Energy and Buildings 151 (2017) 381–392

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

New cool concrete for building envelopes and urban paving: Optics-energy and thermal assessment in dynamic conditions

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ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 10 June 2017
Accepted 20 June 2017
Available online 28 June 2017

Keywords:
Cool materials
Cool concrete
IR pigments
Optic characteristics
Urban heat island
Environmental simulation chamber
in situ monitoring

ABSTRACT

Urban Heat Island (UHI) is an acknowledged effect that causes higher temperatures in urban areas compared to the surrounding rural areas. Such urban overheating directly increases buildings' energy demand for cooling, to reach thermal comfort conditions in the indoor areas. This phenomenon increases energy consumption and, consequently, greenhouse gas emissions in the cooling season. Moreover, it seriously threatens citizens' environmental comfort in urban areas. In this context, the use of cool (high solar reflectance and thermal emittance) materials has been widely acknowledged as a promising passive UHI mitigation solution. However, the application of such cool materials does not comply with the environmental preservation of cultural heritage sites, for architectural reasons. In fact, historical districts, which constitute a large part of European building stock, are often characterized by non-cool, dark colored materials. Therefore, the most common, light-colored cool solutions cannot be applied, since regulations on such protected areas are strict. Indeed, the above-mentioned regulations do not allow the modification of visible parts of the building. In this paper, innovative concrete elements with infrared-reflective (IR) pigments are presented to be used as i) urban paving, ii) building façade elements, and iii) retrofit strategies for walls and pavements in historical buildings. Both in-lab and in-field characterization of the samples are carried out with dynamically varying thermal and radiative forcing. Results indicate that prototypes with IR pigments have higher solar reflectance, up to +15.8% compared to standard concrete prototypes and +12.5% with respect to same color prototypes without high infrared reflective pigments. Moreover, they are able to maintain surface temperatures that are up to −10.6 °C lower with respect to non-IR samples. These results confirm that the presented composite material represents a good solution for passive cooling at building and inter-building scale.

1. Introduction

The expansion of urban areas in the last centuries has been acknowledged to be responsible for Urban Heat Island (UHI) effect generation and recent exacerbation, consisting of an increase of urban temperatures compared to the rural surroundings [1,2]. UHI effect is responsible for both surface and air temperatures increase, leading to urban microclimate deterioration and increased energy demand for cooling to achieve thermal comfort conditions indoor [3,4]. In particular, surface overheating phenomenon can reach up to 12 °C, as documented for day-time UHI in the case of the temperate climate of Tokyo [5], by means of remote sensing. Surface UHI effect is stronger during the day, when solar radiation is stronger. With regards to the UHI effect on air temperature, defined as “atmospheric” UHI, Van Hove and colleagues [6] assessed an increase in temperatures equal to 4.3 K up to 8 K in Rotterdam, during summer. This increase generates higher thermal discomfort in the urban area during the warm season. In this case, UHI effect is greater at night, due to the release of the heat accumulated by the built environment all along the day.

The UHI phenomenon is caused by different factors, such as i) an increase in impervious surfaces, with the consequent lack of green spaces and cool sinks, causing a decrease of evapotranspiration and a decrease in shade, ii) reduced air circulation due to dense urban form, iii) anthropogenic heat accumulation, and finally

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http://dx.doi.org/10.1016/j.enbuild.2017.06.051
0378-7788/

iv) solar heat absorption due to the materials selected for the built environment [7].

Population growth and increasing urbanization are expected to worsen UHI effect: impressive data from the United Nations World Urbanization Prospects [8,9] quantify the world population as more than 7 billion individuals today, expected to reach almost 10 billion in 2050. Moreover, the assessment of the percentage of population living in cities has gone from 29.6% in 1950 to the current 54.0%, estimated to reach 66.4% in 2050. Additionally, urban land cover is increasing twice as fast as the population, and evidence of this growth is reported through projections [10]. While urban land cover extension corresponded to 300,000 km^2 in 2000, it is expected to reach 770,000 km^2 in 2030 and up to 1,200,000 km^2 in 2050. These numbers denote with incontrovertible evidence that cities and consequently the UHI phenomenon will have an enormous growth in the future. At the same time energy demand, which is connected to UHI effect, will increase too, alongside with microclimate deterioration. Indeed, higher temperatures in cities will exacerbate the high-energy demand for cooling during the warmest season, contributing to higher CO_2 emissions and decreasing thermal comfort. For these reasons, the implementation of UHI mitigation strategies will be of primary importance in the years to come.

The construction sector accounts for a large part of global emissions [11,12]. Therefore, when designing the built environment, solutions and mitigation strategies have to be employed to reduce emissions. Both technological and behavioral approaches can be exploited for this purpose, with respect to energy efficiency, UHI mitigation and indoor and outdoor thermal comfort [13–16]. UHI mitigation can be achieved by taking action against its causing factors. Green areas and permeable ground coverage can be used to reduce impervious surfaces [17–19]; urban morphology can be improved to increase air circulation in urban built environments [20–23]; and construction materials can be selected among those with better intrinsic characteristics, and consciously employed to reduce heat absorption [24]. In this paper, materials' heat absorption capability is analyzed, with the aim of reducing their contribution to the UHI phenomenon.

Typical mitigation strategies proposed in recent scientific contributions are usually responsible for around 2 K passive cooling of the outdoor environment [25]. In particular, cool materials are regarded as efficient materials to cool down hot surfaces, and reduce the amount of heat transferred to indoor and outdoor spaces [26,27]. They are characterized by high solar reflectance and thermal emissivity and therefore, they are able to maintain cooler temperature when heated by sun radiation. Classic high-reflective materials are usually light in color [28], and consequently it is not always feasible to employ them at low cost in buildings or open spaces for aesthetic and architectural reasons.

In this view, new cool and darker colored-looking materials have been implemented to be used in the construction sector: these materials exploit the reflection in the infrared (IR) part of the spectrum, while lighter-colored cool materials have higher reflectance in the visible part of the spectrum. In fact, incoming solar radiation is composed by three different parts, depending on the radiation wavelength: the ultraviolet (UV) radiation, which constitutes 5% of the total solar radiation; the visible (VIS) part, which is 43%, and finally the near infrared part (NIR) part, which comprises 53% of the incoming radiation. In this context, highly reflective colored (i.e., brown and light-brown) treated aluminum is analyzed to be used as a façade covering material by Ihara et al. [29]. The analyzed samples were optimized in the NIR part of the spectrum and compared with non-optimized, same-color samples. Results of the study show that optimized dark brown samples achieved +30% higher solar reflectance than same color traditional samples, while with respect to light-brown prototypes this difference was equal to +7%.

In the same scenario, Levinson and colleagues [30] describe a technique to produce cool, dark-colored concrete tiles and asphalt shingles, to be applied as roofing materials. Such prototypes were obtained by means of NIR pigments addition to the paint. The cost-effective application consists of two layers of cool paint to be sprayed on the above-mentioned elements. The results are red, brown, green and blue tiles with higher solar reflectance (0.25–0.60). Similarly, Synnefa and colleagues [31] reported optical properties and thermal performance of prototype cool coatings containing IR reflecting pigments, applied on concrete tiles. The coatings are available in a large range of colors, from black to orange, brown, blue and green and are able to lower surface temperature by about 10 °C, as demonstrated by means of in-field exposure and monitoring.

Increase in Solar Reflectance (SR), due to the addition of cool NIR-reflective basecoats and/or topcoats, is also observed in another study by Levinson and colleagues [32]. Additionally, the behavior of cool-colored acrylic paints is investigated by Uemoto and colleagues [33]: white brown and yellow paints were applied on fiber cement roofing and compared with similar colored paints, but without IR pigments. In their work, a reduction by 10 °C of the surface temperature was assessed in lab by employing a solar-simulator.

The present research originates from these studies, analyzing efficient and effective ways to cool down the expanding built environment through materials' optic characteristics and radiative properties, to mitigate UHI and counteract global warming, while improving outdoor and indoor thermal comfort conditions. However, in this work cool-colored materials are not employed as an additional paint or a coating layer, but as massive composites consisting of an innovative concrete mix design, to be used in urban-paving and for building-envelope applications. This process results in a different, innovative prototype material which has numerous advantages: i) it is homogeneous, not just a topcoat, but consistent all along the prototype's thickness; therefore if cracks or scratches occur on the material, the color and characteristics remain the same, thus requiring less maintenance; ii) it does not require additional manufacturing steps such as painting or spraying a topcoat on its surface (the cool additive is poured directly in the concrete mix); iii) it is suitable for irregular shapes and iv) historical construction, since it can easily replicate almost any color.

In the next sections, the experimental implementation and the main characteristics of this material together with its cooling power are described in detail, through experimental in-lab and in-field investigations. Moreover, a statistical analysis is performed in order to evaluate pigment type and percentage effectiveness in modifying optic characteristics and, consequently, thermal performance.

2. Methodology

The research has been carried out by preparing the cool-colored concrete prototypes in lab. Then, prototypes have been critically characterized in terms of both optics and thermal characteristics. Also, the proposed samples were tested both in a natural (open air, outdoor environment exposure) and artificial (climatic chamber) environment. Finally, data gathered from in-field and in-lab tests were analyzed and conclusions were drawn. The applied methodology is described in detail in the following sub-sections and in Fig. 1.

2.1. Material implementation

Different prototypes were developed considering different concrete mixes, characterized by similar components but varying the colors and quantity of pigments in them (Table 1).