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Review

The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete

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ABSTRACT

The Urban Heat Island (UHI) is a phenomenon that affects many millions of people worldwide. The higher temperatures experienced in urban areas compared to the surrounding countryside has enormous consequences for the health and wellbeing of people living in cities. The increased use of manmade materials and increased anthropogenic heat production are the main causes of the UHI. This has led to the understanding that increased urbanisation is the primary cause of the urban heat island. The UHI effect also leads to increased energy needs that further contribute to the heating of our urban landscape, and the associated environmental and public health consequences. Pavements and roofs dominate the urban surface exposed to solar irradiation. This review article outlines the contribution that pavements make to the UHI effect and analyses localized and citywide mitigation strategies against the UHI. Asphalt Concrete (AC) is one of the most common pavement surfacing materials and is a significant contributor to the UHI. Densely graded AC has low albedo and high volumetric heat capacity, which results in surface temperatures reaching upwards of 60 °C on hot summer days. Cooling the surface of a pavement by utilizing cool pavements has been a consistent theme in recent literature. Cool pavements can be reflective or evaporative. However, the urban geometry and local atmospheric conditions should dictate whether or not these mitigation strategies should be used. Otherwise both of these pavements can actually increase the UHI effect. Increasing the prevalence of green spaces through the installation of street trees, city parks and rooftop gardens has consistently demonstrated a reduction in the UHI effect. Green spaces also increase the cooling effect derived from water and wind sources. This literature review demonstrates that UHI mitigation techniques are best used in combination with each other. As a result of the study, it was concluded that the current mitigation measures need development to make them relevant to various climates and throughout the year. There are also many possible sources of future study, and alternative measures for mitigation have been described, thereby providing scope for future research and development following this review.

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1. Introduction

The aim of this literature review is to present and define the various developments and studies that have occurred with regard to the thermal properties of asphalt concrete (AC), and their associated effect on the environment. This study summarises the surface temperature, albedo and other limiting factors of AC, and links these closely to the urban heat island (UHI) effect. The UHI effect is defined and analysed, and the mitigating methods for this phenomenon ailing urban environments, as described in the literature, is discussed. This review also identifies areas in which there has been minimal study, and provides scope for future research and development accordingly.

2. Background to the urban heat island

The UHI is a global issue that threatens the operation and habitability of our cities and urban environments. According to Oke (1982), the concept of the UHI has been well researched and documented; however, the understanding of the topic is quite limited. This has changed in recent years as a result of a greater focus on global warming and climate effects, the greater prevalence of hotter cities, and due to changes in technology for measurement and analysis. The heat island effect is characterised by the development of noticeably higher temperatures in our cities compared with the countryside that directly surrounds them (Nakayama and Fujita, 2010; Synnefa et al., 2011; Santamouris, 2013b, 2015a). Initial studies conducted by the World Meteorological Organisation (1984) and Oke (1982), cited in Gorsevski et al. (1998), revealed that the UHI effect can increase air temperature in an urban city by between 2 and 8°C. Recent studies illustrate that a more accurate range is between 5 and 15°C (Santamouris, 2013a). The heat island effect arises due to the changing nature of our cities, and is the result of a reduction in vegetation and evapotranspiration, a higher prevalence of dark surfaces with low albedo, and increased anthropogenic heat production (Stone et al., 2010). Therefore, the existing surface conditions of an urban area will directly impact on the chosen UHI mitigation strategies. Akbari and Rose (2008) found that the average urban surface of four different metropolitan areas in the USA were characterised by 29–41% vegetation, 19–25% roofs and 29–39% paved surfaces. This demonstrates that over 60% of an urban surface can be covered by hard, man-made, heat-absorbent surfaces. The authors concluded that knowledge of the urban fabric and surface conditions of a city is important in order to explore the effects of possible UHI mitigation measures.

The UHI can be illustrated by drawing a curve from one side of a city to the other, mapping graphically the temperature change from the rural to the urban environment and back to the rural environment. The 'island' would be represented by the large spike in the centre of the graph, which generally mimics the outline of the structures within the urban area, and is bound by the cliffs either side that mark the urban and rural boundary (Oke, 1982). By illustrating the UHI in this way, it is easy to recognise the profound increased temperature difference to which our cities are exposed. Yang et al. (2015), in their studies on UHI, illustrate the temperature intensities of UHI for various cities around the world. This effect is only getting greater, and, hence, it is important that strategies are developed for adapting to, and mitigating the adverse environmental effects of UHIs (Yang et al., 2015). In most research to date, the primary solution to the UHI has been replacing dark materials with high albedo light-coloured materials for greater solar reflectivity. This, however, is not the only solution (Stempihar et al., 2012), and further methodologies are illustrated in this review.

2.1. Regional atmospheric and geographic conditions

The regional atmospheric and geographic conditions are a key determinant of the UHI effect and its intensity in cities. The UHI effect is significantly affected by the geographic features, climatic conditions, and seasonal variations of a city's particular location. Even the time of day will dramatically affect the intensity of the UHI. Take for example night-time, during which the emissivity of a pavement and the heat radiated into the atmosphere are the most critical contributors to the temperature of the surface and lower atmosphere within an urban canyon (Santamouris, 2013b). Debbage and Shepherd (2015) conducted a study of the fifty most populous cities in the USA using PRISM data (a climate data collection network that incorporates various monitoring methods and stringent quality control measures). The authors found that geography and climate heavily affected the manifestation of the UHI across the US. For example, Salt Lake City exhibited the highest UHI effect due to the high prevalence of calm, clear and stable conditions that are ideal for UHI formation. This localised atmospheric condition resulted in the UHI being most intense during the winter months. In addition, the authors identified mitigation techniques that worked during summer but increased the UHI in