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Effect of ageing on solar spectral reflectance of roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs of commercial buildings

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ABSTRACT

Highly reflective roofs, widely known as cool roofs, can reduce peak surface temperatures and the energy required to cool buildings, mitigate urban microclimates, and offset CO_2. However, weathering, soiling, and biological growth affect their solar reflectance. In this study, the solar spectral reflectances of 12 roofing membranes were measured before the exposure and after 3, 6, 12, 18, and 24 months of natural ageing in Roma and Milano, Italy. The membranes with an initial solar reflectance greater than 0.80, for example, decreased in reflectance by 0.14 in Roma and 0.22 in Milano after two years. Then, for a typical highly insulated commercial building, the annual cooling load savings were calculated to be reduced by 4.1–7.1 MJ m^{-2} y^{-1} per 0.1 loss in reflectance. When the buildings are non-insulated, the savings reduction is 58–71 MJ m^{-2} y^{-1} in Milano and 70–84 MJ m^{-2} y^{-1} in Roma. Ageing yielded a reduction of the cooling load savings that could be achieved with a new white membrane of 14–23% in Roma and of 20–34% in Milano. Moreover, in Milano, an aged, white, highly insulated roof, which has a solar reflectance of 0.56, may reach a surface temperature 16 °C higher than a new roof, which has a solar reflectance of 0.80.

1. Introduction

The microclimate in urban areas is very different from that in non-urban adjacent areas [1–3] and typically leads to relevant differences in the energy needs of urban buildings [4–7] and the peak electricity demand [8]. For instance, for office buildings within the urban area of Milano, the heating energy need is estimated to be from 30% to 60% lower than the needs outside the city, while the cooling need is from 15% to 70% higher [9,10].

To mitigate urban climates and to reduce the cooling energy required, highly reflective roofing materials have been widely suggested and recommended [11–18]. However, especially in an urban environment where air pollution is significantly higher than in rural areas, the surfaces of buildings are subject to weathering and to the deposition of soot and other particulate matter, which cause a change in their reflectance [19–26].

Even if data are available, and unfortunately, the available data are seldom spectral, they are provided by short exposure research programmes or concern only North America. In the U.S. especially, extensive data about more than 2500 roofing products are made available by the Cool Roofing Rating Council (CRRC) for three exposure sites: one in a temperate sub-urban environment in Ohio, which has moderate air pollution [27]; one in a hot-dry extra-urban climate in Arizona; and one in a hot and humid extra-urban climate in Florida. The CRRC reports initial values of solar reflectance (ρ_S) and thermal emittance (ε), as well as three-site average values of each property after three years of natural exposure. At the CRRC's sites, all of the exposed products, excluding those with an initial solar reflectance (ρ_{S0}) lower than 0.20, present losses increasing with ρ_{S0} [22]. For instance, for products with ρ_{S0} greater than 0.80, the three-site average loss of ρ_S after three years is equal to 0.16, with a maximum of 0.24 in Florida and a minimum of 0.08 in Arizona. With regard to the thermal emittance, in the CRRC's database, most variations for products with an initial ε greater than 0.85 are

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within ± 0.05 after 3 years, while if the initial ε is lower than 0.50, there is an average increase of approximately 0.07.

The ageing of high-albedo roofing may naturally lead to a decrease in the energy savings achievable using cool materials (e.g., up to 20% compared to the first year for detached houses in Sacramento, CA) as assessed by Bretz and Akbari [28]. Even if techniques to restore the initial solar reflectance exist [29,30], cleaning does not seem economically or environmentally sustainable when only trying to achieve energy savings.

To complete the available information with data measured in urban environments, which is where most buildings with high energy needs are typically located, a selection of 12 roofing membranes, including single ply thermoplastic, factory-applied coatings on single ply thermoplastic membranes, field-applied coatings on modified bitumen, and modified bitumen with roofing granules, were exposed and analysed in Milano and Roma, Italy. Their solar spectral reflectance was measured when new and after 3, 6, 12, 18, and 24 months of exposure; the impact of solar reflectance variation on the surface temperatures of insulated or non-insulated roofs was then measured and was used to calculate the resulting energy needs for heating and cooling of a typical commercial building in Milano and Roma.

2. Experiment

2.1. Selected materials

Twelve roofing membrane products available on the market with ρ_{S0} values ranging from 0.26 to 0.85 (Fig. 1) and having varying surface roughnesses were selected. Some membranes were somewhat glossy, while others were matte; for each roofing material class (e.g., modified bitumen), products offering different spectral features (e.g., cool and non-cool coloured) were chosen. Those selected comprise a wide set of features of non-black waterproofing materials made of modified bitumen, PVC and polyolefin, with different spectral reflectances, surface roughnesses and open porosity.

2.2. Natural exposure procedure

The selected roofing membranes were exposed to the natural elements at two urban sites: in Roma (41°55′57″N, 12°27′54″E; 35 m above mean sea level) and in Milano (45°28′48″N, 9°13′46″E; 123 m above mean sea level), offering different climates and pollutant concentrations. In both cases, the exposures occurred approximately halfway between the city centres and the peripheries on two non-shaded roofs and were distant from the primary sources of pollution. The roofing membranes were exposed at a low slope (i.e., 1.5% according to Italian code practices [31] and Swiss standards [32]). In Milano, additional specimens were also exposed facing south with a slope of 45°.

The samples were measured when new and after 3, 6, 12, 18, and 24 months of natural exposure, which began on April 18th, 2012. In addition, in Milano, one year later on May 3rd, 2013, a second low-sloped exposure of membranes m02 - m10 was started (Fig. 1) to assess the variability caused by different ageing conditions occurring in short-term programmes. At each time point, the samples were retrieved, measured in the laboratory, and re-exposed; each sample remained unexposed for approximately one week when the measurements were taken. Three samples of 10 cm × 10 cm in size per product were exposed for each site and slope condition; they were fastened to metal frames according to ISO 2810 [33] 80 cm above the roof (Fig. 2). To observe the speed of the reflectance loss, in the second year, 39 additional specimens of membrane m06, which was a white PVC single-ply, were exposed, retrieving three coupons and measuring them each week during the first two months and then every two weeks for the following two months.

2.3. Reflectance measurement method

The spectral reflectance was measured with two identical Perkin Elmer Lambda 950 spectrophotometers, one in Roma and one in Milano; the latter was used after the first year. Both machines were equipped with a 150 mm Spectralon-coated integrating sphere, a photomultiplier tube, and lead sulphide detectors. Reflectance measurements were carried out and compared to a Spectralon calibrated reference in the 300–2500 nm wavelength range with a spectral resolution of 5 nm. The centre point of each sample lit by the measurement beam was used for the analysis; thus, soiling edge effects were excluded. The slit aperture was set to 2 nm in the visible range and in servo mode in the near-infrared range. The servo mode allowed the instrument to automatically change the slit aperture in order to optimize the energy input as a function of wavelength. Broad band values were calculated from the spectral data according to ASTM E 903 [34] using the global solar horizontal irradiance distribution given for air mass 1 at 5 nm intervals, as described by Levinson et al. [35]. The visible band was considered to range from 380 to 780 nm, according to ISO 9050 [36]. For each product and exposure condition (i.e., site, orientation, and slope) for the three specimens, we computed the average spectral curve and then the integrated values.

3. Building energy simulations

3.1. Simulation tool

The evolution over time of solar reflectance already provides an indication of the possible variation in the surface energy balance of the building envelope. However, dynamic heat and moisture transport numerical simulations may provide a deeper insight into the impact of reflectance changes on the hygrothermal performance of the building envelope and on the building energy needs for heating and cooling. The software model WUFI Plus 2.5.3 [37] was used, which was validated within the context of IEA Annex 41 [38]. This model resolves the enthalpy balance with the finite control volumes method, coupling the heat transfer with the liquid and vapour moisture transport in porous media and accounting for both latent heat transformations and the influence of moisture content and temperature on the thermal and moisture transport properties of building materials [39].

As in the work of Levinson et al. [40], the building simulations included the temperature dependency of thermal conductivity (λ). For expanded polystyrene (EPS), $\lambda = 0.034\ W\ m^{-1}\ K^{-1}$ at −20 °C and $\lambda = 0.054\ W\ m^{-1}\ K^{-1}$ at +80 °C from WUFI database were used, in agreement with the provisional formulas for EPS given in ISO 10456 [41]. Simulations were performed with a time step of 15 min.

3.2. Case study

As a case study, a typical one-storey commercial building located in Milano or Roma was considered, which was modelled as a single zone measuring 50 m × 40 m × 6.5 m (i.e., inner dimensions) and east–west oriented with ribbon windows on the south and north façades, precast walls, and a flat precast roof with unprotected membrane (Table 1). The building typology and envelope technology were representative of industrial and commercial sectors in Italy. Internal partitions and furniture provided low thermal inertia, which was offered by the precast building envelope and by 75 m^3 of bottled liquid merchandise, which was modelled as an internal partition 0.10 m thick with water's thermal properties within a polyethylene envelope.