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Effect of pavement materials on surface temperatures in tropical environment

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ABSTRACT

Loss of natural habitat and increased use of man-made materials have led to higher temperatures in tropical urban landscape. One way to handle this issue is by using paving materials that absorb less amount of heat and provide lower surface temperatures. This paper identifies several pavement materials with low surface temperatures for potential use in a tropical climate. The study was conducted in Putrajaya, Malaysia. Paving materials selected were Blue Impala polished granite (BIPG), Rosa Tanggo polished granite (RTPG), Fontana concrete (FC), and asphalt (AS) based on their popularity of use locally. Surface temperatures of these materials were measured using infrared thermal imaging camera in three different environments namely open space (OS), near water (NW), and under shade (US). The readings were recorded for 28 consecutive days from 6:00 to 24:00. Results indicate that BIPG was 15.5 °C cooler than AS during 12:00–15:00 in OS locations. However, BIPG and RTPG surface temperatures increased in NW locations as compared to OS and US locations from 12:00 to 18:00. This study provides information on the use of suitable paving materials to reduce surface temperatures of urban areas in tropical climates.

1. Introduction

Urbanization contributes to both air and surface temperature increases in urban areas when compared to the rural environment (Maimaitiyiming et al., 2014; Santamouris, 2014). The changes in the density of vegetation and their substitution with urban infrastructures can affect world's climate (Wong & Yu, 2005; Zheng, Myint, & Fan, 2014). In recent decades, such changes result in altering the ventilation patterns as well as increasing air and surface temperatures (Grimmond et al., 2010; Sakka, Santamouris, Livada, Nicol, & Wilson, 2012). High temperature in urban areas is due to anthropogenic heat release, reduced vegetation, denser built areas, reduction of air circulation and evapotranspiration in urban canyons, and the increase of urban structural surfaces. These depreciate emission of infrared radiation and exacerbate storage of solar radiation (Oke, Johnson, Steyn, & Watson, 1991; Santamouris, 2014).

The development of commercial, residential, and industrial areas displaced natural environment and result in buildings and paved urban areas covered with impervious and rigid materials (Santamouris, Papanikolaou, & Livada, 2001; Tran, Uchihama, Ochi, & Yasuoka, 2006). New and darker surface materials absorb and store more solar energy and terrestrial infrared radiations. These materials heat up during the day, and then reradiate this heat during the night making urban temperatures higher than the adjacent rural surroundings (Rizwan, Dennis, & Liu, 2008; Synnefa, Santamouris, & Livada, 2006). These high temperatures brought negative effects such as increase in energy demand for cooling (Akbari, Pomerantz, & Taha, 2001; Santamouris, 2013), worsen pollution and create air quality problems (Huang, Ooka, & Kato, 2005), increase health disorders and human discomfort (Santamouris, Synnefa, & Karlessi, 2011), and decrease water quality (Maimaitiyiming et al., 2014).

Santamouris (2014) described ways to mitigate and balance the impact of urbanization to reduce the positive thermal balance of cities. These techniques include planting of greenery, applying natural cool sinks, and improving urban morphology (Maimaitiyiming et al., 2014; Nur, Sanusi, Azlan, & Zamri, 2014; Santamouris, 2014) and using highly reflective and cool pavement materials. Cool pavement materials are materials that potentially make surface temperature lower and release less heat into the environment (U.S. EPA, 2008). The major impact of urban heating is on urban land surfaces, where there is more built up areas including paved areas (Carnielo & Zinzi, 2013; Santamouris, 2013). Developing

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and applying appropriate and cool materials with high reflectivity and thermal emissivity influence thermal performance of urban surfaces. They also contribute to less solar and terrestrial heat storage and water evaporation leading to lower surface temperatures (Carnielo & Zinzi, 2013; Tan, Lim, MatJafri, & Abdullah, 2009). Materials used as building surfaces (both vertical and horizontal) and outdoor pavements played a significant role in heat transfer between urban areas and the surrounding environment (Dimoudi et al., 2014; Doulos, Santamouris, & Livada, 2004) creating isolated urban heat islands (UHI).

Heat island is a stagnant dome of air above urban areas caused by heat absorbed and released by buildings, paved structures, and other impervious surfaces (Christensen, 2005; Emmanuel, 2005). Urban heat island can be categorized into the atmospheric heat island and surface heat island. The Atmospheric Heat Island occurs when there is warmer air in urban areas as compared with rural areas and found in the canopy and boundary layers. Meanwhile Surface Heat Island occurs where there is a higher urban surface temperatures as compared with rural areas and this is found in urban horizontal surfaces such as bare ground surfaces (Li, Harvey, & Kendall, 2013; Radhi, Assem, & Sharples, 2014). In UHI the air temperature of the urban area is warmer than surrounding areas and varies during day and night. The lowest air temperature difference between urban and rural areas occurs during morning time while this difference increases during the day when urban surfaces get warm and heat up the air temperature. The worst condition is found during night time when the heated urban area surfaces transfer heat back to the atmosphere and slows down the process of cooling the air temperature. This results in warmer air temperatures at night (Salleh, Abd.Latif, Mohd, & Chan, 2013; Wong & Yu, 2005). Surface temperature UHI as the second type of urban heat island and is in contrast to air temperature UHI. In surface temperature UHI the highest temperature span occurs during daytime as a result of dense buildings and paved surfaces. However, the minimum surface temperature is during night time (Grimmond et al., 2010). The peak surface temperature is during solar noon hours (Grimmond et al., 2010; Md Din et al., 2014; Outcalt, 1972) During these hours urban surfaces heat up from 27 to 50 °C by the solar radiation. Thus, the surface temperature is significantly much higher than air temperature (Santamouris et al., 2011; Synnefa, Santamouris, & Akbari, 2007).

Pavements cover much of urban surfaces and lead to development of heat island. On the other hand, pavements have the potential to offset urban thermal condition. One of the most effective techniques to mitigate heat island and reduce surface temperature in urban areas is by selecting appropriate pavement materials (Santamouris, 2013; Dimoudi et al., 2014). However, previous studies indicated that pavement materials contributed to high urban surface temperatures in dry and hot climate. As pavement materials will increase surface temperatures and turns air temperatures 2–3 °C higher than the surroundings. For instance, the temperature in Los Angeles, California was 3 °C higher in 1995 than in 1940 (Rosenfeld, Akbari, & Bretz, 1995). In the tropical climate, paving surfaces with low reflective man-made surfaces such as concrete, bricks, and asphalts can bring the air temperature to as high as 40 °C. Krishnan (2007) reported that the city of Putrajaya is 5 °C hotter than other cities in Malaysia due to the urbanization and UHI effect.

In another study it was reported that in 1985 Kuala Lumpur city center had an average temperature of 28.0 °C while its suburbs' had an average temperature of 24 °C. Then in 2004, the city center recorded an average temperature of 29.2 °C while the suburb had an average temperature of 23.7 °C. The study concluded that the main reason for the increase in temperature and UHI intensity in Kuala Lumpur city center was caused by urbanization and the development of industrial land uses. These had replaced vegetation substituting them with multi-storied buildings and pavement materials (Elsayed, 2012).

Salleh et al. (2013) who conducted a study in Putrajaya found that urbanization resulted in a 21% increase in urban land use from 1999 to 2009. This expansion of urbanization correlates with the surface temperature increase from 22 to 38 °C (16 °C increase). It should be noted that even a 1 °C increase in temperature will result in catastrophic ecosystem failure in urban areas (Salleh et al., 2013).

In Putrajaya, among the most common pavement materials used are polished granite, compressed concrete, and asphalt. Thus, this study attempted to identify pavement materials with cooler surface temperatures to mitigate high urban surface temperatures in a hot and humid tropical climate.

2. Methodology

The objective of this study is to identify pavement materials with the lowest surface temperatures for potential use in hot and humid climate by measuring their surface temperatures. The study was conducted in Malaysia's administrative capital of Putrajaya. A study was conducted that includes three phases: First, exploring theories and specifying the knowledge of temperature reduction through the pavement materials, which is supported by literature review and doing an archival analysis. Second, collecting classified plans and maps from Perbadanan Putrajaya (PPJ), conducting a field study to determine climate condition, and collecting meteorological data (on air temperature, sun position, and climate condition from the Malaysian Meteorological Department and Perbadanan Putrajaya) and determining, different time and landscape environments based on previous findings. Finally, measuring the surface temperature of the most dominant pavement materials in Putrajaya at various time periods (6:00–24:00) and landscapes environments (open space, under shade, and near water). The last phase involved the process using the infrared thermal imaging camera (FLIR E60) to measure surface temperatures of the selected pavement materials. The data collected were analyzed by comparing surface temperature and air temperature to understand the thermal behaviors of different pavement materials.

3. Description of materials and sites

3.1. Site location description

Putrajaya is approximately 25 km south of Kuala Lumpur city and 20 km north of the Kuala Lumpur International Airport (KLIA). While Kuala Lumpur remained as the country's capital and premiere financial and commercial center, Putrajaya is the Federal Government Administrative Centre (PPJ, 2013). UHI problems and temperature increase in the worst case scenario occurred along the public artery in the city known as Putrajaya Boulevard (PPB). It is the longest boulevard in Putrajaya connecting Putra Square (Presint1) in the north to the Putrajaya International Convention Centre (PICC, Presint5) in the south. This thoroughfare spread in the center of the federal administrative area and is 100 m wide and 4.2 km long. The PPB was designed with a mixed pavement materials such as white polished granite, rough white granite, red and yellow concrete, and asphalt on a 40 m wide strip with little vegetation. The albedo in PPB varied from 0.3 to 0.4 on the average (ENVI-met Bruse, 2008; PPJ, 2013). The most dominant pavement materials were asphalt and concrete with the average albedo of 0.2 and 0.4 respectively. These are used to pave roads, walkways and parking spaces (Santamouris, 2013; PPJ, 2013). Part of PPB passes through Presint2 (Fig. 1).

Putrajaya consists of twenty Presint (precinct). Presint 2 is located in the center of the city with good access to other parts of the city. It is one of the main tourists' destinations in Putrajaya