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A composite cool colored tile for sloped roofs with high 'equivalent' solar reflectance

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KEYWORDS

Cool roof, cool color, roof tile, solar reflectance, thermal transmittance

HIGHLIGHTS

- Ceramic tiles covers the roofs of Mediterranean cities.
- Their low solar reflectance can cause overheating of the built environment below.
- Cool colors can be exploited to achieve a higher reflectance.

- An equivalent, much higher, reflectance can be achieved by coupling with an aerogel layer and a radiant barrier.

ABSTRACT

Mediterranean cities are characterized by sloped roofs with ceramic tiles of traditional colors such as brick red in different tones. Their solar reflectance is generally low and can cause overheating of the building due to solar gains during the hot season.

In this work, an innovative approach is tested to achieve roof tiles with high capacity of rejecting solar radiation. It consists of using a cool-colored tile with relatively high solar reflectance, combined with a thin insulating layer attached below the tile and made of a silica-gel super-insulating material. An aluminum foil with very low thermal emittance is also applied below the insulating layer. Along the perimeter of each tile, line brushes are attached in order to enclose an almost sealed air space between the aluminum foil and the roof slab below when the tiles are supported on wooden battens.

Composite tiles like that outlined here can provide a strong increase of roof thermal resistance, helpful to control either heat loss in winter, or building overheating in summer. They can be installed onto an existing roof, for instance the sloped tile roof of a historical or traditional building, with no need to modify the roof height and structure.

Introduction

In the last decades the urban heat island (UHI) phenomenon more and more affected the temperature of urban areas, with a sensible increase of air temperature in comparison with the surrounding rural areas. Both controllable and uncontrollable causes may origin UHI; among the latter ones anticyclone conditions, extremely hot seasons, sun intensity, wind speed and cloud cover can be found. Urban design and structure related variables (sky view factor, green areas, building materials), or population related variables (anthropogenic heat and air pollutants), are among controllable variables as reported by [1]. Several consequences are originated by the UHI, the most important ones being the significant change of climate, the increase of greenhouse gases and CO_2 emissions, and the increase of energy consumption of buildings due to the larger use of electricity for air conditioning.

In the last decades the attempt to reduce UHI stimulated the research of several solutions such as solar reflective surfaces [1]. The first studies were carried out since the late 90's when LBNL scientists started to analyze how high albedo materials can either mitigate UHI [2] or reduce energy use [3-4], as well as improve air quality [5]. Studies started in southern U.S., but they were then widened to consider different areas and climates [6]. More recently, in 2012, further analyses on the benefits related to reflective roofs and pavements use were made both in the US [7] and in Europe [8]. Along the years, several generations of cool roofing materials were implemented, as reported in Santamouris [9].

Not only the increase of solar reflective areas but also green surfaces such as green roofs were widely analyzed. Studies on the energy and environmental performance [10] and the surface heat budget [11] of green roofs were carried out more than a decade ago, also trying to establish models for building energy simulation programs [12]. More recently, investigations were made on building energy savings [13], pollution abatement [14] and mitigation potential related to green roof in specific areas such as Chicago [15], tropical areas [16] and Mediterranean regions [17].

This work is focused on a new cool roof generation, characterized by high-reflectance coatings properly added with pigments that create the so called cool colors [18-19], that is colored surfaces with a high reflectivity in the infrared range of the solar spectrum [21-22]. Recent studies on acrylic coatings [23-24] highlighted that not only the coating but also the substrate is crucial for the achievement of an adequate solar reflectance. Moreover, it was found that the use of a ceramic support for both clay roof tiles [24-25] and traditional porcelain stoneware tiles [26-27] can provide very high solar reflectance over the whole solar spectrum and high durability against time.

In this work, an innovative approach is tested to achieve roof tiles with high capacity of rejecting solar radiation. It consists of using a cool-colored red tile with common brick (terracotta) color but relatively high solar reflectance, coupled with a thin insulating layer attached below the tile and made of a silica-gel super-insulating material. An aluminum foil with very low thermal emittance is also applied below the insulating layer to act as radiant barrier. Along the perimeter of each tile, line brushes are attached in order to enclose an almost sealed air space between the aluminum foil and the roof slab onto which the tile is installed. The brushes allow sealing the air space perimeter when the tile is supported on wooden battens. Terracotta tiles are acknowledged to be the finishing layer with underneath ventilation, but the adopted brushes allow sealing the ventilation layer and exploiting the resulting airspace for thermal insulation, also thanks to the radiant barrier provided by the aluminum foil. This can largely offset the loss of the weak cooling effect given by underneath ventilation in summer, while it is however helpful in winter to control heat loss. In fact, a layer of such composite tiles can provide a strong resistance to heat flow through the roof slab below thanks to the combined action the insulating layer and the air space. The contribution of the cool color coating is added in summer, further limiting building overheating and, in combination with that, the negative effects of urban heat island.

The proposed composite tile is intended for installation on uninsulated or poorly insulated roofs with inhabited spaces below by simply replacing the existing tiles. Thanks to the negligible increase of thickness, the tile layer can be installed onto an existing roof, for instance the sloped tile roof of an historical or traditional building, with no need to modify the roof height and structure, and thus the metal gutters and the other finishing elements that are usually present at the roof edges or around skylight windows. As a results, an increase of roof insulation is achieved not far from that provided by a much more invasive installation of a thick insulation layer, at the same time obtaining a shield against solar radiation more effective than that provided by the cool color coating alone.

The behavior of the developed tile is theoretically and experimentally investigated in this work, making a comparison with a common tile with the same brick color. Performance parameter such as solar reflectance, thermal emittance, and thermal conductivity are measured. Moreover, an experimental test rig has been set up.

Materials and methods

Experimental data were collected using two painted clay roof tiles. One of the tiles has been coated by a solar reflective brick red paint with solar reflectance ρ_{sol}=0.46, the other one by a standard paint with the same color but ρ_{sol}=0.22. A white basecoat with high solar reflectance has also been applied to the substrate material before the solar reflective cool color coating in order to exploit the selective transparency of the coating, if any, and thus further enhance ρ_{sol}. This approach was proposed in [28] and tested in previous work [23-24].

The solar reflectance was measured by means of a Devices and Services SSR solar reflectometer [29] compliant with the ASTM C1549 standard test method [30], using irradiance spectrum E891BN. The cool colored tile and the standard one were placed onto two battens mimicking the typical supports for such roof tile. A 2 cm airspace was thus created between the tile and the base below, consisting of a thick polystyrene panel (Fig. 1). A T-type thermocouple was placed below the tile, close to its center, to measure the temperature on the bottom surface of the airspace. In order to control the experimental conditions, another thermocouple was used to track the evolution of the room temperature during the measurement session. The temperature on the tile surface was also measured by a FLIR T-640 infrared camera [31]. Moreover, a black painted aluminum disc with known infrared emittance and an embedded thermocouple was placed in the field of view of the instrument, properly shielded from the lamp light, in order to compare the temperature measured by the thermocouple and that measured by the infrared camera, and thus to detect possible drifts of the surface temperature measurements.

All thermocouples were connected to a Pico TC-08 USB thermocouple data logger [32]. Four halogen lamps were placed over the sample and oriented in order to provide an estimated total irradiance of 870 W/m^2, measured by a Delta Ohm HD 9221 radiometer [33]. Since the instrument is sensitive only in the visible and near infrared range (450-950 nm), the total irradiance value was extrapolated from the measured one by taking into account the sensitivity curve of the instrument, the blackbody spectrum of the lamp filament at its nominal temperature of 4000 K and the transmittance spectrum of the quartz glass protecting the lamps. The obtained irradiance value is about the peak global irradiance of the sun on a low-slope roof surface in a typical Mediterranean climate.

Figure 1. Experimental setup.

The experiments consisted of two different stages: in the first one, the tiles were heated by the lamp system until all temperatures were stabilized, then the lamps were switched off and the surface temperature of the tiles measured by the infrared camera were recorded, as well as the temperature measured by the thermocouples.

In the second stage, the same procedure was followed but an insulating layer was placed below the cool-colored tile. The insulating layer is made of an aerogel, a silica-gel super-insulating material, with thickness 1 cm and thermal conductivity 0.015 W/m/K. The thermal conductivity was verified by a guarded hot plate apparatus available at the University of Modena and Reggio Emilia. An aluminum foil was also applied below the insulating layer, with thermal emittance as low as 0.04. This was measured by means of a Devices&Services AE1 thermal emissometer [34] compliant with the ASTM C1371 standard test method [35]. The surface without aluminum foil has thermal emittance as high as 0.90. To ensure an almost sealed air space below the tile, polyester line brushes were attached along the tile perimeter and a polystyrene frame was also placed around it, in order to avoid transverse heat flux and thus approach a 1D thermal system.

The measured parameters and the used instrumentation are summarized in Tab. 1. The layer structure of the experimental setup is summarized in Tab. 2.

Table 1 – Measured parameters and instruments.

Parameter	Measurement location	Instrument
Solar reflectance	Tile upper surface	D&S SSR solar reflectometer [29-30]
Surface temperature	Tile upper surface, reference disk	FLIR T640 infrared camera [31]
Temperatures	Tile bottom surface, ambient, reference disk	Picotech TC-08 USB datalogger [32] with T-type shielded thermocouples
Irradiance (450-950 nm)	Tile upper surface	DeltaOHM HD9221 photo-radiometer [33]
Thermal emittance	Radiant barrier surface	D&S AE1&RD1 thermal emissometer [34-35]

Table 2 – Layer structure and materials of the test system.

	Thickness [mm]	Thermal conductivity [W/(m K)]
Tile	10	1.0
Silica aerogel	0-10	0.015
Airspace	20	0.031-0.126*
XPS slab	50	0.040

*equivalent value, calculated with/without radiant barrier

In brief, the photo-radiometer was used to estimate the irradiance provided by the lamp system. The reflectometer was used to measure the solar reflectance of the tile upper surface and, from that, to estimate the absorbed fraction of the lamp irradiance. The infrared camera was used to measure the temperature of the tile upper surface, acquired immediately after having masked the lamp system in order to avoid measuring also the reflected radiation, and the temperature of the reference disk. The thermocouple system was used to measure the temperature below the tile, the ambient temperature and that of the reference disk. The offset of measurements by the infrared camera with respect to those by the thermocouple system was corrected by comparison of temperatures measured on the reference disk. The combination of temperature measurements allowed to determine the temperature profile across the tile system.

Provided that the brushes effectively seal the thin air space below the tile in either the described experimental apparatus or the real field application, the air is still in both cases. As a result, the tile behavior predicted here by theoretical and laboratory analyses can be assumed to be representative of that of an actual roof in the same ambient conditions.

Theoretical analysis

A layer of tiles is assumed to be installed on a generic roof with given thermal transmittance U_{roof} [W/m^2/K], that is thermal resistance R_{roof} =1/U_{roof} [m^{2}K/W], built over a heated and air conditioned living space. Using a steady-state calculation approach similar to that outlined in ISO 13790 [36] or already considered in [37-38], the heat flux density q [W/m^2] through the roof surface can be evaluated as follows:

$$q = \left[T_e + \left(1 - \rho_{sol}\right) I_{sol} R_{se} - T_i\right] / \left(R + \Delta R\right) \quad (1)$$

where

T_e external temperature, given by a combination of air and sky temperatures [°C]

ρ_{sol} solar reflectance

I_{sol} solar irradiance [W/m^2]

R_{se} surface resistance by convection and infrared radiation [m^{2}K/W]

T_i internal set point temperature, stabilized by a HVAC system [°C]

R_{roof} roof thermal resistance, inverse of the thermal transmittance [m^2K/W]

ΔR increase of the thermal resistance thanks to sub-tile insulation and sealed air gap with radiant barrier

The steady state analysis was found to provide a satisfactory agreement with the average behavior of roof structures typically used in Southern Europe [38]. In steady state, only thermal resistances must be taken into account, allowing to neglect the actual roof structure with its thermal masses and inertia.

The solar irradiance averaged over the day can be considered for I_{sol}, or even the peak solar irradiance. The average irradiance on a surface with given orientation and slope can be calculated as the ratio the of mean daily irradiation on the same surface and the day length, in this case obtaining from Eq. (1) the average heat flux in the day. The increase of the roof thermal resistance ΔR can be evaluated as the thermal resistance of the insulation layer attached to the tile bottom and the sealed air gap below with the radiant barrier provided by the aluminum foil, reduced by the thermal resistance of the air gap without sub-tile insulation and radiant barrier (often neglected and so not included in R). No condensation/evaporation effects are taken into account in Eq. (1).

The solar reflectance of a cool colored surface can be significantly higher than that of a conventional surface, but still much lower than a white surface. This is the case of the brick red surface considered here, whose solar reflectance is increased from 0.22 to 0.46 thanks to the white basecoat and the cool color coating. However, increasing the roof resistance can have an effect equivalent to a further increase of solar reflectance. More specifically, for a standard tile without insulation below (ΔR=0) an effective solar reflectance $\rho_{sol,eff}$ can be calculated, providing the same net heat flux density q of the composite tile with actual reflectance ρ_{sol} of the cool color coating:

$$q = \left[T_e + \left(1 - \rho_{sol,eff}\right) I_{sol} R_{se} - T_i\right] / R \qquad (2)$$

Equaling the second terms of Eq. (1) and Eq. (2), and then solving with respect to $\rho_{sol,eff}$, one obtains:

$$\rho_{sol,eff} = \rho_{sol} + \left(1 - \rho_{sol}\right) \frac{\Delta R}{R + \Delta R} + \frac{\left[T_e - T_i\right]}{I_{sol} R_{se}} \frac{\Delta R}{R + \Delta R} \qquad (3)$$

The last term in Eq. (3) depends on the local environmental conditions explicitly or implicitly expressed by T_e, I_{sol}, and R_{se}, and the internal set-point temperature T_i; such term is influenced by the location, the surface orientation, the time in the year and in the day, or even the building use. Nonetheless, if $T_e \geq T_i$, as it usually occurs in the hot season of Mediterranean areas, the last term is always positive and can be conservatively neglected. This leaves the equation below for the effective solar reflectance, depending only on the characteristics of roof and tiles:

$$\rho_{sol,eff} = \rho_{sol} + \left(1 - \rho_{sol}\right) \frac{\Delta R}{R + \Delta R} \qquad (4)$$

The behavior or $\rho_{sol,eff}$ with respect to the value of R is plotted in Fig. 2 in order to evidence the potential of the composite tile solution. ΔR was evaluated according to EN ISO 6946 [39] and found equal to 1.2 m^2K/W.

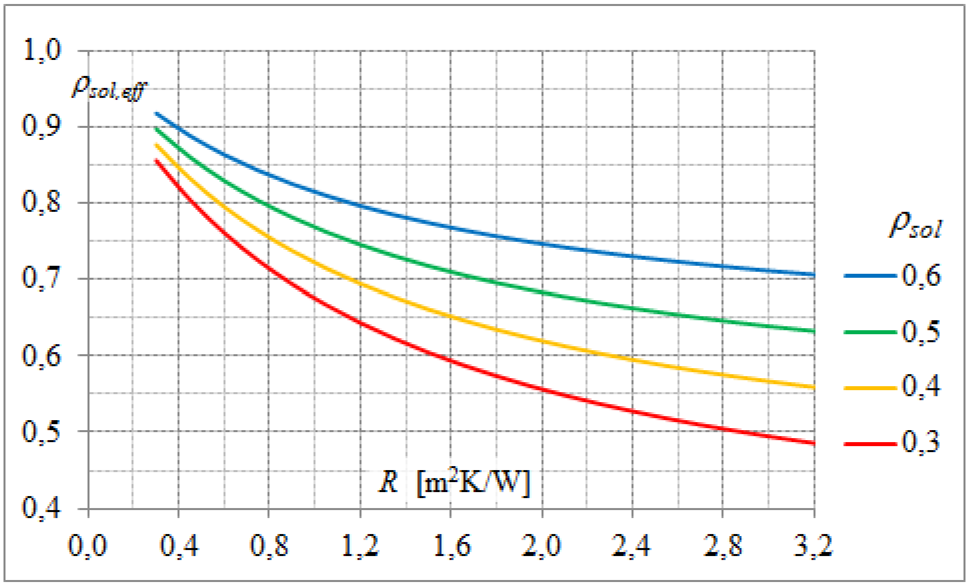

Figure 2. Effective solar reflectance $\rho_{sol,eff}$ vs. roof thermal resistance R and actual solar reflectance ρ_{sol}, for an increase of thermal resistance ΔR = 1.2 m^2K/W.

One con observe from Fig. 2 that, for a typical poorly insulated roof with thermal resistance around 1 m^2K/W, the roof thermal resistance is more than doubled and an equivalent increase of solar reflectance up to a few tens of percentage points is achieved. For a heavily insulated roof with thermal resistance around 3 m^2K/W, again an equivalent increase from 0.10 to 0.20 is achieved, depending on the actual solar reflectance.

A common criticism of cool roofing solutions is related to the loss of solar gains during the cold season. A steady state balance of the roof before the refurbishment proposed hear can be expressed as follows:

$$q_{init} = \left[T_e + \left(1-\rho_{sol,init}\right) I_{sol} R_{se} - T_i\right] / R \tag{5}$$

where

$\rho_{sol,init}$ initial solar reflectance before the substitution of the tiles

Subtracting Eq. (1) from Eq. (5) one obtains than no penalization occurs if the result is not negative. By proper manipulation of such inequality, one obtains:

$$\left[\left(\rho_{sol} - \rho_{sol,init}\right) I_{sol} R_{se}\right] \leq \left[T_i - \left(1-\rho_{sol,init}\right) I_{sol} R_{se} - T_e\right] \Delta R / R \tag{6}$$

or

$$\beta = \frac{\left[\left(\rho_{sol} - \rho_{sol,init}\right) I_{sol} R_{se}\right]}{\left[T_i - \left(1-\rho_{sol,init}\right) I_{sol} R_{se} - T_e\right] \Delta R / R} \leq 1 \tag{7}$$

In other words, no penalization exists in the cold season if the loss of solar gains, expressed by the left side of Eq. (6), is lower than the reduction of heat loss through the roof, expressed by the right side. With an average solar irradiance as low as 100 W/m^2, typical of Mediterranean and sub-Mediterranean areas in the winter months, and surface thermal resistance R_{se} =0.04 m^{2}K/W as proposed by ISO 6946 [39] for winter heating calculation, as well as T_i=20°C, the ratio β in Eq. (7) is plotted in Fig. 3 for several values of T_e and R. One can easily verify that β is always well below1.

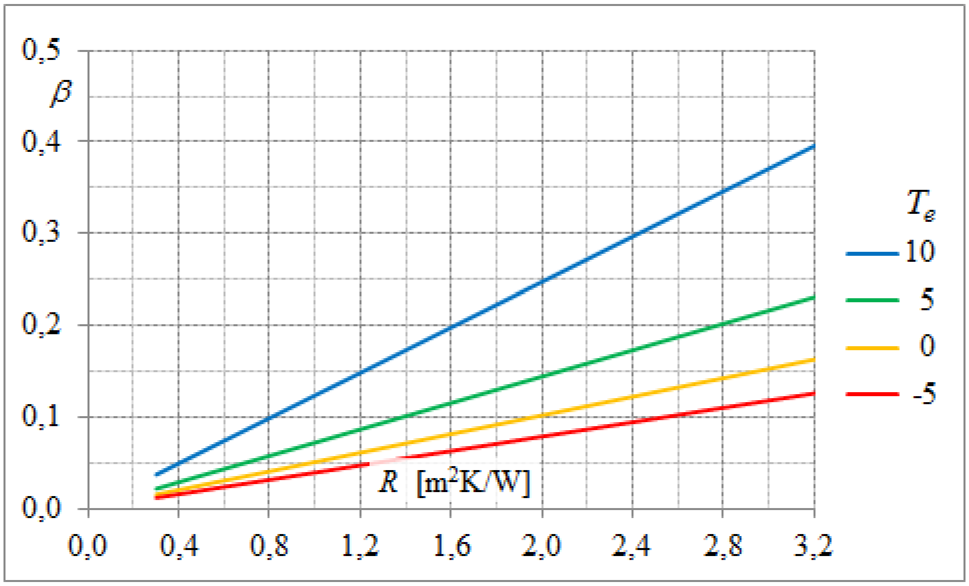

Figure 3. Ratio β vs. roof thermal resistance R and external temperature T_e, for an increase of thermal resistance ΔR = 1.2 m^2K/W.

Experimental results

The theoretical analysis was validated through the experiments previously outlined. As anticipated, steady state conditions were achieved by allowing all temperatures to stabilize. Significant temperature data recorded by thermocouples and the infrared camera are reported in Tab. 3.

Table 3 – Measured temperature data.

	Thermocouples		IR camera
	T_{amb} [°C]	$T_{airspace\ bottom}$ [°C]	$T_{tile\ top\ surface}$ [°C]
Standard tile	23.2	74.0	79.5
Cool colored tile	22.5	51.8	60.9
Cool composite tile	21.9	41.5	61.7

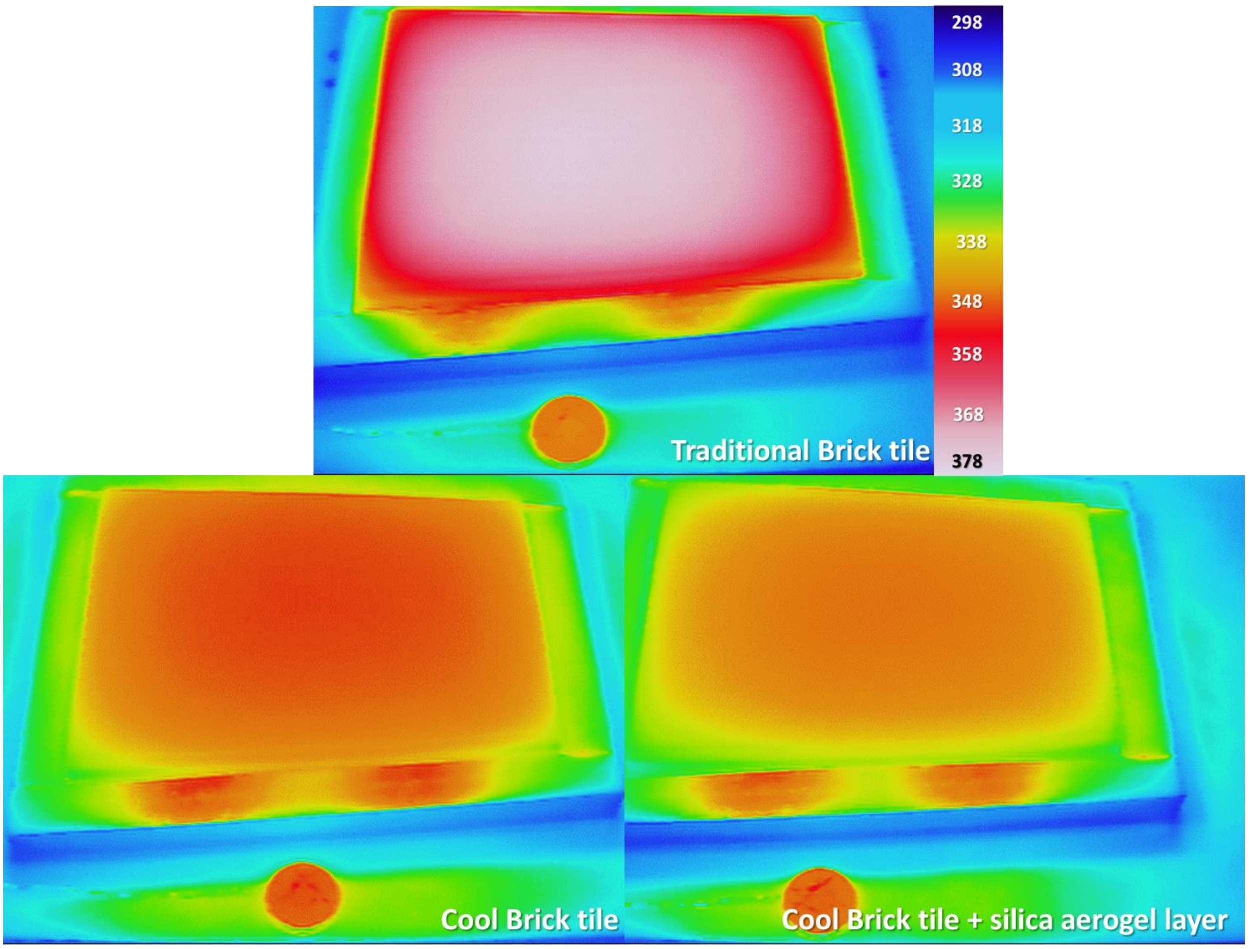

Figure 4. Infrared thermal images (scalebar in kelvin; the same one was adopted for all pictures).

Once the temperature was stabilized, the halogen lamp system was switched off and quickly masked by an insulating panel in order to prevent any residual irradiation from the light source to the measured tile. Immediately after, a thermal picture of the heated tile was acquired by the infrared camera (Fig. 4), from which data reported in Tab. 3 were eventually obtained in terms of average surface temperature in an area around the tile center. Contextually, temperature measurements from all thermocouples were also acquired. The measured temperature were eventually compared to those calculated in steady state (Fig. 5), generally showing a good coherence. More specifically, in Fig. 5 continuous lines are temperatures calculated bottom-up through the slab-tile thickness, squares are temperatures measured on the tile surface, triangles are temperature measured on the airspace bottom surface.

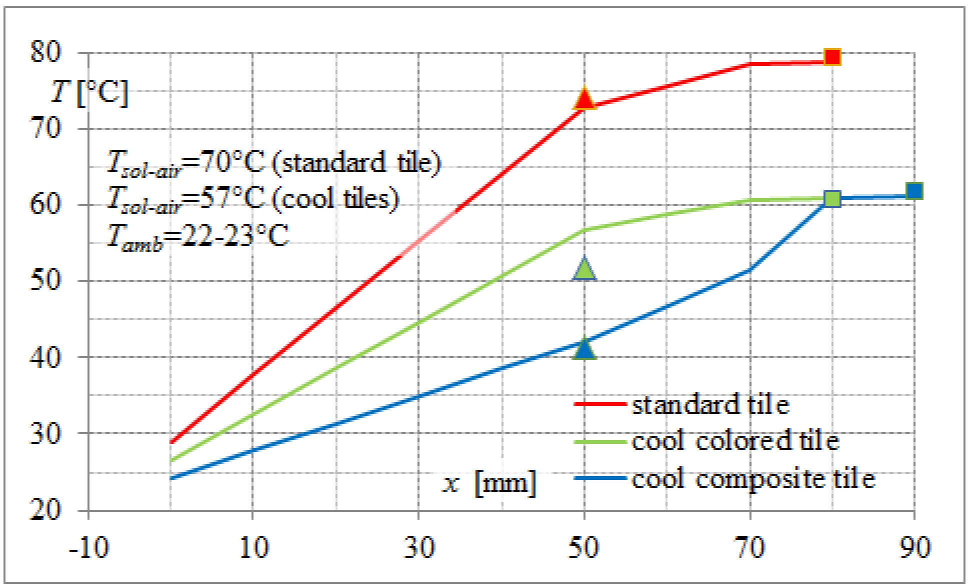

Figure 5. Comparison of measured temperatures (squares and triangles) and calculated temperatures (continuous lines).

Data in Tab. 3 and Fig. 5 show that the cool brick coating alone can provide a sharp decrease of both top and bottom surface temperatures with respect to the standard tile. With ambient temperature 22-23°C, the maximum temperature on the top surface (*x*=80 or 90 mm in

Fig. 5, marked by squares) decreases from 79.5°C to 60.9°C, while the temperature measured on the airspace bottom surface (*x*=50 mm in Fig. 5, marked by triangles) decreases from 74.1°C to 51.8°C. Coupling the cool coated tile with the super-insulating layer and the radiant barrier below allows a further decrease of the airspace bottom surface temperature to 41.5°C. This corresponds to an equivalent solar reflectance higher than 0.60, approaching that of a white cool surface.

Conclusive remarks

In a Mediterranean architectural context it is quite difficult to integrate cool roofs on traditional buildings since a good match of roofing colors with the city skyline is generally required. On the other hand, the actual cool color market can provide building materials which do not reach very high solar reflectance values, generally below 50%. An interesting solution to obtain an increase in energy performances can be represented by a coupled system made of a cool colored roof tile and a thin insulating layer made by silica aerogel and a radiant barrier below. In this paper, an investigation of such layout is presented and preliminary experimental results are reported. The results, achieved in steady state condition but to be verified soon by means of dynamic analysis, showed that a significant improvement can be achieved in terms of rejection of heat gain, reducing the temperature below the tile layer but at the same time promoting heat rejection toward the sky by thermal radiation. This effect has been shown to be mathematically equivalent to an increase of solar reflectance. The cost effectiveness of the proposed approach is also supported by the associated increase of thermal, which is helpful to decrease heat loss in the cold season.

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