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Pigmented glazed ceramic roof tiles in Brazil: Thermal and optical properties related to solar reflectance index

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ABSTRACT

Urbanization and the resulting concentration of people in cities has led to the emergence of Urban Heat Islands (UHI), which is associated with several problems. One strategy for UHI mitigation is the use of cool coatings for pavements and buildings, for instance, on roof tiles. Ceramic roof tiles are widely used in Brazil and in the rest of South America, but they have not been adequately studied regarding their thermal emittance and solar radiation reflectance. These two properties can be used to determine whether or not a roof tile coating can be classed as "cool", according to the Leadership in Energy and Environmental Design (LEED) certification. In this paper, the solar reflectance, thermal emittance and Solar Reflectance Index (SRI) index were determined for "Portuguese" and "American" colored glazed roof tiles, mostly produced in Brazil. Nineteen glazed roof tiles (from four different producers) with different colors were studied according the LEED certification. The thermal emittance was determined using a portable emissometer and the reflectance spectral curves were measured using a UV–Vis-NIR spectrophotometer. All measurements were performed according to the ASTM standards. The colorimetric coordinates in the visible range (for the D65 illuminant) were determined to evaluate the relationship between the luminous reflectance factor (Y) and the SRI. The optical behavior of the colored glazes for the full range of the solar spectrum was determined using the Kubelka-Munk (K-M) model and the relationship between the absorption (K) and scattering (S) coefficients. The results show that most of the colored glazed tiles did not meet the 2013 LEED requirement, that is, SRI ≥ 39 for roof tiles with a steep slope. A polynomial relationship between the Y factor and the SRI was found (R^2 value > 0.95), therefore the tile colors that would probably not qualify for SRI certification could be estimated. The K-M analysis showed that for some glazes there was a high absorption of radiation in the near infrared region, suggesting that the pigments used for these glazes do not exhibit cool properties. Therefore, cool pigments with higher reflectance should be used to improve the performance of the glazes with a low SRI.

1. Introduction

Urbanization is a worldwide trend resulting from the concentration of people in cities. The process has contributed to the emergence of the so-called Urban Heat Islands (UHIs), i.e., urban areas with higher temperatures than the nearby rural regions. Along with urbanization, there are several factors that explain the appearance of UHI in cities, including:

(1) *air pollution* - pollutant gases can cause local changes in the energy and radiation balance, giving rise to photochemical reactions that can lead to the generation of ozone, a highly reactive and toxic gas;
(2) *anthropogenic sources of heat* - anthropogenic emissions of heat and humidity associated with the burning of fossil fuels, air conditioning, etc., contributing to urban heating;
(3) *changes in the radiation balance* - the concentration of buildings in cities, capturing the solar radiation and changing the amount of light reflected by the urban environment as a whole, therefore

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increasing the absorption of solar radiation, with a consequent increase in temperature;

(4) *reduction of green areas* - in urban areas, the extent of evaporation surfaces (lakes and rivers) and evapotranspiration (parks, woods, gardens, boulevards) is reduced, altering the urban microclimates and the conditions of environmental comfort in cities;

(5) *use of materials with high absorption capacity for solar radiation* - the use of materials with low reflectivity in urban constructions provides greater accumulation of heat during the day and emission during the night period, due to the light absorption properties of these materials (Hulley, 2012; Akbari et al., 2009; Heat Island Group, 2016).

The appearance of UHI areas can cause discomfort, increase the energy consumption in buildings, decrease the environmental quality and aggravate diseases related to thermal stress and contamination (Akbari et al., 2009; Heat Island Group, 2016; Romeo and Zinzi, 2013; Solecki et al., 2005; Ashie, 2008; Xu et al., 2012). The heat island effect in medium latitude countries (cold or temperate climates) is most prominent at night, and its intensity is a nonlinear function of the urban population (Lombardo, 1985).

In contrast, UHIs appear during the daytime in cities at subtropical and tropical latitudes due to the high incidence of solar radiation, intensifying the discomfort caused by the rise in temperature and reduction in relative humidity. As an example, thermal analysis based on satellite images over 30 years for the city of São Paulo, Brazil, has shown that the surface temperatures in the downtown area of the urban conurbation were 10 °C higher than the temperatures recorded in "green" areas (Lombardo, 1985).

Over the years, different UHI mitigation strategies have been proposed, including planting trees for shade, increasing green areas in cities and using cool coatings for buildings and pavements (Synnefa et al., 2006, 2007; Santamouris et al., 2011; Akbari and Matthews, 2012; Carnielo and Zinzi, 2013). In many densely populated cities the deployment of green areas is a challenge, making the use of reflective surfaces for buildings and pavements the most viable solution in the short term.

A cool coating is a highly reflective covering material that absorbs less heat and stays cool in comparison to a more traditional coating, when used on a surface exposed to solar radiation. The cool coating reduces the amount of energy absorbed by the surface due to selective absorption and reflection of the spectral wavelength (Pisello, 2017).

In urban areas, the roof surfaces generally account for approximately 20–40% of the total area exposed to solar radiation and the paved area for 29–44% of the total area (Akbari and Matthews, 2012; Xu et al., 2012). The use of cool coatings could result in local and global energy savings, thus being beneficial to the environment (Pisello, 2017).

Most of the available cool roof products were developed for flat roof application, but promising cool coating materials have been recently introduced for tilted roof surfaces, such as membranes, coatings, paintings, metal roofs, shingles and tiles (Pisello, 2017).

In California, "cool community" strategies, including cool roofs, cool pavements, cool walls and urban vegetation, have been identified as effective voluntary measures with the potential to reduce statewide emissions. The Lawrence Berkeley National Laboratory (LBNL) has worked with state and local officials, non-profit organizations, school districts, utilities, and manufacturers to advance the science and implementation of cool community strategies (Gilbert et al., 2016).

As previously discussed, materials used in buildings and other urban structures play an important role in the thermal equilibrium of a city. They absorb the solar radiation (including infrared) and dissipate part of the accumulated heat into the atmosphere by convection and radiation. The thermal performance of materials is mainly determined by their optical and thermal characteristics, where the solar reflectance and the thermal emissivity are the most important factors (Doulos et al., 2004).

In the world scenario, the newest challenge for the building industry is to meet the requirements of the environmental certification systems. One of the main certification systems currently in use is the LEED (Leadership in Energy and Environmental Design). In 2016, Brazil ranked third among the countries with the largest number of enterprises certified by eco-efficiency labels (GBC Brazil, 2016). According to the ranking of the certifying entity, the Green Building Council (GBC) Brazil, the country was placed fourth in 2013, immediately behind the United Arab Emirates, but in 2014 Brazil advanced one position. With 223 certified projects and 950 under approval, Brazil lags behind the United States, which has 21,738 certified buildings, and China, with 581 certifications. In 2014 alone, 135 ventures were registered and another 82 received the LEED certification seal in Brazil. According to the GBC Brazil ranking, São Paulo is the state with the highest number of enterprises registered and certified in Brazil, with 530 certification processes in progress and 144 approved. The state of Rio de Janeiro appears in second place, with 174 certifications registered and 31 certificates, and the state of Paraná is in third place, with 64 certifications in progress and 14 LEED seals (GBC Brazil, 2016).

The LEED certification method assigns point scores for buildings, based on some requirements associated with their design and construction. The ceramic materials used in buildings can contribute to the scoring based on the following factors: the content of recycled material in their composition; the use of regional raw materials for their manufacture; innovation and design (functionality); and the heat island effect. Regarding the heat island effect, the determination of the Solar Reflectance Index (SRI) for opaque ceramic materials (wall, roof and floor tiles) aids the LEED certification. The determination of this index provides a way to quantify the behavior of the material surface when exposed to the incidence of sunlight. It reveals the ability of a surface to reflect solar radiation and to emit thermal radiation, reducing the increase in temperature caused by the incidence of solar radiation on the surface. The SRI of a specific surface changes with the solar reflectance and thermal emittance of the material, and also according to certain environmental conditions, such as the solar flux, the convection coefficient, the air temperature and the sky temperature (ASTM E1980, 2011). In the case of roof tiles for buildings, the SRI value required for a specific material is dependent on the slope of the roof (SRI ≥ 39 for steep slope; SRI ≥ 82 for low slope) (GBC Brazil, 2016). Therefore, the determination of the SRI for ceramic roofing materials is the most important criterion in determining which classes of material can contribute to the mitigation of the heat island effect.

However, to the homeowner, aesthetics and durability are more important issues than the potential to reduce the air-conditioning loads and the electricity bills. Dark roofs simply "look better" than highly reflective white roofs. Owners of houses with pitched roofs visible from the ground level often prefer non-white roofing products for aesthetic reasons (Miller and Kriner, 2001).

Since a high-reflectance low-slope roof cannot be seen from the ground, the roof's functionality is far more important than its appearance. However, in steep-slope roofing the issues of appearance, cost, and durability typically drive the selection of the roofing material because the homeowner wants the roof to complement the décor of the house, while protecting the underlying residential structure for a long period of time at an affordable cost (Miller and Kriner, 2001).

Although Brazil is currently the second largest producer of ceramic tiles worldwide (899 million m^2 in 2015) and the second largest consumer (816 million m^2 in 2015) (Anfacer, 2017), the optical and thermal properties of these materials receive little attention. The same applies to the bricks and ceramic roof tiles sector.

The fact that the optical and thermal properties (e.g., absorption of solar radiation and thermal emissivity) of ceramic tiles, bricks and ceramic roof tiles have not been studied in depth in Brazil could be related to the absence of national legislation on this subject. In general, greater emphasis is given to the mechanical properties (strength) and