarly, Suehrcke et al. (2008) showed that using reflective colours on roofs in hot climates can significantly lower the downward heat flow.

In Malaysia, Al-Obaidi et al. (2013a, 2014e) conducted tests on the performance of the reflective roof, which yielded positive results. Another study by Al-Obaidi et al. (2014d) focused on the effect of roof colours with angles. The researchers found a significant reduction with reflective colour for the aluminium sheets. The reading indicates that maximum record for black-red roof colours was 5.08 °C and for black-white roof colours was 8.06 °C.

In addition, maintaining the cool roof's high solar reflectance over time is necessary. The maintenance of cool roofs is similar to traditional roofs, and making the roofs dirty reduces solar reflectance. Nevertheless, annual cleaning can restore up to 90% of the roof's initial reflectance (Bryan and Kurt, 2010). Coatings can retain most of their solar reflectance with proper maintenance, which is usually reduced by about 20% in the first year after the application of the coating (Bretz and Akbari, 1997).

In 2001, California revised its building energy code, adding cool roofing as an option for energy efficiency (California Energy Commission, 2006). With a minimum solar reflectance of 70% and minimum thermal emittance of 75%, unless it is a concrete or clay tile, has a minimum solar reflectance of 40%. In January 2003, Chicago amended its energy code requirements for low-sloped roofs. The installed low-sloped roofs and must attain a minimum solar reflectance (both initial and weathered) of 0.25 (Wong and Hogen, 2011).

Akbari et al. (2009) reported that retrofitting pavements and roofs with solar-reflective materials in urban areas, particularly in temperate and tropical regions, would offset 44 billion tonnes of emitted CO_2. However, the use of reflective roofs in countries with hot and humid climates such as Malaysia remains limited because of the lack of research to support this method (Al Yacouby et al., 2011; Al-Obaidi et al., 2014d).

2.3. Advantages and disadvantages

Asimakopoulos (1996), Oberndorfer et al. (2007), Aubrey (2010) and Akbariand Matthews (2012) categorised the advantages and disadvantages of the reflective roof systems. All the researchers agreed that the best cool-roof products in tropical climates considerably reduce the maximum solar heat gain by reflecting solar radiation by about 90%. The use of reflective colours lead to higher portions of incident solar radiation by offsetting at least 40 Gt to 160 Gt of emitted CO_2, as well as reduce UHI and energy consumption by lowering the energy demand for space conditioning.

However, reflective roofs lose its reflectivity, owing to the accumulation of dirt and weathering conditions, particularly in large cities. The use of reflective roofs is an effective strategy during hot months, but not during cold months. Moreover, highly reflective roofs result in visual discomfort and glare, and as such, its use is not advisable for areas near flight paths. Thus, the site topography and building regulations limit its application in some cases.

3. Radiative roof (removing unwanted heat from a building)

The radiative cooling approach is a technique based on the idea that any object or surface at a temperature higher than 0 K emits energy in the form of electromagnetic radiation. Given that more than half of heat transfer occurs through thermal radiation, radiant cooling systems is a viable mechanism for controlling surface temperature to reduce indoor thermal environment by removing sensible heat (ASHRAE, 2008). Heat will always flow from warmer to cooler surfaces. However, the radiant exchange process has a minimal effect on air temperature as compared with convection exchange, which accelerates the reduction of the air temperature when air comes in contact with cool surface. In general, radiant cooling methods function by absorbing the heat from hot surfaces inside a building and transferring it to cooler surfaces exposed to external environments, thereby diminishing the heat gain effect (Givoni, 1994).

Most roofs are directly oriented towards the sky, thus receiving maximum solar radiation in low-rise buildings. The roof represents the most effective radiator that can be used either passively or as a hybrid technique (Asimakopoulos, 1996), which can be applied both as a nocturnal radiator and as a cold storage (Kamal, 2012). Several techniques are used for radiative cooling, such as movable insulation, moveable thermal, and flat plat air cooler. Furthermore, paint can be used either on top or beneath the roof as a cost-effective solution.

3.1. The characteristics of the radiative approach

In general, when two surfaces with different temperature face each other, a net radiant flux will occur. The process will be repeated until an equilibrium state is reached, in which both surfaces radiate to cool down. Subsequently, the other side will respond directly if one of the surfaces becomes cooler. For example, a metallic flat-plate radiative air cooler cools down by dissipating infrared radiation to the sky when the sky is a low-temperature environmental heat sink. The heat sinks exchange the radiant heat based on the difference in the temperature between the sky conditions and the building component. In practice, the sky conditions have a significant role that affects the process of radiative cooling strategy as cloud covers, air humidity, and pollution could directly reduce the strategy's performance (Asimakopoulos, 1996).

Radiative system works both day and night. During the day, the roof can function as an absorbent of the heat from the room below (Alvarez et al., 1991). During the night, the roof is exposed to the night sky, losing heat through long-wave radiation and convection (Kamal, 2012). Given that the roof absorbs the most significant part of the solar radiation during hot days, the amount of the temperature that reradiate from hot roof surfaces during the summer time can reach up to 750 W/m^2 when the roof surface temperature is around 65 °C (Bowman et al., 1997). Nevertheless, the potential of surface radiative is reduced when the surface is surrounded by hot air.

Using the roof to maximise long-wave radiation (i.e., night radiation) at night to reduce space cooling in buildings has been employed for centuries. However, its most recent references are from 1984 show that radiation cooling under the night sky is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower

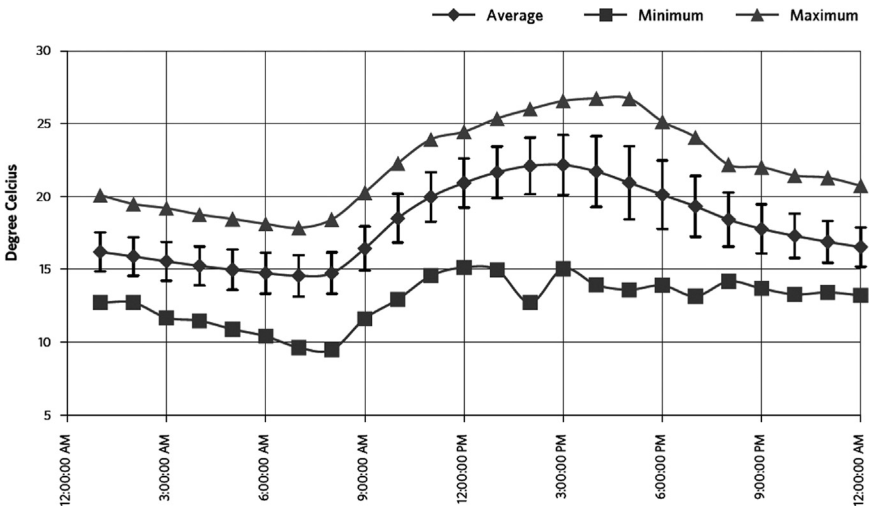

Figure 11 Effective sky temperature in Malaysia (BSEEP, 2013).

temperature. Night time radiation cooling is largely dependent on atmospheric water vapour conditions, which include cloud cover and ambient relative humidity. Low humidity areas, such as desserts and areas at high elevations, can result in large temperature drops. Nevertheless, even mild winds can overwhelm the cooling effects of radiation.

Overall, the daily average cooling potential for July amounted to 63–110 Wh/m^2 of roof surface in the US, depending on the climate locations. During a 10 h night, the cooling potential reaches about 250–450 W/m^2 if all the energy can be effectively utilised. Parker (2005) reported that in Florida, the night-time temperature depression of a white metal roof surface is below the aspirated air temperature from 9 PM to 7 AM. The minimum roof surface temperature is limited by the dew point temperature.

In tropical countries such as Malaysia, the effective sky temperature can determine the performance of night radiation. The Building Sector Energy Efficiency Project (2013) showed that the maximum effective sky temperature is obtained at around 20 °C from 3 AM to 11 AM. This result is a very good indication of the effectiveness of using radiative roofing system in this region, as shown in Figure 11.

In general, horizontal surfaces are good radiators of heat back to the sky. However, under tropical conditions, using different angles are more favourable. To delay the transfer of heat gain impact, traditional architecture designs in hot, dry, and sub-tropical climates serve as very worthy models of radiative cooling by the use of vaulted roofs. To curb the amount of heat gain, a vault element is larger than its horizontal base, which is about three times larger than a hemispherical roof. Hence, this element serves as a large storage surface during the day and a large radiative surface at night (Asimakopoulos, 1996). This process is typical of pitched tropical roofs with surface areas larger than its horizontal base. However, the storage surface value depends on the material properties, solar incident, and roof angles.

The strategy of using roof colour as well as the use of lightweight structures influence the thermal performance of a building, the reflection of incident solar radiation during daytime, and the emission of long-wave radiation during night time (Santamouris, 1990). This approach has the potential to provide a cooling possibility of 0.014 kWh/m^2 a day. To enhance the efficiency of this approach, protecting the roof during the day is preferable. This can be achieved using different strategies, such as reflective, flat plate air cooler or movable insulation system. The potential of these methods significantly increases with movable insulation that lends a cooling potential of 0.266 kWh/m^2 a day (Givoni, 1994).

To effectively apply the technique of using colour methods, considering the physical factors that can potentially reduce the total heat gain is recommended.

3.2. Black body

One of the principles of radiation states that all surfaces emit thermal radiation based on its surface properties. Thermodynamics can be used to assess the maximum thermal energy from the building surfaces. However, the ultimate reference for radiation is the concept of the 'black body' that can generate this energy (radiation) at any temperature and at any wavelength (Asimakopoulos, 1996). A black body is an ultimate body that absorbs all incident radiation impinging on it, for all wavelengths and angles of incidence of the radiation, emitting the maximum radiant energy at every wavelength. The mechanism to describe system performance depends on the black body emission under the same conditions, using the coefficient called emissivity. The emittance refers to a heat ratio emitted from materials compared to a black body on a scale from zero to one. A perfect reflector would have a value of 0; a blackbody would have an emissivity of 1 (Sustainable Buildings, 2013).

The radiation interacts with a body through reflection, transmission, or absorption. Consequently, the radiation incident on a body is partially reflected, partially absorbed, and partially transmitted through the body. The fractions of the absorbed, reflected, and transmitted radiation are called absorptivity, reflectivity and transmissivity,

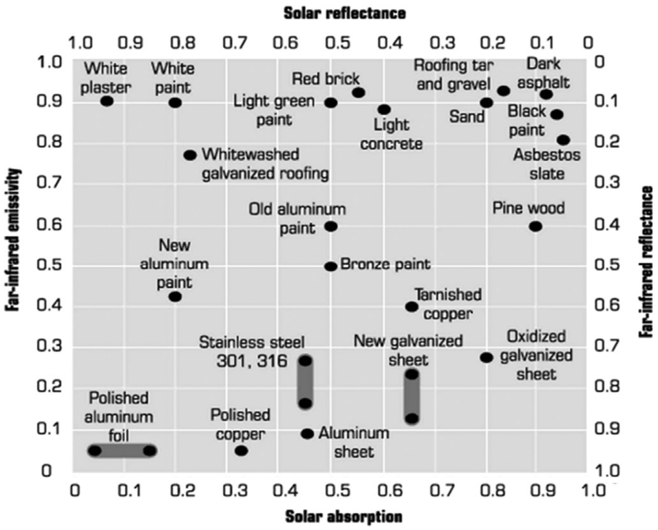

Figure 12 Spectral characteristics of building materials. (*Source*: Florida Solar Energy Centre).

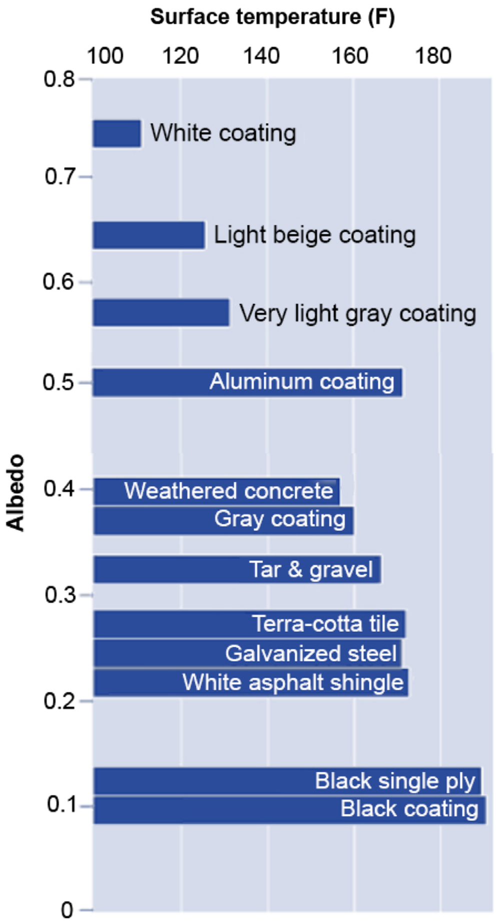

Figure 13 Albedo and surface temperature. (*Source*: Lawrence Berkeley).

respectively, all of which are equal to 1. Distinguishing the material properties involved for two zones of the electro-magnetic spectrum is essential in building physics. Absorptivity is necessary for the solar spectrum wavelengths to assess solar gains. In addition, emissivity is necessary in the long-wave range of the electromagnetic spectrum in order to assess radiative heat losses (Santamouris, 2007).

Radiative heat exchange is completely different from the other transfer mechanisms, namely, conduction and convection (Asimakopoulos, 1996):

- The electromagnetic nature of thermal radiation causes the occurrence of radiative heat exchange even without the presence of a physical medium.
- Conduction and convection becomes stable when thermodynamic systems achieve a balance at the same temperature. However, radiative heat exchange is a dynamic phenomenon.

To better understand the mechanism of radiative heat exchange, the effects of the colour and material properties in building design should be identified.

(1) **Solar reflectance and solar absorptance** Solar reflectance refers to an albedo strategy that involves solar energy reflection after its incidence on a surface material. However, solar absorptance refers to the proportion of the overall solar radiation incidence that is absorbed by the roofing material. A roof with a lower solar absorptance will reflect more heat and keep the roof space relatively cooler compared with a roof with a higher solar absorptance. As shown in Figures 12 and 13, solar absorptance is typically related to the colour of the roof, lower than 0.475 (light), 0.475–0.7 (medium) and higher than 0.7 (dark) (Builidng Sustainability Index, 2013).

(2) **Thermal emissivity and thermal absorptance**: Thermal emissivity refers to a remitted factor of solar energy that absorbs sunlight as infrared or thermal radiation to demonstrate the efficiency of a surface in cooling by itself. Thermal absorptance is the ratio of the fraction of incidence long wavelength radiation absorbed by a physical surface to the incidence on it (ASHRAE Technical Committee 1.6, Terminology). The values for this field must range from 0.0 to 1.0 (Design builder, 2013).

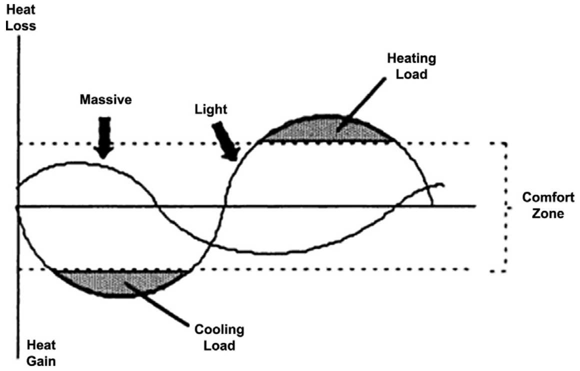

Figure 14 Daily building heating and cooling loads for buildings of massive and light construction (Asimakopoulos, 1996).

The Cool Roof Rating Council used two measurements, namely, solar reflectance and thermal emittance, to examine the performance of a cool-roof product and determine which is more effective. Aubrey (2010) reported that when photons from solar radiation strike a surface of opaque material, these photons are either reflected or absorbed. However, reflectance is significantly reduced if applied on rough surfaces, considering that photons reflect a second time reduces their strength, thereby increasing the effectiveness of the absorbance of the material. The Kirchhoff's Law of Thermal Radiation states that in every band, a passive body must emit the same proportion of thermal radiation as it absorbs. Therefore, a rough or granular surface tends to increase thermal emissivity and diminish solar reflectance compared with the use of a smooth flat surface. Aubrey (2010) showed enhancing solar reflectivity from 0.80 to 0.90 halves the absorbed solar radiation as compared with improving thermal emissivity from 0.80 to 0.90, which increases thermal radiation by only 11%. The study showed that in selecting a radiative roof, solar reflectivity is more effective than thermal emissivity.

Similarly, the radiative approach is related to thermal mass properties as thermal conductivity, specific heat, and density. These properties can effectively help improve the technique performance. Nevertheless, the application of

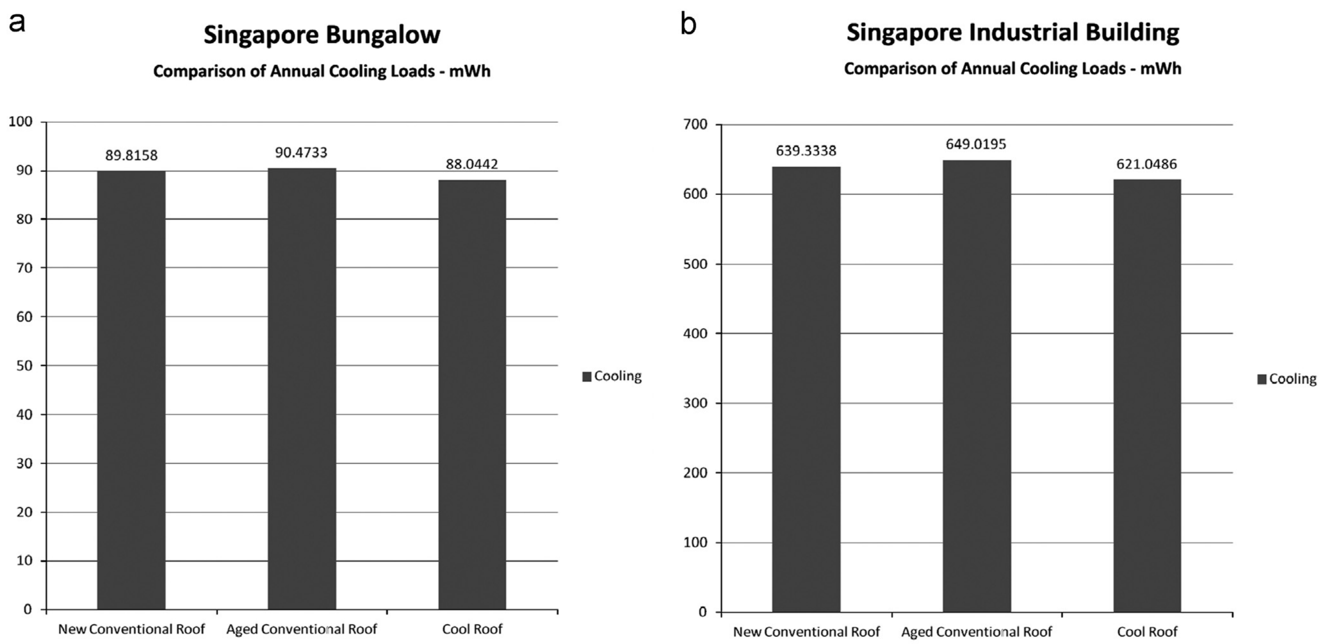

Figure 15 (a) Annual Energy usage for bungalows in Singapore; (b) annual energy usage for industrial building in Singapore (Building System & Diagnostics Pte Ltd., 2011).

this technique will differ for heavy and lightweight constructions, as shown in Figure 14.

3.3. Advantages and disadvantages

Asimakopoulos (1996), Mumma (2002), and Cavelius et al. (2007), reported that radiant cooling systems can work both day and night because this approach possesses the best view of the sky dome, making it an effective radiator. Radiant cooling appears to save more in costs and lifecycle costs in contrast to conventional methods. The best radiative cooling products can considerably reduce the peak solar heat gain to 40 W/m^2.

Nevertheless, dust will accumulate on a roof in reality, which reduces solar reflectance of highly reflective surfaces. This action will keep degrading over long periods. Furthermore, radiant exchange has fewer effects on air temperature, thereby requiring a supportive process to improve the strategy.

Finally, the application of the reflective and radiative approaches is quite effective. According to a study by the Lawrence Berkeley National Laboratory, the savings brought by the use of radiant cooling energy in the US was around 30% in comparison with conventional techniques. Specifically, hot, arid regions saved about 42%, which is higher than cool, humid regions, which had savings of around 17% (Stetiu, 1999). In Singapore, Building System & Diagnostics Pte Ltd. (2011) compared three different types of roof, namely, new conventional roofs, aged conventional roofs, and cool roofs, in domestic and industrial buildings. The cool roof was found to reduce the annual cooling loads significantly, as shown in Figure 15.

4. Conclusion

Implementing reflective and radiative approaches in roofing systems will enhance environmental sinks for heat dissipation, thereby minimising the effect of heat penetrating, as well as contributing to the reduction of internal gains through day lighting and appliances. However, their efficiency depends on the building type, the occupancy patterns, and climatic boundaries (e.g., air temperature, relevant humidity, velocity and direction of winds), which differs from day to day and from one region to another. Therefore, to effectively improve heat rejection from buildings by natural means, the physical characteristics of the building should be sufficiently understood by the designer. Moreover, selecting an inappropriate technique may result in an unpleasant indoor environment.

Hence, the limitations in evaluation tools and insufficient information for both designers and building users are found to be the major reasons for not adopting of passive cooling strategies in tropical houses. Al Yacouby (2011) stated that 68.8% of the respondents in tropical regions, particularly in Malaysia, had no objections to modifying their roof to reduce the need for air conditioning. Such result shows that the respondents are willing to adopt passive cooling strategies in the buildings for economic reasons, for such strategies constitute the most cost-effective methods for creating an optimally cool environment.

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