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# Optical properties of traditional clay tiles for ventilated roofs and implication on roof thermal performance

**Elisa Di Giuseppe**[1], **Simona Sabbatini**[2], **Nikita Cozzolino**[1], **Pierluigi Stipa**[2] and **Marco D'Orazio**[1]

## Abstract

A remarkable advantage of clay tiles roof coverings in hot climates is the realization of a ventilated air layer between them and the roofing underlay that allows a natural and forced convection through the tiles joints and the channel from eaves to ridge, thus cooling the roof materials. However recently, in many countries, regulatory developments on buildings energy efficiency or buildings sustainability certification protocols are increasingly encouraging the use of alternative strategies, with the aim of reducing the urban heat island (UHI) effect and the buildings' cooling consumptions. Among them, the use of 'cool' materials for roof covering. These mandatory or voluntary measures de facto push the construction products market towards specific directions, risking penalizing traditional components such as clay tiles. This article reports the results of experimental and numerical activities carried out in order to extensively characterize the optical properties of clay tile materials and investigate their impact, also coupled with above sheathing ventilation, on the thermal performance of a ventilated roof under warm-temperate climate. In the first phase of the research, the main optical properties of over 30 different clay products have been experimentally characterized in order to

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[1] Department of Civil, Building Engineering and Architecture (DICEA), Universitá Politecnica delle Marche, Ancona, Italy
[2] Department of Materials, Environmental Sciences and Urban Planning (SIMAU), Universitá Politecnica delle Marche, Ancona, Italy

**Corresponding author:**
Elisa Di Giuseppe, Department of Civil, Building Engineering and Architecture (DICEA), Universitá Politecnica delle Marche, Via Brecce Bianche 12, 60131, Ancona, Italy.
Email: e.digiuseppe@staff.univpm.it

get a clear and extensive picture of such properties for the materials spread in the market. In a second phase, starting from the thermal data collected on an experimental real-scale building, a dynamic energy analysis tool was calibrated and used to perform simulations by varying the optical properties of the roof covering thus assessing the impact on the roof temperatures, also in comparison to a clay tiles roof. The results underline that the use of the above sheathing ventilation obtained through clay tiles is an effective strategy to reduce roof temperatures, even if covering materials are not qualified as ‘cool’, thus impacting on both UHI and indoor comfort.

**Keywords**

Roof, ventilation, solar reflectivity, SRI, UHI, clay tile

## Introduction

Clay is used since ancient times to make components for roof coverings, in particular in Mediterranean and Middle Eastern regions. From there, it has been widely diffused around the world due to its excellent hygrothermal properties, durability and aesthetic quality. A remarkable advantage of the use of clay tiles in hot climates is the realization of a ventilated air layer between tiles and roofing underlay given by the arrangement of battens supporting the tiles. This above sheathing ventilation allows a natural and forced convection through the gaps between the tiles and through the channel from eaves to ridge, thus cooling the roof materials, with considerable advantages in hot climates (Di Perna et al., 2011; D’Orazio et al., 2011). Several studies addressed benefits of roof ventilation by quantifying the cooling performance of ventilated roofs in relation to the roof geometry, the tiles shapes, the climatic conditions, both through full-scale models under external conditions (Dimoudi et al., 2006; D’Orazio et al., 2008; Puangsombut et al., 2007) and numerical investigations (Bottarelli et al., 2016; Ciampi et al., 2005; De With et al., 2009).

However, even in some countries of the hottest climatic contexts, the most recent regulatory developments on building energy efficiency or buildings sustainability certification protocols are increasingly encouraging the use of alternative strategies for roof’s passive cooling, with the aim of reducing the urban heat island (UHI) effect and the buildings’ cooling consumptions. Among them, the use of building finishing and roof-covering materials with high solar reflectance (ρ) and emissivity (ε), commonly known as ‘cool’ materials. When exposed to solar radiation, these materials can achieve lower temperatures compared to similar materials with lower reflectance and then to reduce the heat transfer to surrounding air. They are spread in climatic and constructive contexts very different from the Mediterranean ones, mainly characterized by temperate climates and lightweight buildings.

These legislative measures mandatory or voluntary legislative measures for instance indicate the minimum target on the optical properties that the roofing materials are expected to reach, de facto pushing the market of construction products in specific directions. Furthermore, this approach risks not to consider some important aspects that need to be more thoroughly investigated.

First, there is a risk of penalizing the use of conventional but proven technologies, as roof ventilation obtained through clay tiles with balanced optical properties (high emissivity and average reflectivity levels). Furthermore, while in international literature, the use of high-reflectance finishing materials is considered an effective strategy to mitigate the UHI or reduce cooling needs in flat and poorly insulated roofs; in buildings with low envelopes U-values it seems to have a limited impact on interior comfort. Finally, another well-known limit of cool materials lies in the fact that its optical properties cannot be considered stable over time, as materials are subject to chromatic change as a result of sedimentation and natural ageing phenomena. This causes durability issues with obvious repercussions if environmental and economic impacts are considered in the building life-cycle perspective.

This article reports the results of experimental and numerical activities carried out in order to extensively characterize the optical properties of clay tiles materials and investigate their impact, when coupled with above sheathing ventilation, on roof temperatures under warm climate in Italy, also in comparison with unventilated 'cool' roofs. The work is based on the recent national requirements on 'cool' materials for buildings, also considering the actual construction context that pushes towards more and more highly insulated envelopes to face the winter heating issue.

The research was divided into two phases. In the first phase, the optical properties (solar reflectivity and thermal emissivity) of different clay tile products have been experimentally characterized, among the most widespread in Italian market and internationally. This work has allowed to get a clear and extensive picture of such properties, which for decades have been collected in international databases for different types of roofing materials but are not still extensively characterized and documented for more traditional materials such as clay tiles.

In a second phase, starting from the thermal data collected on an experimental real-scale building, the dynamic energy analysis tool EnergyPlus (https://energyplus.net/) was calibrated and used to perform simulations by varying the optical properties of a continuous covering in an unventilated roof and assess the impact on the roof temperatures, in comparison with a ventilated clay tiles roof.

## Roof materials optical properties and impact on UHI and buildings' thermal performance

The UHI effect has been known for decades and particularly investigated in recent years in relation to the global warming intensification. It implies a rise in temperatures in urban aggregates compared to surrounding areas, mainly due to the high concentration of surfaces characterized by low solar reflectance (buildings, pavements and roads), the lack of vegetation or water surfaces capable of cooling the air by evaporation or evapotranspiration and the limited action of air currents because of the morphology of buildings and roads. It is rather current in the literature of the last decades the usefulness of ‘cool’ materials to limit the UHI. Recent extensive reviews on this topic have been carried out by Santamouris (2014), Akbari and Kolokotsa (2016) and Pisello (2017).

However, the benefits that would result from the use of reflective materials for summer comfort inside buildings are still matter of scientific debate if the annual energy balance is considered. The advantages of the reduction of summer heat gains could indeed not balance the reduced free solar gains during the winter phase. This issue needs to be further explored, also considering the constructive features of the building – in particular the envelope thermal resistance – and the climatic context (Ascione et al., 2016; Di Giuseppe and D’Orazio, 2014; Gagliano et al., 2015; Piselli et al., 2017; Pisello et al., 2015).

On this topic, Hernández-Pérez et al. (2014) made a comprehensive review. They have found considerable variability on the results obtained from experimental and analytical works aimed to investigate the impact of reflective materials on building energy consumption and summer indoor thermal comfort. Furthermore, most of the existing studies are focussed on the heat transfer of solid homogeneous roofs with a low slope. Authors underlined that more work is needed to analyse the influence of reflective materials in more complex configurations such as ventilated roofs or tiled pitched roofs.

An example in this direction is the work performed by Levinson et al. (2007), which tested six cool coloured tiles with a solar reflectance difference between 0.15 and 0.41 with respect to the same traditional tiles in 1:10 scale model houses in California. The author recorded a surface temperature reduction by 5–14 K and a heat flux reduction of 13%–21%. Nevertheless, roofs were only slightly insulated (R-value = 1.9 $m^2$ K/W).

Pisello and Cotana (2014) investigated the possibility of applying a prototyped cool clay tile on a traditional residential building in central Italy. They presented the results of a 2-year continuous monitoring campaign: an entire year in the original configuration and for another entire year in the ‘cool’ configuration, with the final aim of quantifying both the summer benefits and the winter penalties of such a solution in residential buildings in temperate climate conditions. The daily average operative temperature registered a decreasing of approximately 2 K in June–August and, in winter, the average daily values decrease was consistently less than 0.5 K. Nevertheless, the roof measured thermal transmittance was 1.14 W/$m^2$ K.

Concerning numerical studies, the papers reviewed by Hernández-Pérez et al. (2014) reported that reflective roofs provided variable savings on an annual basis (considering the heating penalty), generally between 1% and 20%, depending on the type of climate and the insulation of the roof.

Pisello et al. (2016) carried out a 2D finite element analysis to investigate the indoor air temperature and air velocity field inside an attic room located in central Italy, obtained considering: (i) a roof with traditional brown-coloured brick tiles and (ii) the same roof with innovative cool clay tiles. The main results show up to 2.79 K and 1.54 K air temperature difference between the cool and traditional roof configurations. Nevertheless, the result is obtained with a roof thermal transmittance of 1.14 $W/m^2 K$, which is quite high considering the actual requirement for this geographic location. In addition, the 'hot' roof scenario is characterized by brown-coloured brick tiles, which represent a particular colour for clay. In highly insulated building components, as those requested by recent targets towards nearly zero-energy buildings, savings due to cool materials risk then to be almost zero. Energy simulations on these building typologies can be used to decide whether reflective materials are recommended in specific climatic and construction contexts, also considering a life-cycle approach that takes into account their inherent durability.

Despite the fact that the scientific debate on the effectiveness of cool materials is still open in relation to the issues highlighted, in some countries, the latest regulatory developments on building energy efficiency or voluntary environmental certification systems are increasingly encouraging the use of reflective coating materials not only to face the UHI phenomenon but also to reduce the summer energy consumptions.

Worldwide, several environmental building-rating systems require specific targets for roofing optical properties. For instance, Leadership in Energy and Environmental Design (LEED, https://new.usgbc.org/leed) of United States, Green Building Council, one of the most widely used green building-rating system in the world, in the certification for building design and construction and for building operations and maintenance, includes a specific credit on the heat inland reduction. It requires minimum Solar Reflectance Index (SRI) values, by roof slope: an initial SRI of 82 (or a 3-year-aged SRI of 64) for low-sloped roofs and an initial SRI of 39 (or a 3-year-aged SRI of 32) for steep-sloped roofs. SRI thresholds for building materials are included in other building-rating systems such as Estidama, the certification developed by the Abu Dhabi Urban Planning Council (https://www.upc.gov.ae/estidama), BEAMPlus, Hong Kong's assessment system of building sustainability performance (https://www.hkgbc.org.hk/eng/BEAMPlus.aspx) and ITACA, the Italian buildings sustainability assessment protocol (http://www.itaca.org/valutazione_sostenibilita.asp).

Furthermore, in Italy, heat island effect and/or buildings summer comfort issues are addressed through some mandatory legislative instruments and volunteer certification protocols. Among the compulsory measures, there are the Ministerial Decrees 26 June 2015 and 24 December 2015 (Gazzetta Ufficiale, 2015a, 2015b), that suggest threshold values for the radiative properties of building components. The first one, enacted in transposition on the European Directive 2010/31 (European Commission, 2010) on buildings energy efficiency, requires to carry out a cost-benefit analysis on the use of finishing materials with high solar reflectance (0.65 for flat roofs – 0.30 for pitched roofs) or passive cooling technologies (as ventilated roof or green roof) 'in order to limit the energy consumption of air conditioning in summer and reduce interior temperatures'. In section '2.2.3 Mitigation of the impact on microclimate and of air pollution' of the Ministerial Decree DM 24 December 2015 (Gazzetta Ufficiale, 2015a), defining minimum environmental criteria for public administrations, it is suggested that the use of finishing materials with a high SRI in new buildings and renovation projects for at least 75% of the envelope surface. In particular, an SRI greater than 29 shall be used for roofs with a slope >15%, an SRI greater than 75 for those with a slope ≤15% and an SRI of at least 29 for other surfaces (i.e. pavements and parking lots).

These legislative measures are actually pushing the construction products market towards specific directions.

Roof-covering materials are actually available with an extremely wide variety of colours and optical properties. Some materials are used with their ‘natural’ colourings and properties, such as some clay or metals, or may be subjected to special treatments to make them ‘cool’ on the visible and the infrared spectrum (0.4–2.5 $\mu$m). As an ordinary white or clear material reflects most of the solar energy in the visible spectrum leading to glare problems in urban contexts, in recent years, cool coloured materials and coatings have been developed. Cool roof products and technologies have been generally produced for flat-roof applications, but specific solutions are recently being developed for tilted roof surfaces. They usually consist of membranes, coatings, shingles, paintings, metal shakes or shingles and tiles (Pisello, 2017).

Table 1 provides the typical ranges of roof materials optical properties (solar reflectivity $\rho$, thermal emissivity $\varepsilon$ and SRI) obtained from the analysis of 327 materials samples reported in 20 papers.

It can be seen how some materials, in their natural colouration, are characterized by a wide range of solar reflectivity values, while the realization of a white or ‘cool’ surface treatment makes it possible to narrow to reflectivity values greater than 0.55. As for the waterproofing membranes, the reflection obtained with a cool or smooth white surface treatment is over 0.76.

Clay, ceramic or concrete tiles show a solar reflectivity ranging from 0.1 to 0.77 depending on the surface treatment, while their emissivity is restricted between 0.8 and 0.9.

Detailed databases with information on the optical properties of commercial roof products are provided by the Cool Roof Rating Council (http://coolroofs.org/) and the European Cool Roofs Council (http://coolroofcouncil.eu/). Nevertheless, still few data are available on traditional or treated clay tiles. This justifies the measurement carried out and described in the following section.

## Methodology

### Characterization of clay tiles optical properties

In the first part of this study, 66 flat samples, sized about 6 cm × 6 cm derived from 33 representative clay roof tiles (of which 10 typologies with engobe and 2 with a reflective coating) were characterized in terms of solar reflectivity, thermal emissivity and CIE L*a*b* (CIELAB) colour space. The SRI of the samples has been then calculated. The following section describes the laboratory measurements procedure, the reference standards and the instruments used.

**Table 1.** Typical ranges of roof materials optical properties (solar reflectivity ρ, thermal emissivity ε and Solar Reflectance Index (SRI)) obtained from the analysis of 327 materials samples reported in 20 papers.

| Building roofing material | | ρ | ε | SRI | References |
|---|---|---|---|---|---|
| Clay, ceramic or concrete tiles | Natural or coloured | 0.1–0.77 | 0.8–0.98 | 19–85 | Alchapar et al. (2014), Kolokotroni et al. (2013), Pisello et al. (2014), Ferrari et al. (2014), Di Giuseppe et al. (2012), Kultur and Turkeri (2012), Akbari et al. (2008), Radhi et al. (2014), Ferrari et al. (2013a, 2013b), Libbra et al. (2011a, 2011b), Prado and Ferreira (2005) |
| | Treated with white or cool engobes | 0.55–0.9 | 0.88–0.9 | 86–88 | Kolokotroni et al. (2013), Pisello et al. (2014), Kultur and Turkeri (2012), Akbari et al. (2008), Radhi et al. (2014), Ferrari et al. (2013a, 2013b, 2013c), Libbra et al. (2011b), Prado and Ferreira (2005) |
| Waterproofing membranes | Natural or coloured | 0.04–0.82 | 0.78–0.91 | 5.0–44 | Kultur and Turkeri (2012), Radhi et al. (2014), Libbra et al. (2011a), Revel et al. (2014), Zhang et al. (2013) |
| | With cool or white surface | 0.76–0.9 | 0.9 | – | Zhang et al. (2013), Ferrari et al. (2013)b |
| Stainless steel | Natural or coloured | 0.2–0.73 | 0.25–0.9 | – | Prado and Ferreira (2005) |
| | With cool or white surface | 0.61 | 0.9 | – | Prado and Ferreira (2005) |
| Stone or similar | | 0.04–0.69 | 0.89–0.92 | – | Radhi et al. (2014), Levinson et al. (2014) |
| Green roof | | 0.08–0.23 | – | – | Zhao et al. (2014) |
| Other Metals | Natural or coloured | 0.07–0.8 | 0.05–0.9 | 39–87 | Di Giuseppe et al. (2012), Kultur and Turkeri (2012), Radhi et al. (2014), Prado and Ferreira (2005), Mastrapostoli et al. (2014), Pacific and Electric Company (2000) |
| | With cool or white surface | 0.59–0.89 | 0.85–0.89 | 113 | Di Giuseppe et al. (2012), Libbra et al. (2011a), Ferrari et al. (2013b), Mastrapostoli et al. (2014), Pacific Gas and Electric Company (2000) |
| Others | Natural or coloured | 0.03–0.81 | 0.83–0.94 | – | Libbra et al. (2011a, 2011b), Karlessi et al. (2009), Synnefa et al. (2007) |
| | With cool or white surface | 0.69–0.89 | 0.86–0.88 | – | Libbra et al. (2011b), Zhang et al. (2013) |

Reflectivity measurements were carried out with two instruments: a Konica Minolta spectrophotometer (Ultraviolet and Visible, UV–Vis region) from 360 to 800 nm and a PE-Spectrum One NTS FT-NIR spectrophotometer (near infrared region, NIR) from 800 to 2500 nm, according to technical standard ASTM E903-12 (2012). Combining spectral informations obtained from both instruments, measurements were carried out in a total wavelength range of 360–2500 nm, covering the whole solar spectrum.

The latter spectrophotometer was equipped with a 150 mm Spectralon-coated integrating sphere (NIRA) produced by Labsphere, allowing the scanning of large areas of the samples. The spectral resolution was 16 $cm^{-1}$ with 64 scans in each of the reflectance measurements. Samples were measured in duplicate, in order to validate the vibrational data. For NIR analysis, spectrum acquisition was performed by inserting the sample to be analysed in the supplemental integrated sphere previously described, considering the range between 800–2500 nm. Before each acquisition, background scan was acquired within the empty sphere, in the same range.

The broad band values in the visible, near infrared and solar spectra were then processed according to standard ASTM E903-12, according to the weighted ordinate method. The solar reflectance has been obtained by integrating the spectral reflectance over the standard spectral irradiance distribution included in standard ASTM G173-03 (2012). At this aim, the hemispherical reference solar spectral irradiance on 37°-tilted surface has been used because the aim of the study in linked to sloped roofs.

Measurements for the thermal emissivity characterization have been carried out according to standard ASTM E1933-14 (2014) and according to Usamentiaga et al. (2014).

Once the solar reflectance and thermal emissivity values were measure, the SRI was calculated using the procedure ASTM E1980-11 (2011), second approach, considering a convective coefficient $h_c = 12\,W/m^2K$. According to the standard, SRI is estimated with an average error of 0.9 and a maximum error of 2.

Finally, through a Konica Minolta spectrophotometer (UV–Vis region), the three coordinates of CIELAB colour space for each sample have been detected in 5 points for each sample and then interpreted through SpectraMagic NX software. Their average values have then been calculated. $L^*$ coordinate represents the lightness of the colour ($L^* = 0$ yields black and $L^* = 100$ indicates diffuse white); $a^*$ represents its position between red/magenta and green (negative values indicate green, while positive values indicate magenta) and $b^*$ represents its position between yellow and blue (negative values indicate blue, and positive values indicate yellow). Preliminarily to measurements, calibration operations were performed with the two references (white/black).

## *Building case study and energy simulations*

During this research phase, the dynamic energy analysis tool EnergyPlus was calibrated through the thermal and climatic data collected on a real-scale experimental

**Figure 1.** View of the experimental building near Ancona (Italy).

building and used to assess the impact on the covering and indoor temperatures given by the roof-covering optical properties and the presence of a ventilated air gap.

The experimental building is located near Ancona, in the central Italian coast (2064 Degree Days, 43°37′N 13°22′E). It has a surface area of 80 $m^2$ in one level and a sloped roof (Figure 1).

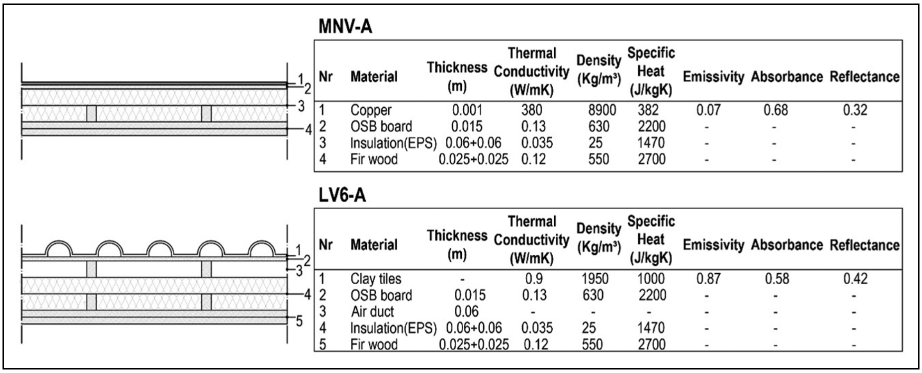
The building has a unique internal room and no windows, to provide the same interior conditions to all the roofs and avoid solar heat gains. The side walls of the building are built with multi-layered insulating panels made of polyurethane resin (PUR) and an air cavity of 30 cm, in order to reduce the impact of solar radiation on the walls. The floor is insulated with 20 cm of extruded polystyrene panels in order to obtain almost adiabatic conditions towards the ground.

The main roof gable (10 m long, 6.4 m wide, 17° tilt) is exposed to the south; the other one (10 m long, 3.4 m wide, 30° tilt) is exposed to the north. Each pitch is divided into six roof modules of the same width (1.50 m each). The common element among all the roof coverings is the insulation layer, which is made of two crossed layers of expanded polystyrene (EPS) panels with a total thickness of 12 cm ($U = 0.25\,W/m^2K$). The six roof modules are then differentiated by the height of the ventilation duct (0, 3 and 6 cm), the kind of slab (wood or concrete) and the kind of covering (clay tiles or copper). Further details on the experimental building are reported in D'Orazio et al. (2010, 2012).

This work focusses on the thermal performance of two of the six roof:

- An unventilated roof with a continuous copper covering (called MNV-A);
- A ventilated roof with a clay tiles covering (called LV6-A).

In this way, it was possible to compare the performance of a ventilated clay tiles roof with that of an unventilated roof characterized by a continuous covering,



**MNV-A**

| Nr | Material | Thickness (m) | Thermal Conductivity (W/mK) | Density (Kg/m³) | Specific Heat (J/kgK) | Emissivity | Absorbance | Reflectance |
|---|---|---|---|---|---|---|---|---|
| 1 | Copper | 0.001 | 380 | 8900 | 382 | 0.07 | 0.68 | 0.32 |
| 2 | OSB board | 0.015 | 0.13 | 630 | 2200 | - | - | - |
| 3 | Insulation(EPS) | 0.06+0.06 | 0.035 | 25 | 1470 | - | - | - |
| 4 | Fir wood | 0.025+0.025 | 0.12 | 550 | 2700 | - | - | - |

**LV6-A**

| Nr | Material | Thickness (m) | Thermal Conductivity (W/mK) | Density (Kg/m³) | Specific Heat (J/kgK) | Emissivity | Absorbance | Reflectance |
|---|---|---|---|---|---|---|---|---|
| 1 | Clay tiles | - | 0.9 | 1950 | 1000 | 0.87 | 0.58 | 0.42 |
| 2 | OSB board | 0.015 | 0.13 | 630 | 2200 | - | - | - |
| 3 | Air duct | 0.06 | - | - | - | - | - | - |
| 4 | Insulation(EPS) | 0.06+0.06 | 0.035 | 25 | 1470 | - | - | - |
| 5 | Fir wood | 0.025+0.025 | 0.12 | 550 | 2700 | - | - | - |

**Figure 2.** Cross-section of the two roofs analysed and main thermal and optical properties.

whose optical properties could be parametrized in a simulation model, in order to compare the thermal performance of the two roofs. Figure 2 shows the cross-section of the roof typologies under investigation and their main thermal and optical features.

External climatic conditions (global solar radiation, external temperature, external relative humidity, wind speed and direction) and building indoor air temperature and relative humidity have been detected almost continuously every 10 min since January 2008. Similarly, thermal measurements on each roof are provided by:

- PT-100 thermal resistances for all surface temperatures (internal slabs, insulation facing the air cavity and both sides of clay tile coverings);
- Air temperature probes in the ventilation ducts;
- Heat flow metres for heat flux through the roof slabs.

The accuracy of PT-100 and air temperature probes (Lsi Lastem DMA 572.1) is ±0.15°C. The accuracy of the heat flow metres (Hukseflux HFP01) is ±5%. The results of a preliminary calibration of the probes were taken into account for the interpretation of the experimental results.

The building was preliminary modelled through Design Builder (https://www.designbuilder.co.uk/), a graphical user interface for EnergyPlus software. The roof was considered as consisting of the single typology MNV-A, that is, the unventilated copper roof. Air infiltration was set at 0.05 $m^3/s$ and internal gains for electric equipment at 2 $W/m^2$. The model was calibrated considering the climatic and thermal conditions detected in August 2009. Simulations were then carried out, by varying the roof-covering solar reflectivity and looking for the reflectivity level able to obtain a thermal performance of the roof similar to that obtained by the clay tile ventilated roof (LV6-A). Five increasing reflectivity levels of the roof covering were

**Table 2.** Reflectivity levels of the roof-covering set in the energy simulations.

| Simulation number. | ρ | Comment |
|---|---|---|
| 1 | 0.30 | Reference value according to Italian Ministerial Decree 26 June 2015 (Gazzetta Ufficiale, 2015b) |
| 2 | 0.42 | Solar reflectivity of the roof LV6-A |
| 3 | 0.50 | – |
| 4 | 0.65 | Reference value according to Italian Ministerial Decree 26 June 2015 (Gazzetta Ufficiale, 2015b) |
| 5 | 0.70 | – |

considered for the energy simulations, starting from $\rho = 0.30$ (reference value according to Italian Ministerial Decree 26 June 2015; Gazzetta Ufficiale, 2015b), including $\rho = 0.42$ (the value of the clay tiles covering), $\rho = 0.65$ (reference value according to Italian Ministerial Decree 26 June 2015; Gazzetta Ufficiale, 2015b) and two further levels. The simulation settings are summarized in Table 2.

## Results

### *Reflectivity, emissivity and SRI of clay tiles*

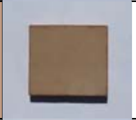
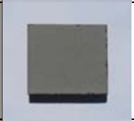
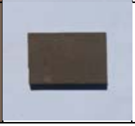
Table 3 reports the results of the clay tiles samples characterization in terms of: solar reflectance (ρ), thermal emissivity (ε), SRI and CIE L*a*b* coordinates. An image of each sample and the corresponding RGB colour is also provided.

It can be noted that solar reflectance for these materials ranges from 0.125 to 0.63. There are a significant number of samples with reflectivity values lower than 0.35. This mainly depends on the presence of dark engobes on the surfaces. Thermal emissivity is between 0.886 and 0.907, demonstrating no significant numerical variations. Resulting SRI values range from 10 to 76.

By way of example, the spectral reflectance curves of three selected representative samples are plotted in Figure 3. They represent a light colour, a dark colour and a reflective clay tile, respectively, samples number 8, 23 and 16. The solar spectra of these samples highlight, as expected, that the reflective sample (16) has the higher reflectance values in the whole wavelength, compared to the light (8) and dark (23) ones. These properties are indeed generally sensitive to the colour of the samples.

Finally, Figure 4 represents the values of solar reflectance and SRI of all the samples sorted in an increasing order. As a reference, the figure also indicates the cited values of SRI reported in LEED rating system and of solar reflectance reported in the Italian Ministerial Decree 26 June 2015. From the graph, it can be noted that all the analysed materials have total reflectivity values and SRI lower than the reference values for flat roofs (respectively, 0.65 and 82). As for the

**Table 3.** Optical properties of the 33 clay samples analysed: CIE L*a*b* coordinates, solar reflectance (ρ), thermal emissivity (ε) and Solar Reflectance Index (SRI).

| Sample number | CIE L*a*b* coordinates | | | Colour | Image of the sample | Solar reflectivity | Thermal emissivity | Solar Reflectance Index | Sample number | CIE L*a*b* coordinates | | | Colour | Image of the sample | Solar reflectivity | Thermal emissivity | Solar Reflectance Index | Sample number | CIE L*a*b* coordinates | | | Colour | Image of the sample | Solar reflectivity | Thermal emissivity | Solar Reflectance Index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L* | a* | b* | | | ρ | ε | S.R.I. | | L* | a* | b* | | | ρ | ε | S.R.I. | | L* | a* | b* | | | ρ | ε | S.R.I. |
| 1 | 56.778 | 20.054 | 28.194 | ■ |  | 0.470 ± 0.009 | 0.901 | 55 | 12 | 48.766 | 9.412 | 14.64 | ■ |  | 0.352 ± 0.013 | 0.897 | 39 | 23 | 32.79 | 3.692 | 5.506 | ■ |  | 0.125 ± 0.036 | 0.896 | 10 |
| 2 | 48.482 | 19.974 | 23.792 | ■ |  | 0.383 ± 0.012 | 0.893 | 43 | 13 | 66.304 | 7.202 | 21.402 | ■ |  | 0.518 ± 0.009 | 0.891 | 61 | 24 | 67.106 | 10.952 | 18.304 | ■ |  | 0.531 ± 0.008 | 0.887 | 62 |
| 3 | 48.698 | 20.876 | 20.91 | ■ |  | 0.406 ± 0.011 | 0.893 | 46 | 14 | 52.48 | 18.482 | 20.642 | ■ |  | 0.439 ± 0.010 | 0.896 | 50 | 25 | 59.266 | 1.29 | 2.582 | ■ |  | 0.395 ± 0.011 | 0.896 | 44 |
| 4 | 49.79 | 21.354 | 23.994 | ■ |  | 0.399 ± 0.011 | 0.896 | 45 | 15 | 57.568 | 15.626 | 20.77 | ■ |  | 0.465 ± 0.010 | 0.886 | 53 | 26 | 50.364 | 23.798 | 27.084 | ■ |  | 0.425 ± 0.010 | 0.907 | 49 |
| 5 | 42.94 | 13.458 | 15.264 | ■ |  | 0.342 ± 0.013 | 0.891 | 37 | 16 | 75.68 | 6.886 | 22.532 | ■ |  | 0.633 ± 0.007 | 0.891 | 76 | 27 | 48.262 | 24.486 | 27.476 | ■ |  | 0.378 ± 0.012 | 0.900 | 42 |
| 6 | 43.912 | 5.96 | 10.596 | ■ |  | 0.286 ± 0.016 | 0.889 | 30 | 17 | 55.646 | 8.33 | 24.886 | ■ |  | 0.352 ± 0.013 | 0.895 | 39 | 28 | 50.478 | 16.904 | 20.746 | ■ |  | 0.407 ± 0.011 | 0.903 | 46 |

(continued)

**Table 3.** (continued)

| Sample number | CIE L*a*b* coordinates | | | Colour | Image of the sample | Solar reflectivity | Thermal emissivity | Solar Reflectance Index |
|---|---|---|---|---|---|---|---|---|
| | L* | a* | b* | | | ρ | ε | S.R.I. |
| 7 | 56.326 | 10.396 | 16.708 | ■ |  | 0.352 ± 0.013 | 0.893 | 50 |
| 8 | 68.504 | 9.294 | 27.36 | ■ |  | 0.551 ± 0.008 | 0.892 | 65 |
| 9 | 57.078 | 6.338 | 22.076 | ■ |  | 0.392 ± 0.011 | 0.901 | 44 |
| 10 | 52.028 | 24.678 | 28.304 | ■ |  | 0.450 ± 0.010 | 0.891 | 51 |
| 11 | 57.672 | 18.174 | 20.454 | ■ |  | 0.476 ± 0.009 | 0.894 | 55 |
| 18 | 59.376 | 11.278 | 16.22 | ■ |  | 0.125 ± 0.036 | 0.893 | 54 |
| 19 | 53.582 | 22.46 | 28.938 | ■ |  | 0.451 ± 0.010 | 0.889 | 52 |
| 20 | 41.114 | 10.928 | 15.232 | ■ |  | 0.321 ± 0.014 | 0.888 | 34 |
| 21 | 52.616 | 0.394 | -0.556 | ■ |  | 0.316 ± 0.014 | 0.896 | 34 |
| 22 | 46.658 | 25.178 | 26.748 | ■ |  | 0.312 ± 0.014 | 0.894 | 33 |
| 29 | 39.22 | 8.698 | 9.482 | ■ |  | 0.293 ± 0.015 | 0.904 | 31 |
| 30 | 74.508 | 7.818 | 24.282 | ■ |  | 0.611 ± 0.007 | 0.900 | 73 |
| 31 | 55.582 | 17.274 | 21.514 | ■ |  | 0.459 ± 0.010 | 0.900 | 53 |
| 32 | 58.744 | 2.592 | 12.864 | ■ |  | 0.430 ± 0.010 | 0.900 | 49 |
| 33 | 48.878 | 1.524 | 2.4 | ■ |  | 0.345 ± 0.013 | 0.900 | 38 |

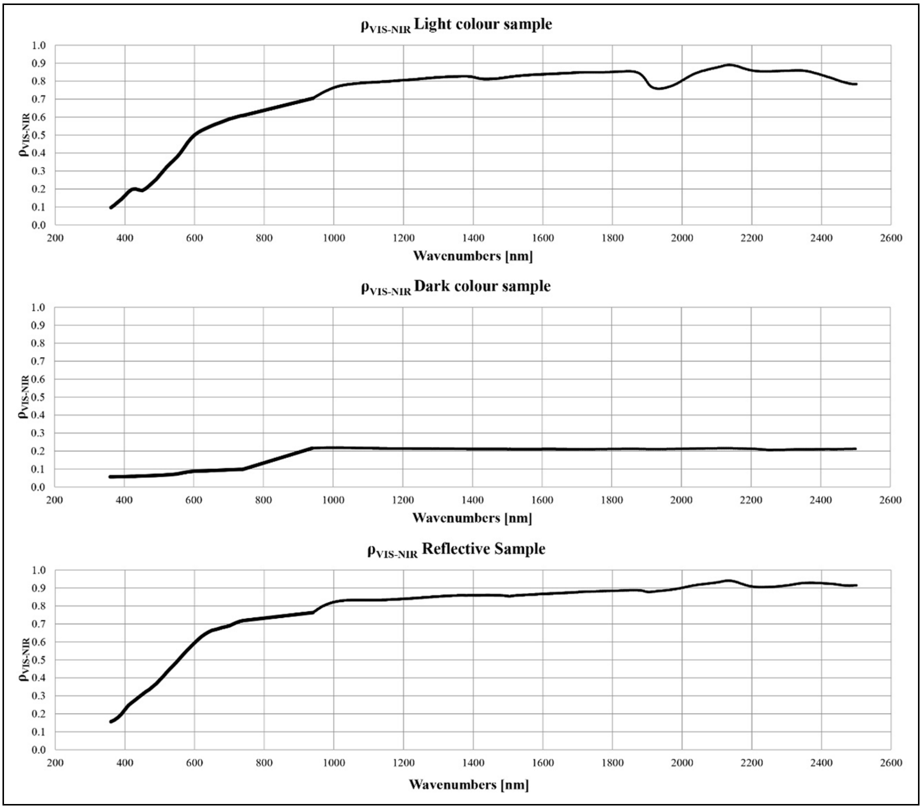


**Figure 3.** Spectral reflectance curves of the samples number 8, 23 and 16, representative of a light colour, a dark colour and a reflective clay tile.

reference values for sloped roofs (0.3 and 39), almost all clay samples have higher solar reflectivity values, except for those characterized by very dark engobes.

## *Impact of roofing optical properties and batten space ventilation on roof thermal performance*

First, results of the experimental building thermal monitoring during a typical summer week, in August 2009, are reported. Graphs in Figures 5 and 6 represent the trends of the external air temperature, the global solar radiation and the roof temperatures. The hours of intense solar radiation during the day are about 6–8, with a maximum intensity around 800–900 W/m$^2$. The external air temperature reaches daily peaks between 27° and 34°C. Even during night-time, it occasionally decreases under 21°C.

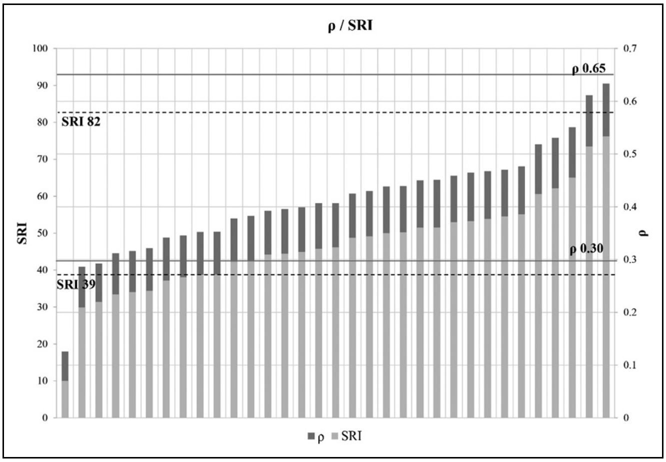


**Figure 4.** Summary of the solar reflectance and the SRI of all the samples sorted in an increasing order. The reference values of 0.30 and 0.65 for the reflectivity, and of 39 and 82 for the SRI are highlighted.

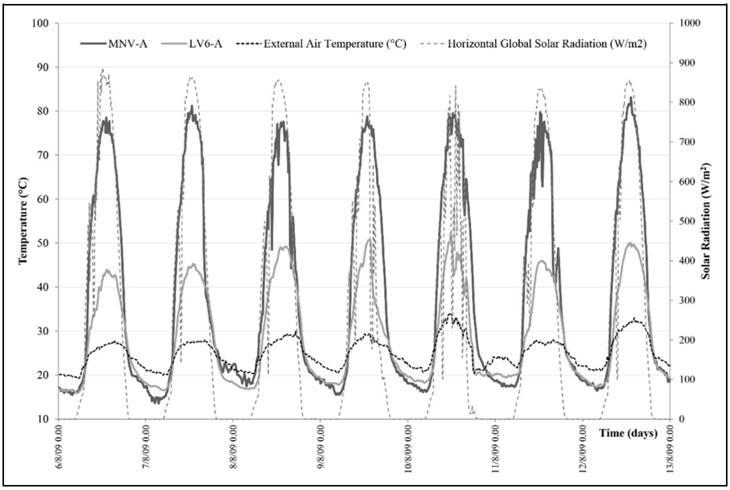


**Figure 5.** External roof-covering surface temperatures during a typical summer week, August 2009 (°C).

In particular, Figure 5 represents the roof-covering surface temperatures for roofs MNV-A and LV6-A. It can be noted that a great difference in the temperature peakes reached daily by the unventilated copper roof (around 80°C) and those of the ventilated clay tiles roof (about 45°C–50°C). This gap is not only due to the

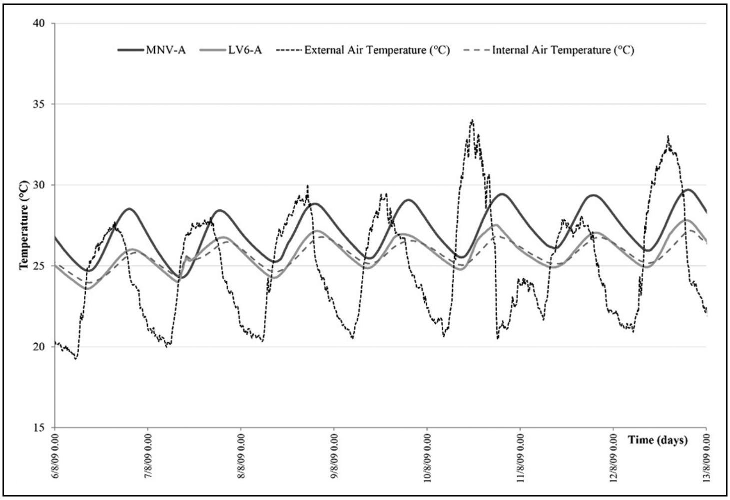


**Figure 6.** Internal surface temperatures on the roofs slabs during a typical summer week, August 2009 (°C).

different optical properties of the covering materials but also to the beneficial cooling contribution of the roof ventilation through the air channel and the tiles joints.

Figure 6 reports the internal surface temperatures on the slabs. The difference between the two roofs is steadily around 2°C, highlighting how the covering features (in terms of both optical properties and ventilation) are able to affect indoor conditions.

Finally, the following graphs in Figures 7 and 8 show the results of the energy simulations performed. They report the temperature trends on the covering and the roofs slabs during one week, obtained as a result of the parametrization of the five levels of unventilated roof-covering reflectivity, also compared with the real temperature detected in the ventilated clay tiles roof. These graphs can be then read in direct comparison to those in Figures 5 and 6.

Figure 7 represents the roof-covering temperature trends. As expected, the covering temperatures increase with the decreasing reflectivity values. It can be noted that the roof model with $\rho = 0.42$, that is, the same reflectivity as the real clay tiles roof, reaches higher temperatures than this one. The difference in the maximum temperature levels are over 25°C and are then ascribable to the effects of the roof ventilation. Furthermore, the covering temperature reached by the ventilated clay tiles roof is even lower to that obtained simulating the unventilated roofs with solar reflectivity of 0.7.

Figure 8 represents the internal surface temperatures on the slabs. The noteworthy observations are similar to those expressed for Figure 7. Also concerning the slab surface temperatures, the roof model with $\rho = 0.42$, that is, the same reflectivity as the real clay tiles roof, reaches higher temperatures than this one, for about

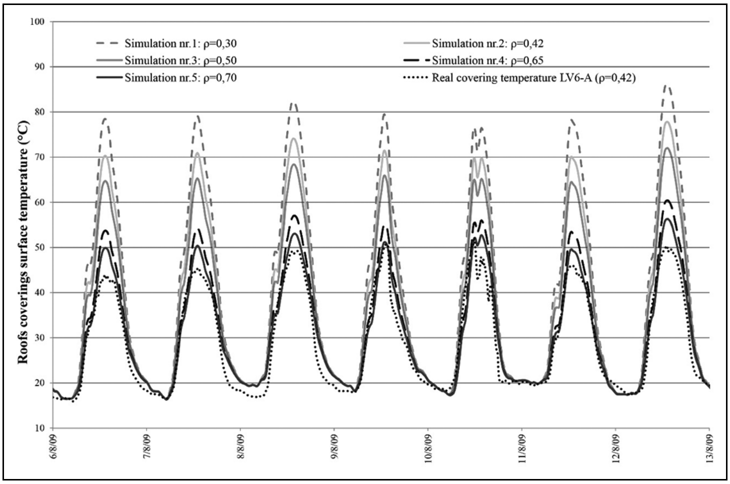


**Figure 7.** Roofs coverings surface temperatures obtained as a result of the parametrization of the unventilated roof-covering reflectivity, also compared with the real covering temperature detected in the ventilated clay tiles roof.

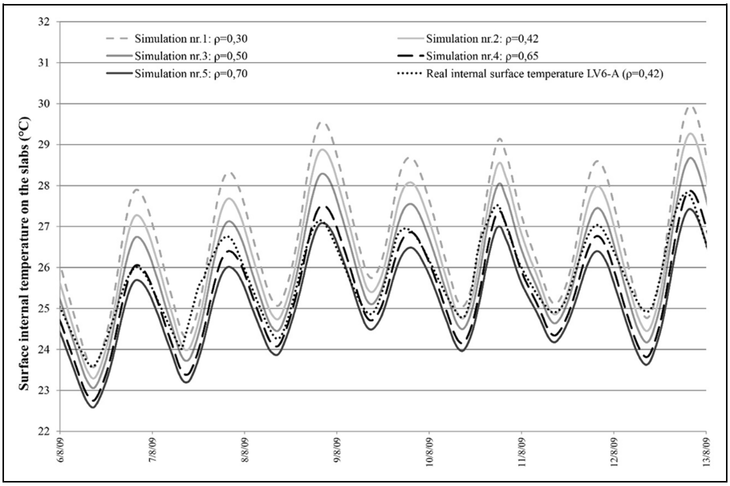


**Figure 8.** Internal surface temperatures on the slabs obtained as a result of the parametrization of the unventilated roof-covering reflectivity, also compared with the real temperature detected in the ventilated clay tiles roof.

1–2°C. The internal surface temperature reached by the ventilated clay tiles roof is comparable with those obtained simulating the unventilated roofs with solar reflectivity between 0.65–0.7.

## Conclusion

In literature, the benefit and effectiveness of clay tiles roofs ventilation for roof passive cooling are widely recognized. However recently, many international regulatory developments or buildings sustainability certification protocols are increasingly neglecting such traditional technology and instead encouraging the use of 'cool' materials with the aim of reducing the UHI and the buildings' cooling consumptions. These measures, mandatory or voluntary, de facto push the construction products market towards specific directions, risking penalizing traditional building components such as clay tiles.

This work addressed this issue in two ways. First, the main optical properties (solar reflectance and thermal emissivity) of over 30 different clay products have been experimentally characterized in order to get a clear and extensive picture of such properties for the materials spread in the market and extend the actual available databases on the optical properties of commercial roof products. Then, the thermal performance of a full-scale ventilated clay tiles roof under real summer climatic conditions in Italy was investigated and compared to that of an unventilated continuous copper covering roof. Finally, the monitoring data collected on the roofs were used to calibrate an energy simulation model and to perform simulations by varying the optical properties of the continuous roof covering, thus assessing their impact on the roof temperatures, also in comparison to the real temperatures detected on the clay tiles roof.

The results of the experimental characterization highlighted a great variety on the values of clay tiles solar reflectivity (0.12–0.63), given by the several possible surface treatments (engobes) available in the market for aesthetic reasons and possible applications. The emissivity is high and its variability range limited (between 0.88 and 0.91). Almost all the analysed samples show solar reflectivity values higher than 0.30 (the reference value for sloped roofs in the Italian legislation) and an SRI higher than 39 (the reference in LEED certification), except for those characterized by very dark surfaces. Also considering the high durability of these materials, the optical properties of clay tiles can be then considered good and balanced.

The summer-monitoring activity on the two full-scale roofs displayed a great difference in the temperature peaks reached daily by the continuous copper covering (around 80°C) and those of the clay tiles (about 45°C–50°C), not only due to the different radiative behaviour of the materials but also due to the beneficial cooling contribution of the roof ventilation through the air channel and the tiles joints. This is reflected to a 2°C temperatures difference in the internal surface of the slabs, with consequences on indoor comfort conditions.

The good thermal performance of the ventilated roof is further demonstrated through the simulation activities. From the direct comparison of the real ventilated clay tiles roof and the simulated roof with the same solar reflectivity but unventilated continuous covering arises a difference in covering temperatures over 25°C and in slab temperatures until 2°C that is due to the cooling effects of the roof ventilation.

The results obtained then underline that the use of the above sheathing ventilation obtained through clay tiles is an effective strategy to reduce roof temperatures, even if covering materials are not qualified as 'cool', thus impacting both UHI and indoor comfort.

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