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Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation

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ABSTRACT

Buildings are responsible for about the 40% of the global annual energy consumption, therefore, innovative strategies for buildings' energy efficiency are under development. Strategies of re-roofing with "cool" materials have a non-negligible cooling energy saving potential, as they contribute to the reduction of the peak ambient temperatures during summer and, moreover, they contribute to the improvement of the urban microclimate by decreasing the intensity of heat island phenomena. In this paper, the experimental characterization and optimization of a new membrane for buildings' roof is carried out. To this aim, laboratory measurements were performed to determine its optic-energy properties and, therefore, to optimize its "cool roof" behavior. A full scale field test was also setup in order to measure the global solar radiation reflected by each membrane, before and after optimization, with varying boundary conditions, e.g. time during the day, seasonal period, and weather conditions. The in-field experimental campaign allowed to characterize the optic-energy behavior of the cool membranes in real boundary conditions, showing non-negligible variation of measured solar reflection capability with varying environmental constraints in winter conditions. The research showed interesting results from the in-lab optimization campaign, and non-negligible unreliability due to environmental agents affecting in-field albedo measurement.

1. Introduction

Buildings' energy consumption in developed countries has increased up to 40% [1], and has exceeded other major sectors such as industry and transportation. In particular, a considerable increase in the energy requirement for cooling has been detected [2,3], given the increasing urban temperatures due to important climate change phenomena such as urban heat island [4]. In fact, urban heat island and global warming are able to increase the near surface ambient temperature in cities, by consequently modifying buildings' energy balance [5]. While urban heat islands all around the world are widely investigated [6], the research about the impact of global warming on urban climate still consists of a few works proposing several methodologies to quantify such effect [7] in terms of CO_{2eq} offset. The urban heat island phenomenon is imputable to several factors: urban dense constructions' configuration [8], solar absorptive materials exposed to solar radiation used for buildings' envelope [9], impervious surfaces limiting evapotranspiration [10], released anthropogenic heat, and, in general, lower urban albedo than the extra-urban areas [11].

In this panorama, several experimental and numerical studies have been performed in order to develop mitigation solutions and passive cooling strategies within different climatological boundaries [12,13]. The mitigation technique we are focused on in this work consists of the increase in the albedo of buildings' envelopes and urban paving [14,15], with a particular attention dedicated to horizontal roofs exposed to the solar radiation [16]. In fact, roofs cover at least 25% of urban surfaces, and increasing their reflectivity would have a significant effect on city total energy balance [17,18]. Additionally, the use of infrared reflective materials for re-paving urban surfaces [19,20] is encouraged in [21] for countering the negative effects of global warming such as the increase of cooling energy demand in conditioned buildings. In this panorama, cool colored ceramic tiles, acrylic paints, and bituminous membranes for building envelope applications were developed and experimentally tested [22], by taking into account both cool roof and facade applications.

Many studies have been carried out [23–27] in order to assess the effectiveness of such "cool solutions" for the energy saving both at building scale and at inter-building level. Laboratory and

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Nomenclature

SW: standard white roof membrane, sample I
SG: standard grey roof membrane, sample II
W + P: white +30% white paste roof membrane, sample III
W + P-opt: white +30% optimized white paste roof membrane, sample IV
W + PCM: white +10% paraffin roof membrane, sample V
T_{out}: average daily outdoor dry bulb temperature [°C]
α_{out}: outmost (maximum or minimum) value of albedo registered in each considered day and time interval of measurement [–]
$\bar{\alpha}_{ref}$: average albedo measured in summer clear days in the 12:00–2:00 p.m. time interval [–]
$\bar{\alpha}_{2-3}$: average albedo measured in summer clear days in the 2:00–3:00 p.m. time interval [–]
$\bar{\alpha}_{w}$: average albedo measured in winter clear days in the 12:00–2:00 p.m. time interval [–]
$\bar{\alpha}_{cl}$: average albedo measured in summer cloudy days in the 12:00–2:00 p.m. time interval [–]
$\bar{\alpha}_{3-5}$: average albedo measured in summer clear days in the 3:00–5:00 p.m. time interval [–]

in-field measurements of the solar reflectance of light-colored roofing membranes were performed by [28] with varying weather conditions, in order to investigate how the aging and weathering forcing can reduce membranes' thermal-optic performance. Replacing a dark roof with a solar-reflective white cover could decrease the annual conditioning use by almost 20% [29,30], but these benefits due to cool roofs application could be decreased by soiling and weathering processes [31,32]. Therefore, several studies have been performed [33] in order to investigate the variation of the solar reflectance of cool sheet membrane roofs over time and how the building energy use is affected. Additionally, the variation of the solar irradiance and solar reflectance with (i) surface orientation, (ii) solar position, and (iii) atmospheric conditions has been studied [34,35]. In this scenario, several methodologies have been proposed for achieving reliable measurement of the solar reflectivity of both flat and sloped surfaces, in order to properly predict the solar heat gain absorbed by such surfaces. In fact, the angular and spectral distribution of solar radiation changes with solar position and sky conditions. Consequently, the measured value of solar reflectance varies during the course of the day and of the year, given its dependence to the incident angle and wavelength of the solar radiation.

The present research concerns the experimental investigation of the optic-thermal properties of several types of roofing membranes in terms of solar reflectance, thermal-emittance, and in-field albedo. In particular, the possibility to measure the solar reflectivity at large solar zenith angle typical in winter and spring/fall conditions is here questioned. Additionally, the influence of weather agents on the measured albedo is investigated. Several quantitative observations are carried out, with the aim to analyze the albedo variability when field measurements can be taken according or not to the reference international standard procedure [36]. Finally, the variability of the in-field albedo due to varying environmental agents is quantified by taking into account the results collected by the present experimental campaign on polyurethane based membranes for cool roofs.

2. Purpose of the work

The present research concerns the experimental analysis and optimization of a waterproof membrane for cool roof application, considered as an effective urban heat island mitigation technique [37,38]. This technology consists of a polyurethane-based liquid almost white membrane, which is frequently used for roof covering in Italy in both residential and industrial buildings with flat and low-sloped roof.

The experimental campaign aimed at characterizing the cool membrane with varying environmental conditions was carried out through coupled in-lab and in-field analyses. In particular, the analysis of five different prototype membranes was carried out, i.e. (i) standard white, (ii) standard grey, (iii) standard white with additional 30% white paste, (iv) standard white with additional 30% optimized white paste, and (v) standard white with 10% integrated paraffin as phase change material. The optical-thermal properties of such innovative membrane were investigated through a dedicated in-lab measurement campaign, in terms of solar reflectance and thermal emittance. During the in-lab process, the optimization of the cooling potential was performed by increasing specific components, i.e. titanium dioxide (TiO_2) and hollow ceramic microspheres. Additionally, the superficial finishing of the membrane, named "white paste", was improved in sample (iv) with the purpose to minimize its sticky effect, typical of polyurethane base products, affecting their self-cleaning capability.

An in-field monitoring campaign was therefore carried out in order to measure the albedo variation of the membranes with varying several weather boundary conditions, both before and after optimization.

The main objective was to study the measured albedo variation due to different environmental factors, such as the daily time of measurement, the seasonal variation during the course of the year, and the cloudiness. In fact, important variations of in-field measured albedo are expected with varying realistic boundary conditions affecting the reliability of the acknowledged [36] measurement procedure. A final quantitative evaluation with respect to the standardized measurement method was carried out in realistic weather conditions, in a temperate climate zone at 43° N Latitude, since precision and bias statement has not been established yet and the field measured solar reflectance, according to [36], is expected to vary both from one location to another and with time.

3. Materials and methods

The main steps of the research are described as follows:

- selection of the cool roof membranes for cool roofs;
- development of the prototype samples for laboratory measurements;
- development of the field test setup for measuring albedo in the field;
- in-lab experimental analysis for the characterization and optimization of the thermal-optical properties of the prototype membranes;
- in-field monitoring campaign for the measurement of the albedo of the membranes with varying environmental boundary conditions in winter months and comparison with respect to summer observations;
- data analysis and discussion of the main findings.

3.1. Laboratory analysis

The purpose of the preliminary in-lab analysis was the definition of the main optic-thermal properties of the polyurethane based membranes, i.e. solar reflectance and thermal emittance. The measurement of the radiative properties of 10 × 10 cm prototype samples was carried out by means of spectrophotometer and portable emissometer, according to standard methods reported in ASTM E903-6 (2010) [39] and ASTM C1371-04A (2010) [40],