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On the colours and properties of building surface materials to mitigate urban heat islands in highly productive solar regions

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ABSTRACT

An experimental study was conducted to assess the impact of building surface materials on urban heat islands (UHI) in highly productive solar regions. The study involved 32 surface materials commonly used in Bahrain and was performed during the summer period. The current work focuses on finishing materials at horizontal surfaces and examines the influence of material thermophysical and solar properties on their surface temperatures (*Ts*) and surface air temperatures (*Ta*) under clear sky conditions. A twofold assessment was deployed: first, experimental measurements of horizontal sample materials exposed to solar irradiation on a flat roof, and the second assessment involved full-scale experiments of roofs with different construction configurations. The analysis showed that the standard error of measurement in measured temperatures for all roofs was less than 3.5 °C, the standard error of mean was between 1.5 and 2.5 °C and the largest difference in standard deviations was 4 °C, indicating low bias. The range of errors in measurements was highest for the temperature of a dark porcelain roof. Overall, the errors were similar over all roofs. This work suggested that white and light colour materials were important to cope with surface UHI, while cool materials were beneficial and sensitive to highly productive solar regions, whereas materials with low heat storage capacity were significant as an atmospheric UHI reducer.

1. Introduction

Properties and configurations of buildings have a significant impact on the thermal performance of urban environments. Such properties and configurations influence the development of urban heat islands (UHI), particularly when surface temperatures of exposed materials (*Ts*) become higher than their adjacent air temperatures (*Ta*) due to high solar irradiation – surface UHI. The increase in *Ts* affects the intensity of local and downwind air temperatures – atmospheric UHI, especially closer to the surfaces, due to various convective heat fluxes from the surfaces [1]. Increases in temperatures influence the quality of life as can be seen in the increased energy consumption for air-conditioning, elevated greenhouse gas emissions and compromised human comfort. Two recent studies [2,3] examined the development of UHI phenomena in Bahrain and assessed their impact on the electricity consumption. Industrial regions were found to have higher UHI values due to various human activities including anthropogenic heat and sensible heat fluxes from urban surfaces such as roads and roofs. During the summer months, an increase of up to 10% in electricity consumption for air-conditioning occurred in those industrial regions.

Many sources assessed the role of urban surfaces in the development of UHI and proposed many solutions in order to reduce their impact on atmospheric and surface UHI. Some made use of vegetated systems [4–6] while others utilised white and cool materials. Past simulation analyses and test cell studies showed that the performance of materials under the sun was strongly correlated to the solar reflectance and the infrared emittance [7–10]. The former represents the ability of a material to reflect solar irradiation, while the latter relates to the ability of a material to release absorbed heat [11]. Materials with low values of reflectance or emittance would not typically be considered cool. Similarly, a high reflectance value alone will not result in a “cool” material nor will a high emittance value alone. In order to accurately determine the “coolness” of any given materials, the solar reflectance index (SRI) can be a useful measure [12,13]. It is a composite value of solar reflectance and thermal emittance calculated using the equation in ASTM E1980 [14]. In practice, SRI value for black surfaces would be close to 0 while for white surfaces, the SRI value would approach 100%. Normally, dark colour materials have a lower solar

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reflectance than light colour materials. Recently, however, some dark coloured materials have been developed with higher reflective values due to the use of cool coatings or some thermophysical treatments, and consequently have a high SRI. Therefore, cool materials are those coloured materials with high solar reflectance [15].

A recent study [16] proposed an international campaign to use cool materials in cities worldwide in order to reduce cooling energy and mitigate summer UHI. This technique is widely used for roofs, pavements and recently facades. Various techniques have been used to assess the performance of cool materials including laboratory and mathematical analyses. Such techniques are important for any accurate assessment. Experimental studies are also important to get realistic measurements. However, to show the intersection between surfaces and urban elements, full scale experiments are needed. For example, a laboratory and mathematical analysis of roof materials was conducted in Brazil to calculate the temperature that each material can reach when exposed to solar irradiation [17]. The analysis demonstrated that same coloured metal and ceramic materials reached different temperatures according to their radiative properties. Another laboratory analysis [18] reported quantitative values of radiative properties for a few types of materials and discussed which material characteristics affect such properties. These radiative properties were assessed in a field experiments in Turkey to give a realistic assessment of material performance [19], while in Athens a field study in a very large application of cool pavements was carried out to reflect the performance of paving materials in real conditions [20]. This study documented the use of cool paving materials and showed that the use of cool pavements contributed to the reduction of the peak *Ta* and *Ts* during the summer.

The technique of cool roofs was used to measure the performance of facades in dense urban environments by using a reduced-scale of four street canyon rows [21]. The results showed that the cool coating preformed better than a standard coating. Although this study was able to give realistic measurements, the real interaction between vertical surfaces and building elements was explained by in-situ measurements in Malaysia [22]. This study came to the conclusion that heat storage capacity was the main influence contributing to the UHI impact. With more types of facade materials, a systematic analysis was carried out in Athens using two techniques, including in-situ measurements and experimental measurements [23]. The results showed that the temperatures during the summer period depend, first of all, on their orientation and secondly on their colour and other physical properties. A similar analysis was conducted in Kuwait [24], but this time with the use of simulation software. Orientation, colours and thermal properties such as thermal mass and thermal inertia were the main highlighted factors. Orientation defines the angle of incidence of the solar rays and the duration of insolation in addition to the hours of the day when it occurs, while colours determine the radiative properties of the surfaces. Thermal mass is the capacity of a material to absorb, store and release heat. This heat storage capacity can be determined by the specific heat capacity, density and thickness. It depends significantly on the thermal conductivity. The analysis concluded that orientation, colours and thermal properties have a profound effect on the performance of surfaces, particularly for west wall orientations.

The current work assesses the performance of finishing materials on horizontal surfaces and examines the influence of material properties on their surface temperatures (*Ts*) and surface air temperatures (*Ta*) under clear skies. The focus is placed not only on the radiative properties but also on the role of heat storage capacity. This work conducted experimental studies in real conditions in order to get realistic measurements. It also performs full scale experiments to reflect the interaction between surfaces and urban elements, such as architectural masses and building structures.

2. Materials and methods

The Materials and methods section first presents the study site and its climatic conditions. It then introduces the examined surface materials and case study roofs. It explains techniques of data collection and experimental measurements. This section finally evaluates errors and uncertainties in experimental measurements.

2.1. Study site and climatic conditions

In the current work, SITRA was selected. It is an industrial and residential urban island near Manama. Recent statistics show arid and semi-arid conditions: rainfall is low, irregular, seasonal and variable, relative humidity is also high, and temperatures are variable but high as shown in Fig. 1. An important point to note is that the level of solar irradiation is similar in all areas of Bahrain, which experiences a high level of solar irradiation [25]. The highest monthly averages of direct, diffuse and normal solar irradiation are 585, 383 and 716 W/m^2 respectively. The maximum hourly values range from 820 to 1000 W/m^2 at noon in the month of June.

2.2. Materials and samples

The materials examined during the experimental study are usually applied on roofs, facades and external or paved floors in Bahrain. The focus of this work is placed on roof and floor surface materials. 32 samples of commonly used materials were examined. Some were with different sizes to examine the effect of mass and thickness. The samples were divided into five categories including: metal, felt, concrete, stone (e.g., sand stone, granite, marble, etc) and ceramic. Specifications were obtained from manufacturers, suppliers and contractors, in addition to data from major documents in the literature review [26,27]. These specifications enabled the physical, thermal and radiative characteristics of materials to be analysed (Table 1). The SRI was calculated using the equation in ASTM E1980 [13]. Samples of the examined materials were arranged as shown in Fig. 2. They were fixed on to an insulated wooden board which was fixed on a flat roof with a 20 mm air gap using wooden stands to ensure that there was no contact between the roof and board to avoid thermal bridges.

2.3. Full-scale experiments

The need for more accurate and truthful measurements of *Ts* and *Ta* for roofs led to an extensive amount of *Ts* and *Ta* measurements. The selected roofs were located in the residential area of

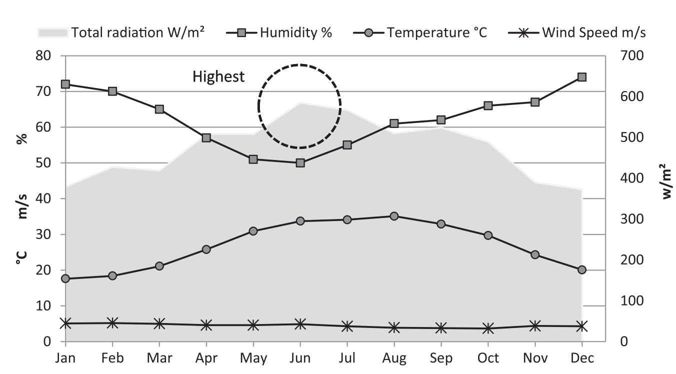

Fig. 1. Climatic elements of Bahrain.