EVOLUTION OVER TIME OF UV-VIS-NIR REFLECTANCE OF COOL ROOFING MATERIALS IN URBAN ENVIRONMENTS

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ABSTRACT

Highly reflective building envelope materials are widely identified as an effective design option to limit the peak surface temperatures of roofs in summer conditions, thus mitigating the urban microclimates and the energy demand for cooling. However, especially surfaces having high solar reflectance are subject to soiling (i.e. deposition of soot and other airborne particles), in addition to ageing, and biological growth. All these processes reduce the reflectance of bright surfaces (and increase the reflectance of surfaces having reflectance lower than roughly 0.20). As a result, a decrease in the solar reflectance of a cool roof yields to higher surface temperatures and a reduction in the energy savings expected thanks to high albedo roofing. Furthermore, the durability is also impacted.

To quantify this effects, we exposed in the urban environment in Milano and in Roma (Italy) 14 roofing membranes, including synthetic, factory applied coating on synthetic membranes, field applied coatings on modified bitumen, asphalt shingles. For each product class (e.g. synthetic membranes) we selected a high reflectance product and a mid-low reflectance one. We measured the UV-Vis-NIR spectral reflectance of three samples per product before the exposure – begun in April 2012 – and after 3, 6, and 12 months. Herein we present the results of the first year of natural exposure, reporting a remarkable loss in the solar reflectance, sometimes exceeding 15% of the initial value already after the first three months of natural exposure and in some cases by more than 30% after one year, depending on their initial value.

With the measured curves of solar reflectance over time as input data, we performed finite differences numerical modelling (by means of the software tool WUFI 5.2) of heat and moisture transport through typical roof assemblies. We analyzed the variation in the surface temperature and heat flux due to the change in solar reflectance, and we obtained relevant differences. For instance, in case of a highly reflective flat roof (with initial solar reflectance equal to 0.852, reduced to 0.624 after one year) over 14 cm of expanded polystyrene on a reinforced concrete slab (U-value of the roof assembly equal to 0.267 W m^{-2} K^{-1}) we computed a significant increase in peak surface temperatures (during the first summer up to 7°C, and up to 14°C more at the end of the first year , assessed in the context of Milano, Italy). Knowledge about the soiling trends for different building envelope materials allows to better estimate the cooling energy demand of buildings, plan cleaning and maintenance operations (whether viable and sustainable), and to assess the service life and the life cycle, and eventually study the benefits of possible anti-soiling treatments.

KEYWORDS

Cool materials; solar reflectance; soiling; ageing; natural exposure.

1 INTRODUCTION

In the Literature there are several studies assessing the evolution over time of the solar reflectance of building envelope materials (e.g. Berdahl *et al.*, 2002; Bretz & Akbari, 1997). In addition, data can be retrieved from the databases made available by the U.S. Environmental Protection Agency (U.S. EPA) and by the U.S. Cool Roofing Rating Council (CRRC), which report clean and aged - after three years of natural exposures - solar reflectance (SR) and thermal emittance (TE) for 2469 products (as of August 2013). More in detail, the CRRC manages the natural exposure of roofing products at three sites in the U.S. (and the aged SR and TE are the average after three years at the three sites): one in a temperate and polluted sub-urban environment (in Ohio), one in a hot-dry extra-urban climate (in Arizona), and one in a hot and humid extra-urban context (in Florida). It is interesting to note that none of the exposure fields is located within an urban area (for obvious reasons of space required for the exposure facilities and the cost of land use). At the CRRC's exposure sites, as analysed by Sleiman *et al.* (2011), excluded the roofing products with initial solar reflectance (SR_{T0}) lower than 0.20, all the exposed products present losses in SR increasing with SR_{T0}. For instance, for products with SR_{T0} of more than 0.80, after three years SR is in average about 20% lower than the initial value, with a variation of about 15% depending on the exposure site. Moreover, as noted by Sleiman *et al.* (Sleiman *et al.*, 2011) these databases do not include spectral data, useful for understanding the agents producing the variation in reflectance, and study possible countermeasures. This aspect has been investigated on a set of roofing membranes by Berdahl *et al.* (Berdahl *et al.*, 2002), who identify the atmospheric soot particles deposing onto the buildings' surfaces as the main agent producing the variation in reflectance; they also observe that soot absorbs more at low wavelengths than in the NIR, leading to yellowing of surfaces. However, even if data are available - alas seldom spectral - about the magnitude of the variation of optical and radiative properties over time of roofing materials and even about the effect of alternative cleaning procedures (Levinson *et al.*, 2005), these concern almost only the North American contexts.

Herein we present the results of the first year of natural exposure in urban environments in Milano and in Roma (Italy) of 16 roofing materials, including roofing membranes (single-ply synthetic, field applied coating on modified bitumen, asphalt shingles). For each product class (e.g. synthetic membranes) we selected a high reflectance product and a mid-low reflectance one. We measured the UV-Vis-NIR spectral reflectance of three samples per product before and after 3, 6, and 12 months of natural exposure. Using the measured data, we computed - for Milano's climate context - the exterior surface temperatures and heat fluxes for flat roofing assemblies typical of industrial and commercial buildings, both well insulated and with no insulation. The purpose of this study, thus, is to portray the early trends (after the first year of natural exposure) of the solar reflectance of roofing membranes when exposed to the environmental conditions typical of European cities. Moreover, with this work we aim to assess the impact of soiling on the exterior surface temperatures and the heat flux of flat roofs.

2 SELECTED MATERIALS

To assess the effect of soiling on roofing materials we selected from the market 14 roofing membranes, trying to include all the possible features that could lead to a different dirt pickup. For each product class we chose a "standard" option, a "cool" alternative (namely having higher reflectance in the NIR than in the visible portion of the solar spectrum), and, if available, a photocatalytic alternative. We included products with SR_{T0} ranging from 0.237 to 0.868, having a smooth or rough surface (to different degrees); moreover, some membranes are somewhat glossy (with a perceivable specular component) while others are matte (Tab. 1).

Table 1: Selected roofing membranes, and initial solar reflectance.

Code	Description	Initial solar reflectance
m1	Grey flexible polyolefin (matte and with anti-slip surface)	0.256
m2	Grey flexible polyolefin with white factory applied elastomeric coating (glossy)	0.852
m3	White flexible polyolefin (matte and with anti-slip surface)	0.762
m4	White thermoplastic polyolefin (glossy)	0.824
m5	Grey PVC membrane (glossy)	0.464
m6	White PVC membrane (matte)	0.838
m7	Cool beige thermoplastic polyolefin (matte)	0.593
m8	Polymer-bitumen with extra white field applied elastomeric coating	0.805
m9	Polymer-bitumen with white field applied elastomeric coating	0.731
m10	Polymer-bitumen with white TiO_2 photoactive field applied coating	0.765
m11	Polymer-bitumen with white field applied elastomeric coating type B (glossy)	0.718
m12	Polymer-bitumen with cool coloured elastomeric field applied coating	0.386
m13	Photoactive asphalt shingle	0.282
m14	Standard asphalt shingle	0.234

3 NATURAL EXPOSURE AND MEASUREMENT PROCEDURES

Since cool roofing products are widely recommended as an option to mitigate urban climates, we decided to expose the selected samples at two locations within two urban areas with different climates: Roma and Milano, in both cases about halfway between city centre and periphery. The exposure is performed on two non-shaded roofs and distant from main specific sources of pollution (e.g. a particular industrial plant), thus subject to the background pollution and soil deposition (in addition, in Milano a weather station is positioned on the same roof and an air quality station is less than 300 m far). The roofing membranes were exposed low sloped (1.5% as recommended by both Italian and Swiss application standards); in Milano replicates were also exposed south oriented with a slope of 45 degrees. For each product three samples of 10 cm x 10 cm in size each were exposed for each site and exposure condition, and they had been fastened to metal frames, 80 cm above the roof.

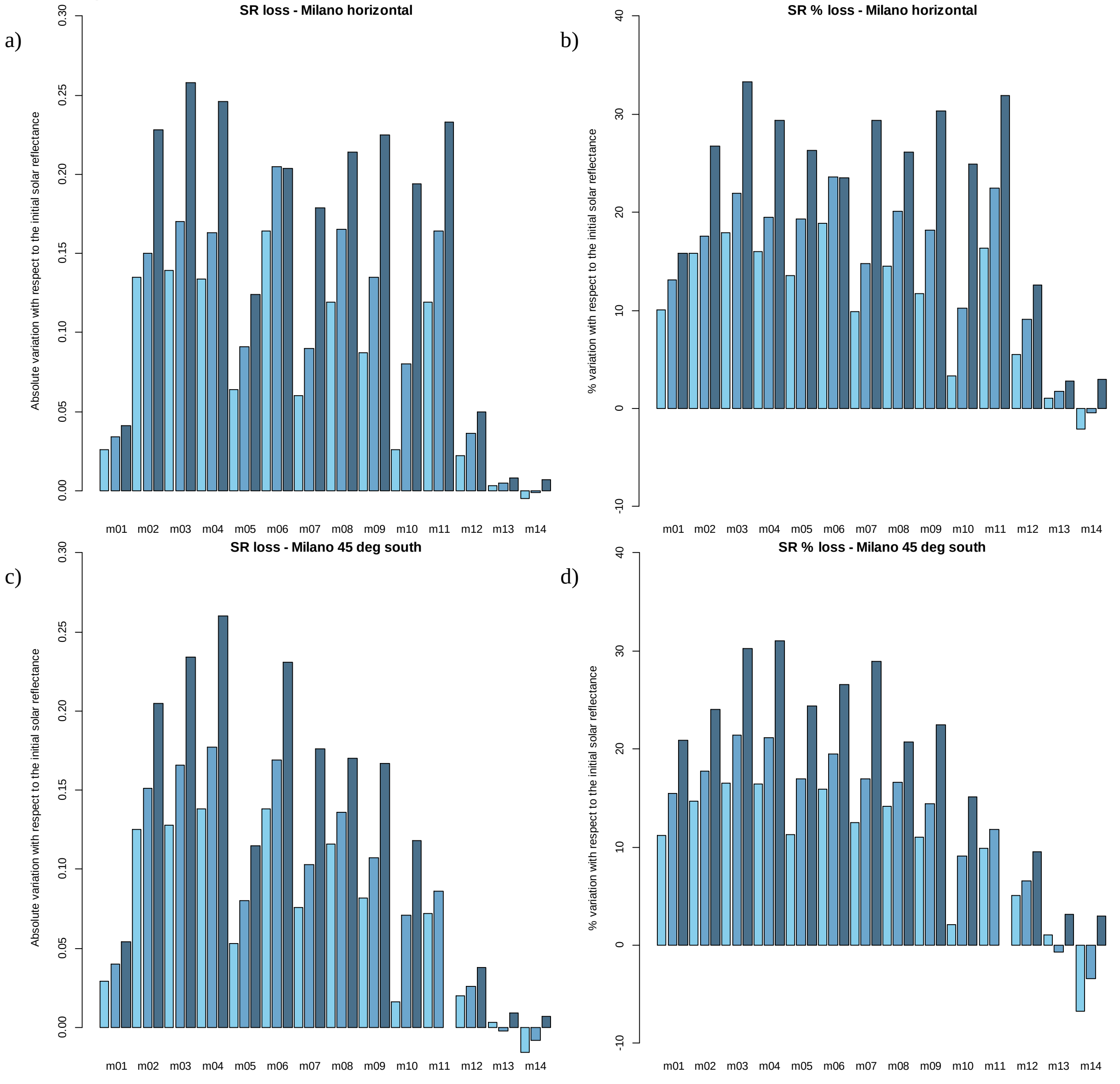
The same samples were measured when clean, and after 3, 6, and 12 months of natural exposure, begun on April 18th 2012, they were retrieved, measured in the laboratory, and re-exposed. All the measurements were performed with a UV-Vis-NIR spectrometer (Perkin Elmer Lambda 950 with 150 mm integrating sphere with PMT/PbS detectors) from 300 to 2500 nm, sampling each 5 nm. Each sample was just measured in the central point, considering as representative the portion of the sample lit by the measurement beam, namely a rectangle of about 3 mm x 20 mm, thus using the rest of the 100 mm x 100 mm samples just to exclude the edge effects. As averaging procedure (to compute the solar, UV, visible and NIR integrated values) we used that detailed in the ISO 9050 standard (ISO, 2003), which uses an air mass 1.5 global horizontal solar spectral distribution. For each product and exposure condition (i.e. site, orientation, and slope), for the three replicates we computed the average spectral curve, and then the integrated values.

4 UV-VIS-NIR REFLECTANCE WITH TIME: FIRST YEAR RESULTS

Herein we present the solar reflectance trends (absolute and as a percentage of the initial value) for the three exposure conditions (Roma and Milano horizontal, and Milano facing south with a slope of 45 degrees) for all the aged membranes, while for the sake of synthesis we present the spectral data only for the eight membranes which are mostly differentiated in terms of spectrum among those tested.

At both the exposure sites we observe remarkable variations of solar reflectance after one year of natural exposure, and in any case the changes at the CRRC's sites after three years are of the magnitude of the variations that we measured after six months of exposure in Milano and Roma. For instance, for membranes with initial solar reflectance greater than 0.80 (Sleiman *et al.*, 2011), at the Florida exposure site the average absolute loss in SR for the tested products is of 0.238 ± 0.146, while it is of 0.077 ± 0.060 and 0.173 ± 0.092 respectively in Arizona and in Ohio, namely, in average roughly 0.162, or 18% of the initial value after three years. For products within the same range (0.8-1.0) of SR_{T0} (namely membranes, m2, m4, m6, and m8 of our collection, see Tab. 1) we computed after just six months absolute losses of 0.171 (Fig. 1a) in Milano (of 0.158 for 45° slope, Fig. 1c), as in Ohio (the most urban site among those managed by the CRRC), and of 0.116 in Roma (Fig. 1e), while after one year we measured in Milano losses equal to 0.223 (0.217 for 45° slope) and of 0.154 in Roma. Considering any possible term of comparison, we see that after one year of natural exposure at the two polluted urban sites in Roma and Milano we observe the same or a greater magnitude of solar reflectance loss than at the CRRC's sites. In general, the membranes that we exposed having SR_{T0} between 0.2 and 0.3 (e.g. m1, m13, and m14) do not show relevant absolute variations over time (roughly 0.02-0.05). It is however interesting to note that the SR of the single-ply grey membrane (m1) shows a monotonic decreasing trend, while for the asphalt shingles (m13 and m14) SR fluctuates over time, sometimes exceeding the initial value when the gaps between beads are filled with soot (and other particulate matter), which has higher reflectance than the bitumen substrate (as discussed in detail by Berdahl *et al.*, 2012). Considering the general trend of losses in solar reflectance for all the membranes having SR_{T0} greater than 0.40 (i.e. all but m1, m13, and m14), we note that, after one year the average absolute loss in Milano ranges from 0.15 to 0.25 for low sloped membranes (from 0.10 to 0.25 for 45° tilted samples), in Roma it ranges roughly from 0.08 to 0.16. The loss of solar reflectance of samples low sloped and tilted by 45° (south oriented) in Milano is not remarkably different. Once again looking at the most reflecting membranes of the collection (i.e. with SR_{T0} greater than 0.80), we compute that the relative (as a percentage of the initial value) solar reflectance loss is of about 26.7% for low sloped samples, and of about 26.1% for 45° tilted samples. Differences are larger at 3 and 6 months, thus when the soiling is less conspicuous.

The spectral curves (Fig. 2 and Fig. 3) allow a deeper understanding of the action of depositions on the reflectance of roofing membranes. The abatement of reflectance is evident mainly in the visible and in the first part of the near infrared, and it is interesting to note that for all the bright membranes, the shape of the spectra is altered especially in the first part of the visible portion of the spectrum (more precisely between 420 and 600 nm), while after about 600-800 nm the spectrum is substantially shifted down, retaining the original shape. Although, as obvious, the absolute values of reflectance of samples exposed at the two sites are different, is noticeable that the shape of the spectra of the aged membranes is almost the same both in Roma and Milano, suggesting that in metropolitan areas just the intensity of deposition is different, while the basic ingredients of soiling (e.g. products of combustion from vehicles' engines and heating plants) are the same. There is actually a difference in terms of shape of the spectra between the horizontally exposed samples and those tilted of 45°. For the latter ones the effect of depositions between 420 and 600 nm is slightly less pronounced than for the low sloped specimens. In addition, comparing the results for clean and soiled membranes with different initial spectral reflectances, we note that when the reflectance is lower than 0.40 after 1500 nm the impact of soiling in the last portion of the NIR seems to be negligible (Fig. 2 d, e, and f). Similarly, the case of membrane m12 (Fig. 3 g, h, and i), a cool coloured field applied coating on modified bitumen, is remarkable in showing which is the optical behaviour of soot in the visible, since the spectral reflectance of that membrane is unchanged just in the visible.



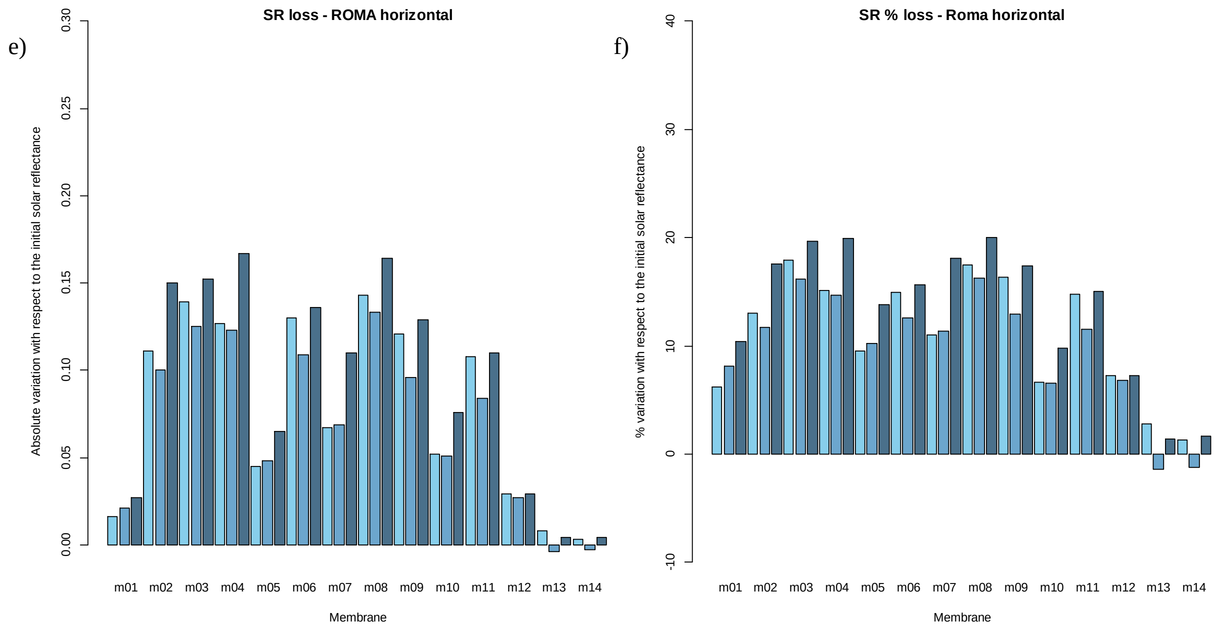
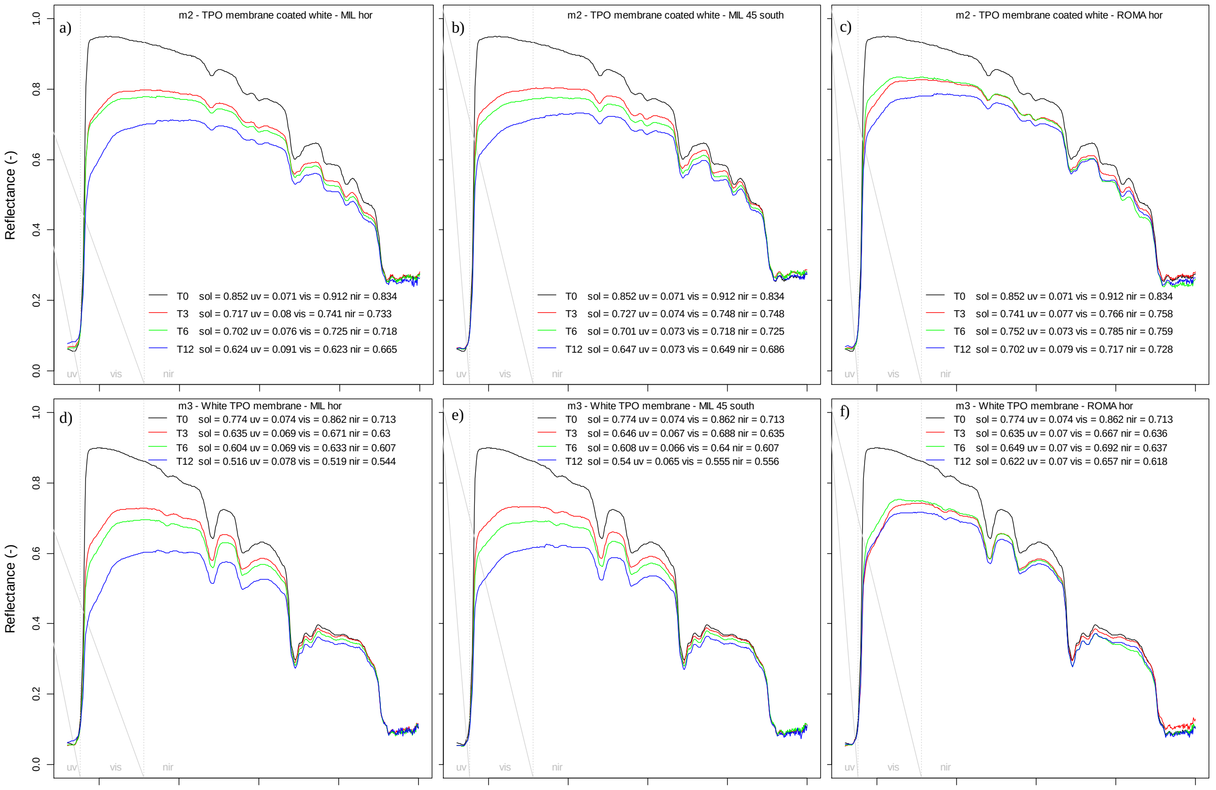


Figure 1: Absolute solar reflectance variation after 3 (light blue), six (blue), and 12 months (dark blue) in Milano for low sloped samples (a) and samples tilted by 45° (c) and low sloped in Roma (e). Relative (percentage of the initial value) loss of solar reflectance in Milano low sloped (b), Milano 45° tilted (d), and Roma (f).

MILANO horizontal	**MILANO 45 deg south oriented**	**ROMA horizontal**



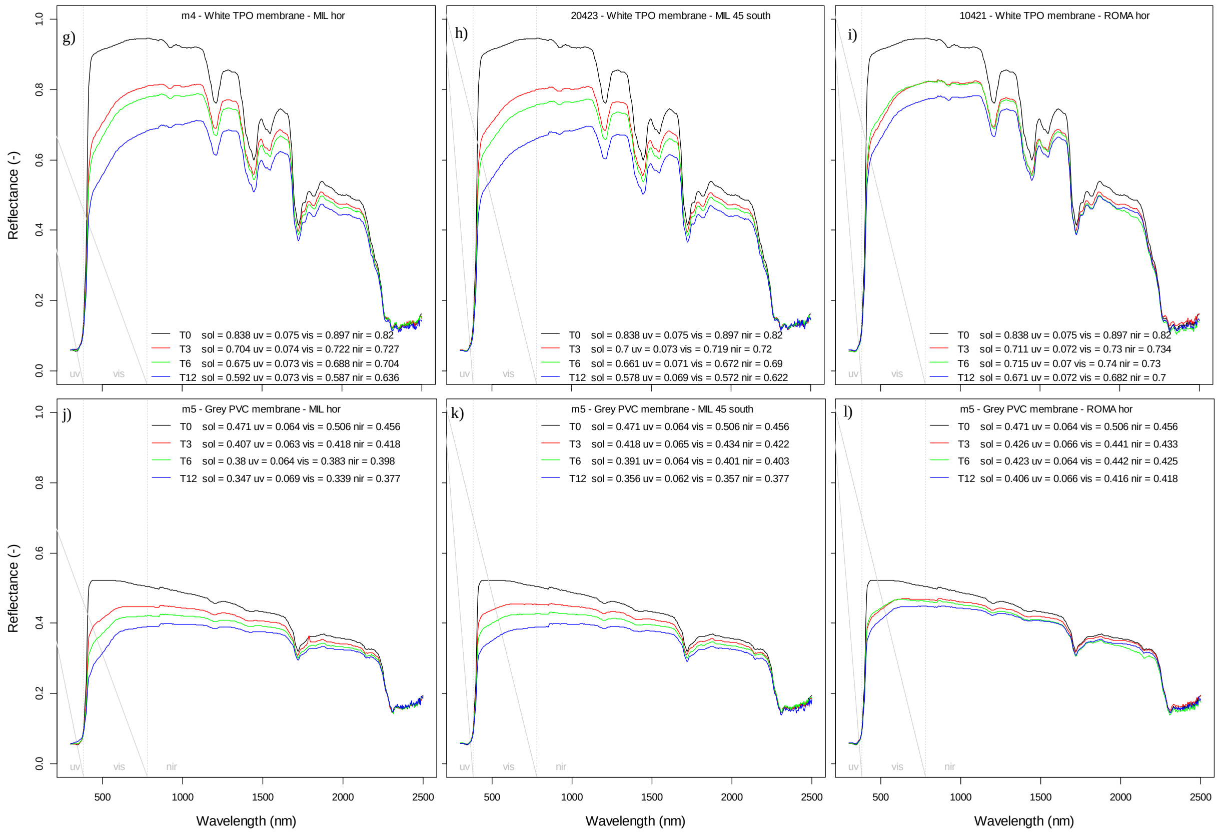
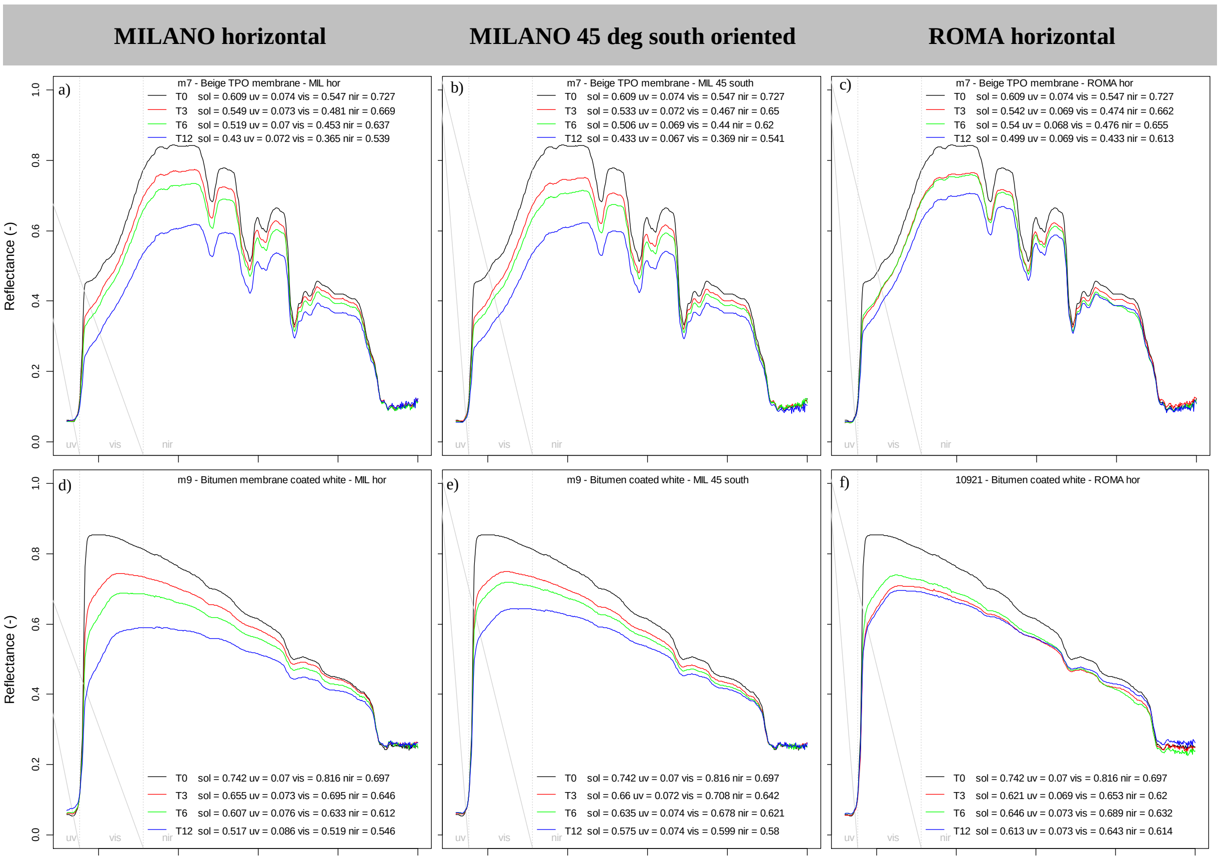


Figure 2: Spectral reflectance and computed solar, UV, visible, and NIR reflectance for the membranes m2, m3, m4, and m5 after 3, 6 and 12 months in Milano (low sloped and 45° sloped south oriented) and in Roma.



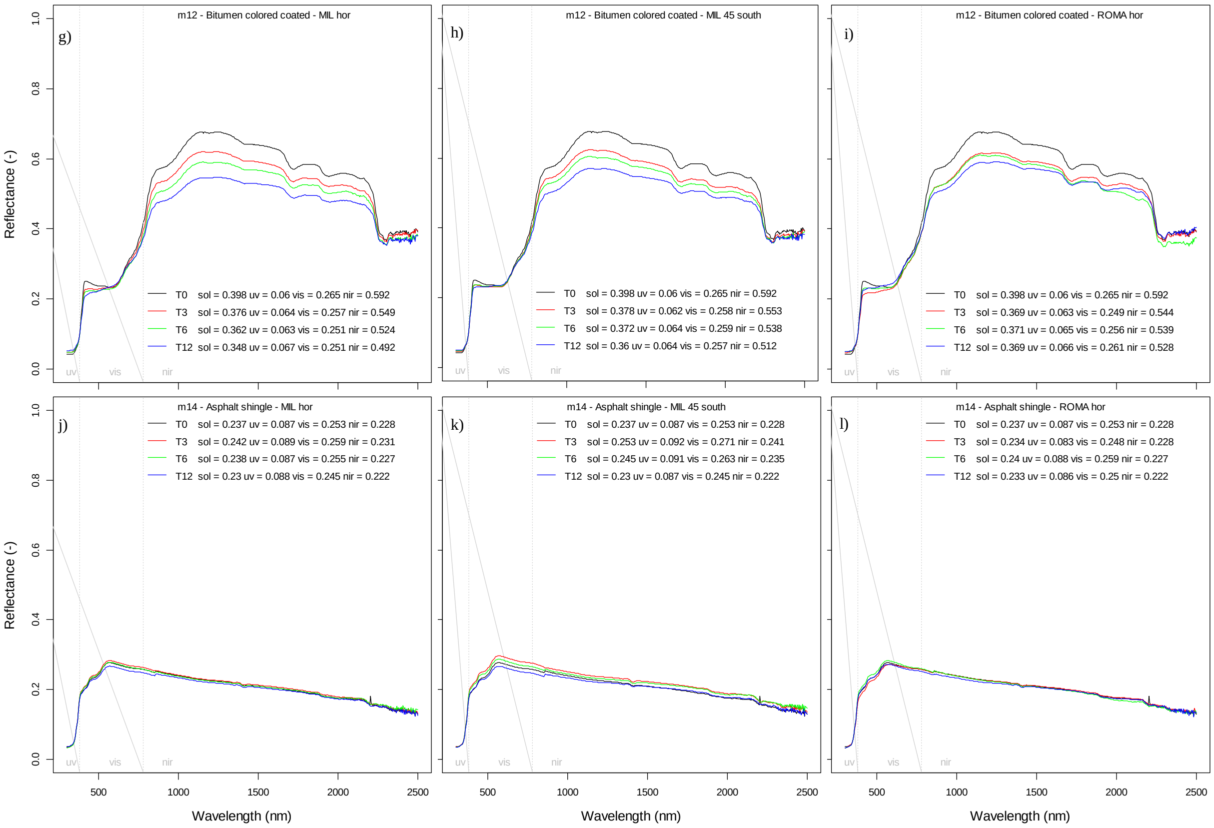


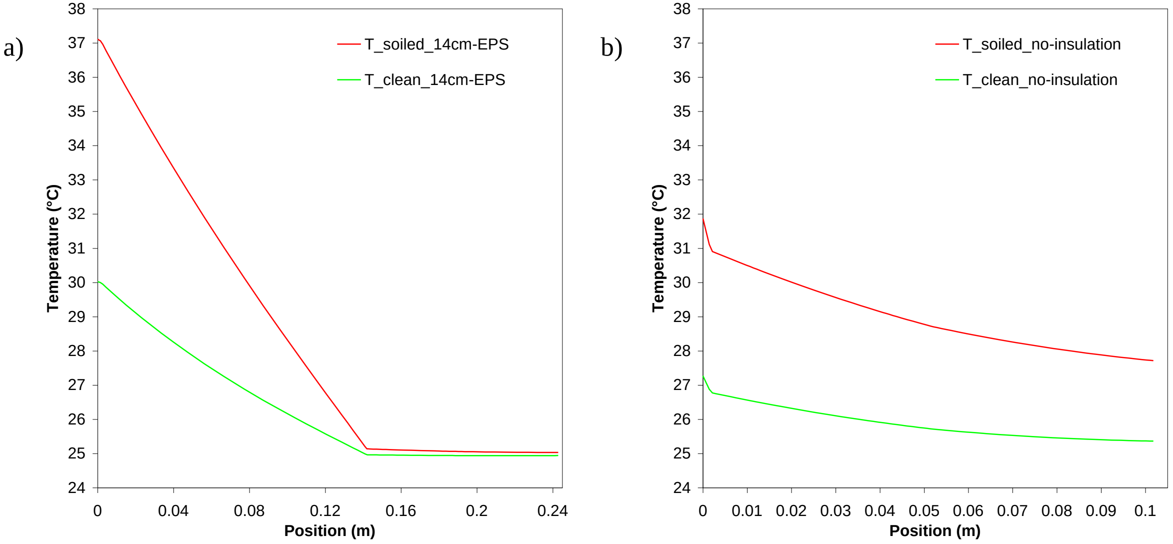
Figure 3: Spectral reflectance and computed solar, UV, visible, and NIR reflectance for the membranes m7, m9, m12, and m14 after 3, 6 and 12 months in Milano (low sloped and 45° sloped south oriented) and in Roma.

5 COMPUTED SURFACE TEMPERATURES AND HEAT FLUXES

Once that the evolution over time of the solar reflectance of a given roofing product is known for a specific context - or a reliable estimate is made using a regression representative for a class of products in a possible context of application, such as urban climates in Southern Europe - it is important to assess when and whether these changes are relevant for the building energy demand and the microclimate. To investigate this aspect we performed numerical modelling of heat and moisture transport through typical (for the Italian context) precast flat roofing assemblies for industrial and commercial buildings, considering the case of well insulated roofs and woofs without insulation. In detail, we considered a double-T precast concrete slab, with a wing 5 cm thick, with additional 5 cm of concrete screed and, in case of insulation, a vapour retarder (1 mm of polyethylene), 14 cm of expanded polystyrene (EPS) and the roofing membrane (U-value = 0.267 W m^{-2} K^{-1}), while in case of no insulation the membrane is applied onto the screed (U-value = 4.087 W m^{-2} K^{-1}). The case without insulation is representative for either a non-retrofitted building or a building where an industrial activity takes place (e.g. with a furnace or computer servers) dissipating heat and keeping the indoor temperature constant at 20°C in winter without the need of a heating plant, while demanding cooling in summer.

The numerical simulations were performed by means of the software tool WUFI 5.2 (www.wufi.de), based on a finite volumes physically based model, which couples and resolves numerically (up to convergence) two equations dealing, respectively, with one-dimensional transient heat and moisture transport, and is capable of taking into account the latent transformations, as well as the dependency of the thermal properties on temperature and moisture content. For the exterior climate, we used hourly data from 15 April 2012 to 15 April 2013 - namely the period of exposure of the membranes - collected by a weather station in Politecnico di Milano (latitude: 45.4798; longitude: 9.2297) on the same roof were the samples were exposed. For the indoors, we assumed 20°C when the exterior temperature is lower than 10°C, 25°C when the exterior temperature higher than 20°C, and linearly interpolated values in between. Then, we considered the case of membrane m2, a flexible polyolefin topped by a white glossy elastomeric coating, with SR_{T0} equal to 0.852, and 0.717 after 3 months, 0.702 after 6 months, and 0.624 after one year of natural low sloped exposure in Milano (Fig. 2a). Then we modelled two cases: with constant SR (as clean), and with SR as a function of time using the measured data (intermediate values were linearly interpolated).

Considering peak summer conditions, for instance close to solar noon in a typical clear sky summer day (in this case July 21st), we see that the exterior surface temperature of a well insulated flat roof is 7°C hotter just after 3 months of natural exposure than if kept clean (Fig 4a), while there is little difference at the interior surface temperature, given that the building is conditioned. In case of a non-insulated roof, instead, the difference between soiled and clean condition is smaller (about 4.5°C) at the exterior surface, while it is of about 2.5°C at the interior surface (Fig. 4b). Looking at hourly values all through the year we see that, already in its first summer of service life, the soiled roof is 7-8°C hotter than the clean roof if insulated, and 5°C if not insulated. In the end of the first year of service life, the roof is dirtier, and already in the first part of April the soiled roof is hotter than the clean roof by about 14°C or 8°C, respectively if insulated or not. Finally, considering the heat fluxes at the interior surface we note that, not surprisingly, in case of high insulation, the difference between soiled and clean roof is negligible. On the other hand, for a non-insulated roof, the peak incoming heat fluxes when the roof is soiled (in average 38 W m^{-2}) are more than double than when the roof is clean (in average 16 W m^{-2}). In winter condition, instead, a non-insulated clean roof transfers more heat than the soiled one even by about 15 W m^{-2}.



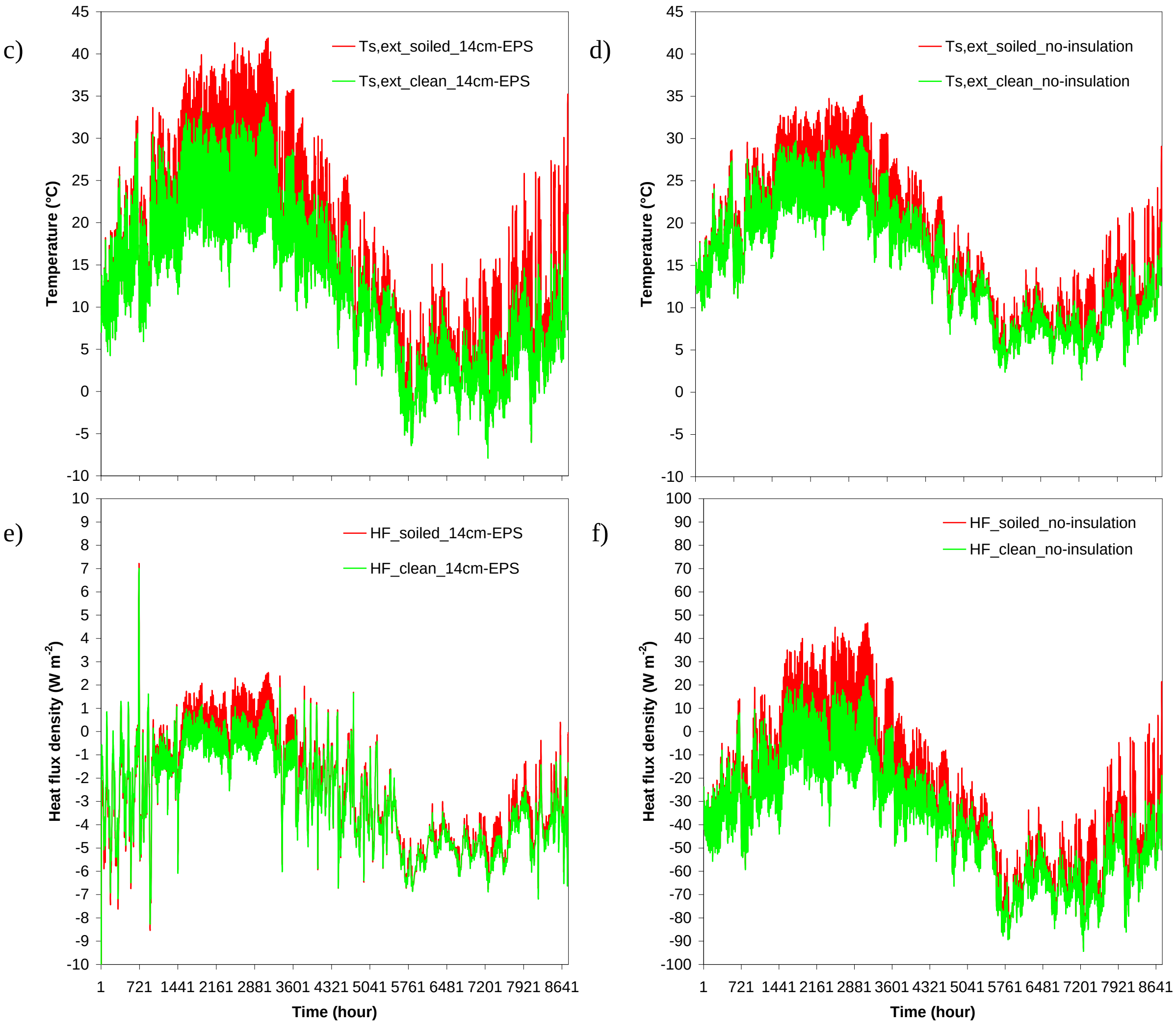


Figure 4: Temperature profiles (from the exterior surface to the interior) with 14 cm of EPS (a) and with no insulation (b) on a typical summer day (21st July) at 13:00 local time; hourly exterior surface temperatures with high (c) or no insulation (d); and hourly heat flux density at the interior surface with high (e) or no insulation (f).

6 CONCLUSIONS

Since cool roofs are identified as an effective option to mitigate heat islands and reduce the cooling energy demand of buildings, several studies were performed in the U.S. to determine how long a roof may retain its high albedo, but there are only few experiences in Europe. Thus, to assess the effect of dirt deposition on albedo in Italian cities, in April 2012 we exposed both in Milano and in Roma 14 roofing membranes retrieved from the market, measuring their reflectance when clean and after 3, 6, and 12 months. After the first year of natural exposure in Milano we compute a reduction of SR by sometimes more than 30% of the initial value, for instance for the membranes with initial SR greater than 0.80, while for the samples exposed in Roma the peak reductions are of about 20%. Especially, we note that the losses observed after three years of exposure at the CRRC's sites were achieved in Roma and Milano just after six months. We also computed the surface temperatures and the heat fluxes for typical roof assemblies for industrial and commercial buildings, when the roof is soiled and when is modelled as always clean. In summer, just after 3 months of service life, the soiled roof is 7-8°C hotter than the clean roof if insulated, and 4-5°C if not insulated. In the end of the first year of service life, the roof is dirtier, and already in the first part of April the soiled roof is hotter than the clean roof by about 14°C or 8°C, respectively if insulated or not. If for well insulated roofs the influence of soiling on interior surface temperatures and heat fluxes is negligible, for a non-insulated roof, the peak incoming heat fluxes when the roof is soiled are more than double than for a clean roof (in average 38 vs. 16 W m^{-2}).

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