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# On a cool coating for roof clay tiles: development of the prototype and thermal-energy assessment

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**Abstract**

Clay tiles are the most common roof covering in Italian buildings, in particular in traditional residential buildings. Given the important role of the roof characteristics for building energy efficiency and indoor thermal comfort conditions, innovative solutions for improving the thermal-energy performance of such diffused roof element has become a key research issue. In this view, cool roof applications represent an effective solution to this aim. The present work deals with the analysis of innovative coatings for traditional clay tiles, aimed at increasing their "cooling" potential. Several pigments with the sodium silicate as binder are tested in terms of reflectance and emittance, which mainly determine the cool roof performance. Additionally, the year-round performance of the proposed tile is evaluated when applied to a single family residential building located in central Italy. The developed cool roof solution is characterized by the same visual appearance of traditional "natural brick" color tiles, while the solar reflectance is higher than natural terracotta tile by 13%. Therefore its thermal performance is optimized in order to reduce the roof overheating and the consequent energy requirement for cooling. Results of dynamic simulation of the case study building show how the proposed tile is able to decrease the number of hours when the indoor operative temperature of the attic is higher than 26°C by 18%, while the same effect in lowering the indoor temperature below 20°C in winter is less than 1%. Therefore, the proposed solution could be considered as an interesting strategy for new buildings or for traditional roof retrofitting, without producing any significant architectural impact, even in traditional or historic buildings, where more invasive solutions are too difficult to be implemented.


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*Keywords:* cool roofs; roof solar reflectance; clay tile; indoor temperature; energy efficiency in buildings; dynamic simulation

## 1. Introduction

The huge households energy requirement for cooling in Italy [1] guided toward the investigation of innovative passive solution for building energy efficiency in summer conditions. One of the most promising solutions consists of cool roofs, which are those roofs which present high solar reflectance and high thermal emittance characteristics [2-3]. The benefits of these roofs' typologies have been widely investigated all over the


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world during last decades [4]. In fact, several numerical and experimental researches showed important benefits in terms of energy saving for cooling in case of different buildings' uses, e.g. residential buildings [5], office buildings [6]. The same technology also presents important benefits at larger inter-building scale [7-8], because it is able to contribute to the urban heat island and global warming mitigation [9-10]. To this aim, the principal application of cool roof solutions still concern high reflectance coating or membranes, typically applied on flat roofs, for the easier and cheaper installation procedure [11].

In this perspective, the increased building energy demand for cooling in Italy would require the widespread implementation of such a technology. Despite that, the regulation about the preservation of the architectural and environmental heritage, represents the major restriction to the spread of this technology. In order to minimize the visual impact of these applications, that are typically light in color [12, 13], several researches aimed at elaborating cool coating with high reflectance capability in the near infrared region of the solar spectrum, and visible reflectance close or equivalent to the one of existing "non cool" applications [14].

In Italy, in particular, this research issue also concerned the development of traditional clay tiles with relatively good "cool" potential, and acceptable visual appearance, to be applied in traditional or hedged-in buildings [15-17]. Given the large majority of buildings with clay tiles, the development of cool roof techniques aimed at sprawling application to existing buildings represents a strategic solution, in particular for cooling energy saving and urban heat island issue in historical city centers.

In this view, the present paper deals with the development of new coatings for clay tiles, which optical-energy performance is measured in terms of solar reflectance and thermal emittance, which mainly determine the "cool" capability of these materials. A balanced choice of the tile coating is carried out, by taking into account simultaneously the reflectance characteristics and the visual appearance, which should be as less impacting as possible, compared to natural red tiles. Additionally, year-round assessment of the thermal effect of the chosen most performing tile is evaluated, when applied to a residential building in central Italy. Therefore, the dynamic simulation model of the case study building is elaborated and both summer benefits and winter penalties are quantified in terms of indoor thermal behavior. Finally, the year-round performance is compared to the one of traditional clay tiles.

## 2. Methodology

The research consists of two main parts. The preliminary work lies in the analysis and the optimization of a cool roof clay tile with the same visual appearance of natural tiles for traditional roofs. The second part of the work consists of the analysis of the year-round performance of such chosen tile with respect to existing clay tile, when applied to a typical residential building in central Italy.

### *2.1. Elaboration of the prototyped tiles*

Different kinds of new tile are prepared and compared with a natural tile (N) and with a white engobe tile (W) already elaborated [3], containing the pigment $TiO_2$, which is a strongly scattering, weakly absorbing, stable, inexpensive, and also photo-catalytically active white pigment [18]. The sample name and composition of the coatings are reported in Table 1. The used coating - encoded colored coating – contains pigments with sodium silicate in water as binder. For comparative purposes both tiles (N and W) have also been coated with solely the binder, to evaluate its specific effect.

A group of tiles is prepared with the technique known as *velatura* in artistic field [19]. The tile is characterized by three layers: (i) substrate, (ii) white engobe basecoat, (iii) thin pigmented topcoat, as shown in Figure 1 (Three-layer tile, type 3). The colored layer is relatively diluted, with the aim to change the visual appearance with the least possible modification of the important performance shown by the white basecoat in terms of reflectivity.

Table 1. Codenames and composition for the elaborated samples[a].

| Sample code | White engobe | Binder[a] | Coating Al | Colored Coating Pigments | | | Tile type in Figure1 |
|---|---|---|---|---|---|---|---|
| | | | *Aluminium [g]* | *Y [g]* | *R [g]* | *B[g]* | |
| N | - | - | - | - | - | - | |
| N-Si | - | yes | - | - | - | - | |
| W | yes | - | - | - | - | - | |
| W-Si | yes | yes | - | - | - | - | |
| W-Si-C1 | yes | yes | - | 7.2 | 1.4 | 1.6 | 3-layer tile, type 2 |
| W-Si-C2 | yes | yes | - | 0.72 | 0.14 | 0.16 | 3-layer tile, type 2 |
| W-Si-C3 | yes | yes | - | 0.72 | 0.14 | 0.16 | 3-layer tile, type 2 |

[a] binder used is always sodium silicate dissolved in water at 18% w/w.
[b]as mentioned in the text colored coating applied on C2 and C3 are the same, but they were applied twice in C2 and only once in C3.

Different types of *velatura* are tried, with increasing dilution of the pigments: *velatura* encoded C1 contains a coating with a rather high amount of pigments, *velatura* C2 contains a coating with a quite diluted pigment and it is applied in two consecutive times, one layer above another. *Velatura* C3 has the same composition of C2, but only one layer of coating is applied.

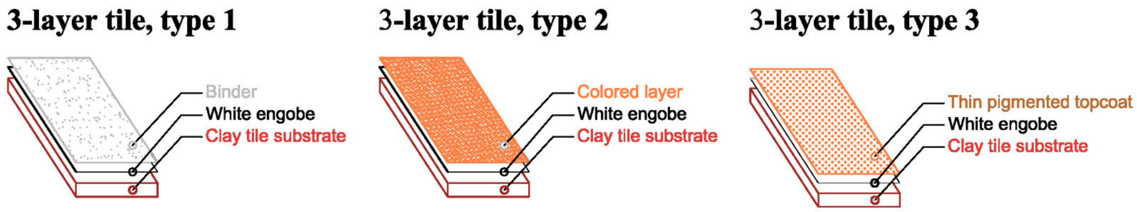


Fig. 1. Schematic description of prototyped samples of tile.

Small coupons of 7×7 cm are cut from tiles and covered with experimental coatings. The coatings are applied upon the tiles immediately after preparation by means of a paint-brush. The coated tiles are allowed to dry at room temperature for 2 weeks before measurements.

The chosen pigments and the used binder are easily commercially available at low price. A mineral binder of sodium silicate was selected. As regards colored pigments, natural mineral earths are preferred, because of high stability under weathering conditions, light oxidation and corrosion [20]. Iron oxide-based yellow (encoded with Y in Table 1), red (encoded with R) and brown (encoded with B) are used as pigments. Relative amounts of various pigments are chosen on the basis of previous work that used the same kinds of pigments and carried out investigation to finding colour mixtures which mimic terracotta colour [15].

Visual appearance of the tile and its performance in terms of solar reflectance are considered as the key parameters to guide in the choice of the tile for the further part of the investigation.

### *2.2. Experimental characterization of the tiles*

The experimental analysis aimed at characterizing tiles' prototypes is carried out through solar reflectance and thermal emittance measurements. The solar reflectance of each sample is measured through spectrophotometer with integrating sphere, a Shimadzu SolidSpec 3700, which principal characteristics are reported in Table 2. More detailed technical features of the instrument are reported in [15]. The measurement procedures are defined in [21], by considering the solar spectrum reported in [22]. The thermal emissivity measurement are carried out through a portable AE1 RD1 emissometer, following the procedure description reported in [23]. The samples for both these instruments were prepared as square 7×7cm planar clay tiles.

Table 2. Details of the spectrophotometer.

| | |
|---|---|
| Spectral bandwidth | UV/VIS: 0.1-8 nm (8 steps)<br>NIR: 0.2-32 nm (10 steps) |
| Spectrum interval | 240÷2600 nm |
| Accuracy | ±2% of reading |

## 3. Case study

### *3.1. The building*

The analysis of the thermal-energy performance of the proposed clay tile is carried out in a single-family residential building located in the suburban area close to Perugia, in central Italy. The building consists of a 3 floor house which location and architectural details are specified in Table 3. The detailed description of the building is reported in [24].

Table 3. Details of the case study.

| | |
|---|---|
| Building technical details | Period of construction: 1973<br>Masonry resistant structure<br>No insulation layer present in the envelope |
| Building details | Ground floor area: 124 $m^2$<br>First floor area: 197 $m^2$<br>Second floor area: 192 $m^2$ |
| Climate characteristics of the location | Daily average maximum/minimum peak temperature:<br>· Winter: 7.8°C - 1.8°C<br>· Spring: 15.9°C - 7.4°C<br>· Summer: 27°C - 16.5°C<br>· Fall: 17.7°C - 10.4°C<br>Rainfall rate: 850 mm<br>Eliophany: 5.8 h/day |
| Positioning | Perugia, Italy<br>Latitude: 43°06’59.09”<br>Longitude: 12°18’38.79”<br>Elevation above sea level: 522 m<br>Degree Days: 2204 |

The building represents a very common single family residential building in Italy, where traditional materials such as masonry covered by plaster on both sides, and terracotta tiles, are used, without any insulation panel in the envelope. In fact, the construction was built before the enforcement of the Italian law for building energy saving. Additionally, the choice of this building was carried out for other motivations. First, the case study building is located in a green area close to the city (Figure 2), where an environmental commitment is present, consisting of the possibility to use only non-impacting materials and finishing for buildings. In this view, high reflective white tiles are not allowed, and the traditional “terracotta” color should be applied of the building roof. Second, the building is the object of continuous monitoring campaign by University of Perugia, which began on 2009. Therefore, both the meteorological conditions of the site and the indoor microclimate of the attic are under control through two coupled monitoring stations [25]. Also the in-field thermal properties of the envelope have been characterized through transmittance in-field measurement of the walls, ceilings and roof. The reflectance of the roof, in-field measured with the albedometer positioned over the roof of the house, gives the required information about the potential solar heat gain through the roof which could be reflected thanks to cool roof solution, which are object of this research. The Inter-Building Effect [26] affecting the building performance is not taken into account, given its negligible impact on the overall thermal-energy performance of the house, as reported in [27].

Fig. 2. Aerial view of the case study positioning.

### 3.2. The numerical model

In order to assess cool roof performance on the case study building with varying roof layout and thermal-energy properties, the dynamic simulation model of the single family residential building is carried out through EnergyPlus simulation environment [26-27]. First, the geometry and the architectural layout of the structure are described; second, the envelope characterization is carried out through the description of all the characteristics of materials and techniques. The analysis of the performance of the proposed cool roof application concerns the attic of the house, which is a free-floating thermal zone where almost none usually occupy the area. Then the effect of the reflective tile is evaluated in terms of indoor operative temperature, which impacts indoor thermal comfort perception. The characterization of different envelope techniques of the house is reported in Table 4, for what concerns the attic opaque walls and the windows.

Table 4. Principal characteristics of the attic envelope.

| | |
|---|---|
| Attic opaque wall | <u>Overall thermal properties:</u><br>Thermal conductance: 0.858 W/m$^2$<br>Thermal transmittance: 0.749 W/m$^2$<br><u>Internal surface:</u><br>Convective heat transfer coefficient: 2.152 W/m$^2$K<br>Radiative heat transfer coefficient: 5.540 W/m$^2$K<br>Surface resistance: 0.130 m$^2$K/W<br><u>External surface:</u><br>Convective heat transfer coefficient: 19.870 W/m$^2$K<br>Radiative heat transfer coefficient: 5.130 W/m$^2$K<br>Surface resistance: 0.040 m$^2$K/W |
| Window glazing system | Total solar transmission (SHGC): 0.742<br>Direct solar transmission: 0.670<br>Light transmission: 0.801<br>Transmittance value: 2.842 W/m$^2$K |

The thermal analysis of the prototyped tiles is carried out in both summer and winter conditions, by taking into account the climate boundary conditions of Perugia, Italy. The case study city, located in central Italy, is positioned in an “E” climate zone, characterized by 2289 degree days. Table 5 reports the principal monthly climate data of the location for outdoor dry bulb temperature and solar radiation. The considered weather station is positioned at 520 m above the see level, encoded as Perugia 161810 (IGDG). The weather hourly data of the site are collected from the database of the Europe WMO Region 6 used by EnergyPlus engine [28].

Table 5. Principal monthly characteristics of the weather conditions of the considered site.

| Monthly Statistics for Dry Bulb temperatures °C | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Maximum | 12.6 | 15 | 17.4 | 20 | 26.2 | 29.8 | 34.3 | 34.1 | 29.8 | 24 | 17.3 | 12.9 |
| Minimum | -3.7 | -6 | -1 | 3.1 | 7.6 | 8.6 | 12.6 | 13.8 | 9.4 | 5.8 | -0.6 | -1 |
| Daily Avg | 4.3 | 5.4 | 7.3 | 11 | 15.4 | 19.5 | 22.3 | 22.1 | 18.5 | 13.5 | 9.5 | 5.3 |
| Monthly Solar Irradiance Wh/m² (noon on 21st of month) | | | | | | | | | | | | |
| ib (beam) | 789 | 809 | 820 | 835 | 840 | 820 | 811 | 798 | 800 | 765 | 714 | 740 |
| id (diffuse) | 95 | 129 | 160 | 175 | 172 | 177 | 174 | 167 | 142 | 126 | 110 | 90 |

ib (beam) = Clear Sky Noon Beam Normal Irradiance on 21st Day

id (diffuse) = Clear Sky Noon Diffuse Horizontal Irradiance on 21st Day

The thermal year-round numerical analysis is carried out by comparing the performance of the attic with the new prototyped tile (P tile) with respect to the same thermal zone with natural red clay tiles on the roof (N tiles). Table 6 synthetically reports the reflectance values of the two considered tiles which are modeled into the building dynamic simulation environment.

Table 6. Reflectance characteristics of the considered tiles.

| | |
|---|---|
| Natural red clay tile:<br>*N tile* | Ultra Violet reflectance: 8.79%<br>Visible reflectance: 31.11%<br>Near Infra-Red reflectance: 65.88%<br>Solar Reflectance: 45.28% |
| New chosen tile W-Si-C3:<br>*P tile* | Ultra Violet reflectance: 20.14%<br>Visible reflectance: 40.04%<br>Near Infra-Red reflectance: 74.71%<br>Solar Reflectance: 57.48% |

## 4. Discussion of the results

### *4.1. Optical performance of the tiles*

Visual appearance of the new samples is shown in Figure 3, where also the natural terracotta clay tile (N) and the white engobe tile (W) are reported for comparison purposes. The figure clearly shows how the application of the binder does not change significantly the original visual appearance of the tile, which is "terracotta" for the N series, and white for the W series (samples N-Si, W-Si). On the other hand, application of the colored coating C1 leads to a quite dark brown tile, even when applied over white tile. The visual appearance of tiles with *velatura* layer is quite similar to the natural terracotta tile in both cases where diluted *velatura* is used (W-Si-C2 and W-Si-C3), whereas the color is rather dark brown when the pigments amounts is higher such as in sample W-Si-C1. Reflectance spectra of the various samples are reported in Figures 4 (a-b). The values of solar reflectance calculated following the procedure detailed in Section 2.2 are reported in Table 7. Figure 4-a reports the solar reflectance spectra of the natural terracotta tile (N) and the white engobe tile (W), and the same two samples with the sole binder applied (N-Si and W-Si). It is clear how the binder, transparent and of similar chemical nature as the clay, only slightly affects the spectra, with a small general decrease of the reflectivity. In particular, it exerts an almost insignificant effect in the natural terracotta tile, with the value of $R_{SOLAR}$ being almost unchanged (Table 7). For the white tile the effect is a bit higher, with decrease of the $R_{SOLAR}$ value of 3 points (Table 7). The selected binder can be therefore considered good, especially if compared with the performance of organic binders such as acrylic matrix [16]. . Application of a further, colored, layer, does not change so much the situation for the natural terracotta tile, but leads to a more significant decrease of reflectivity in the white tile, as expected, because of the presence of absorbing pigments. In terms of values of $R_{SOLAR}$ the two samples W-Si-C1 and N-Si-C1 are quite similar, with values of 35 and 37 respectively (Table 7).

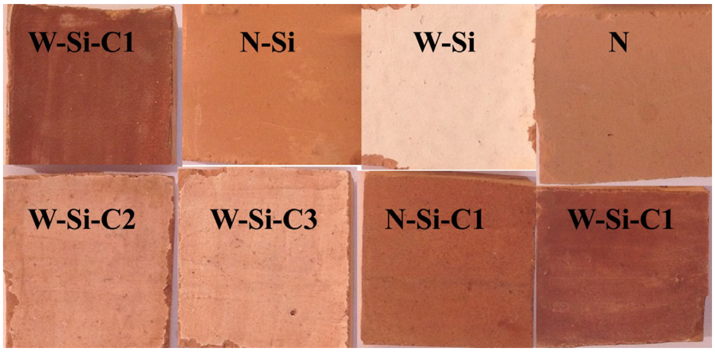


Fig. 3. Visual appearance of the prototyped tile samples.

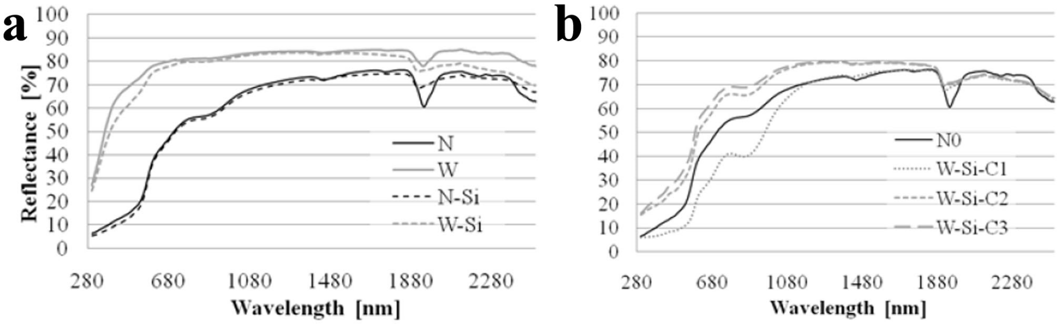


Fig. 4 (a-b-c). Solar reflectance spectra of the new tiles compared with the unmodified N and W tiles.

Figure 4-B shows the effect of application of *velatura* layer upon the white engobe tile. The tile W-Si-C1, which is also rather dark, has a reflectance rather worse than natural terracotta, at least in the whole range 300-1500 nm. On the other hand, application of the diluted *velatura* leads to an improved performance with respect to the natural tile, especially in the case of application of only one layer (W-Si-C3). It is evident that the reflectance spectrum is significantly better in the UV region, in the VIS region and in the NIR region, up to about 1900 nm. With respect to the white tile containing only the binder (W-Si), the effect of the *velatura* layer corresponds to important decrease in $R_{VIS}$, as expected for the presence of pigments that has to give color and to absorb in the VIS region. Also a relatively high decrease in $R_{UV}$ and $R_{NIR}$ is observed. The whole performance in terms of $R_{SOLAR}$ is rather good for a colored tile, being 58%: it is significantly higher than natural tile by 13%. For this reason, this last tile W-Si-C3 is selected for further work in this paper.

### *4.1. Thermal analysis of the proposed roof*

The year-round evaluation of the effect of the proposed tile on the indoor thermal behavior of the attic is dealt with in this section. Figure 5 reports the profile of the attic operative temperature with respect to the outdoor dry bulb temperature during one week for each season. Each week is selected as the week with the nearest average temperature compared to the season daily profile, as suggested in [23]. The temperature profiles show how the prototyped tile is able to decrease the indoor operative temperature in summer, with lower effect in winter and autumn. These results are confirmed by the capability of the proposed tile to affect the number of hours when the indoor operative temperature is higher than 26°C in summer and lower than 20°C in winter, as detailed in Table 8. Additionally, Figure 6 reports the effect of the prototyped tile in lowering the monthly average, maximum and minimum operative temperature of the attic. The year-round results show that the maximum effect consists of decreasing the thermal peaks, in summer months in particular. In fact, given the higher solar radiation contribution in summer than in winter months, the cool roof benefit is highlighted during the moments when its effect is mostly required: in hottest months and in the hottest hours of the day.

Table 7: solar reflectance and thermal emittance of the various samples

| Sample code | $R_{UV}$ 300-380 nm | $R_{VIS}$ 380.5-780 nm | $R_{NIR}$ 781-2500 nm | $R_{SOLAR}$ 300-2500 nm | Thermal |
|---|---|---|---|---|---|
| N[a] | 8.8 | 31.1 | 65.9 | 45 | 0.90 |
| N-Si | 7.1 | 29.5 | 64.7 | 44 | 0.90 |
| W[a] | 45.3 | 74.1 | 82.8 | 77 | 0.88 |
| W-Si | 39.7 | 69.4 | 81.3 | 74 | 0.89 |
| W-Si-Al | 37.3 | 62.9 | 72.9 | 66 | 0.87 |
| W-Si-C1 | 6.3 | 20.0 | 59.1 | 36 | 0.89 |
| W-Si-C2 | 18.3 | 41.9 | 72.9 | 55 | 0.91 |
| W-Si-C3[b] | 20.1 | 46.0 | 74.7 | 58 | 0.90 |

[a] [15]
[b]as mentioned in the text colored coating applied on C2 and C3 are the same, but they were applied twice in C2 and only once in C3.

Table 8. Number of hours with temperature higher than 26°C in summer and lower than 20°C in winter.

| | Number of hours when T>26°C from April to September | | Number of hours when T<20°C from October to March | | Percentage increase of T<20°C hours | Percentage decrease of T>26°C hours |
|---|---|---|---|---|---|---|
| | N tile | P tile | N tile | P tile | | |
| Air temperature | 4178 | 4196 | 1997 | 1695 | +0.43% | -17.82% |
| Mean Radiant temperature | 4161 | 4187 | 2073 | 1745 | +0.62% | -18.80% |
| Operative temperature | 4170 | 4193 | 2037 | 1721 | +0.55% | -18.36% |

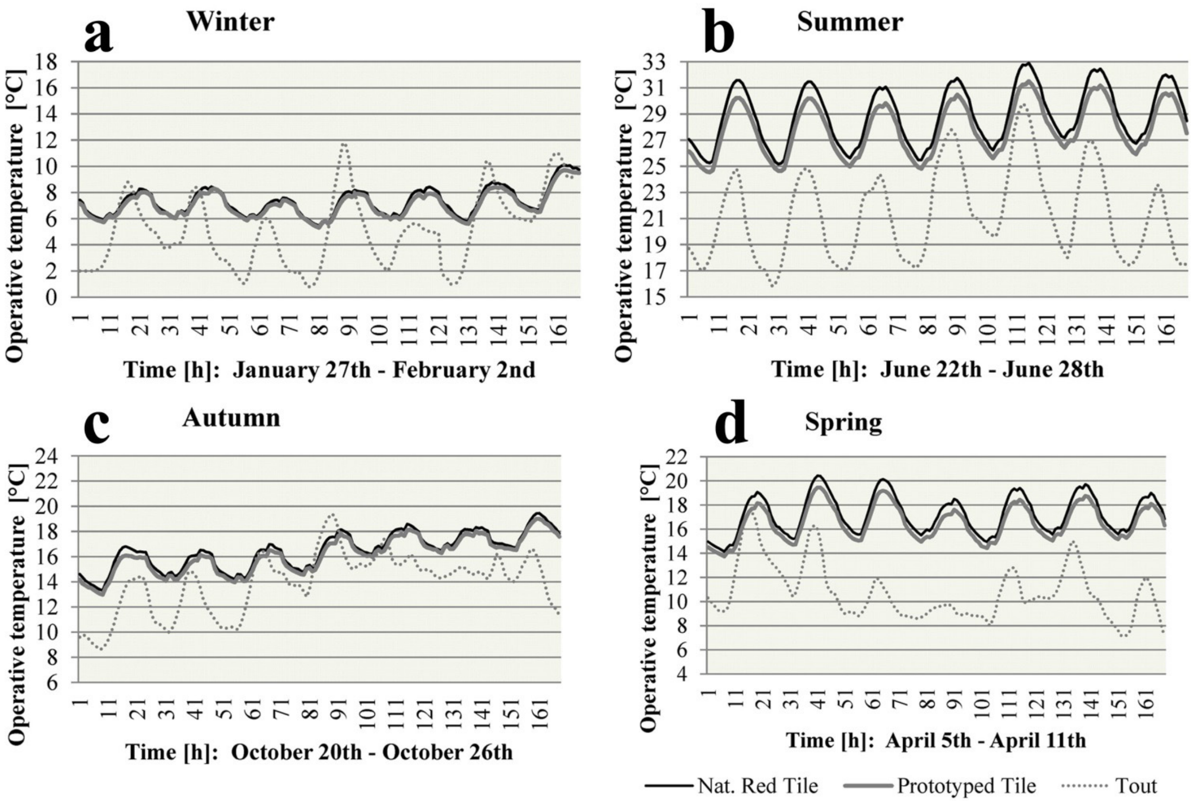


Fig. 5. Weekly thermal profiles of the attic operative temperature and outdoor dry bulb temperature with N and P tile.

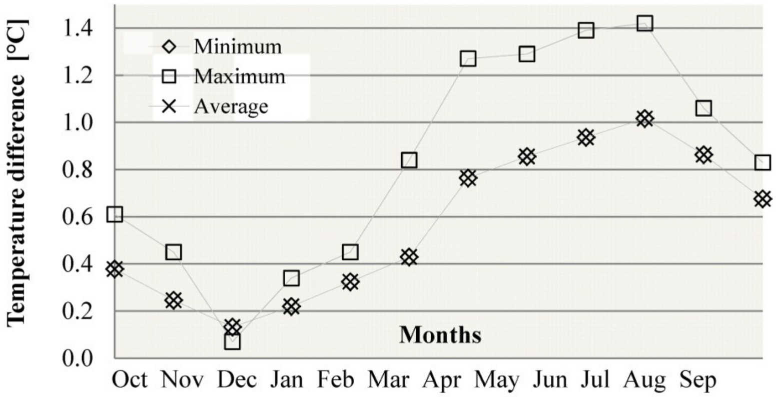


Fig. 6. Weekly thermal profiles of the attic operative temperature and outdoor dry bulb temperature with N and P tile

## 5. Conclusions and future developments

Important research contributions are carried out aiming to develop innovative cool roof solutions and high reflectance coatings for application to new and existing buildings, in several climate contexts. In particular, recent research efforts also concern the elaboration of innovative cool coatings with high reflectance capability in the near infrared interval of the solar spectrum, in order to reduce the architectural and the environmental impact of very light color coating in buildings and urban areas. It is during the very recent years that researchers working in this area started to think about the development of cool clay tiles, which represent a very common and traditional roof covering technique in Mediterranean countries. The present research deals with the development of new coating for clay tiles, specifically elaborated in order to optimize the infrared reflectance capability, without affecting the visual appearance of such roof element, which make the prototyped tile able to be applied in historical city centers and hedged-in buildings. In this paper, first, the development of the coating is described and its application on clay tile substrate is discussed. The performance of this roof element are then investigated in terms of (i) visual appearance, (ii) reflectance and (iii) emittance. These properties represented the guide parameters for the following choice of the tile, which thermal behavior is investigated in a case study residential building in central Italy.

The experimental analyses showed that the elaborated coatings are able to reflect the solar radiation in the near infrared spectrum by 75%, i.e. 10% more than traditional tiles, with equivalent visible appearance. The emittance does not present any substantial difference.

The numerical analysis, carried out in a residential building with sloped roof covered by clay tiles, showed that the application of the chosen tile is able to reduce the number of hours when the attic operative temperature is lower than 26°C by about 18%, while the hours when the indoor operative temperature is lower than 20°C in winter are increased just by less than 1%. Therefore, the proposed solution could represent an effective strategy for improving indoor thermal comfort conditions in attics of existing traditional buildings, even in temperate climates, characterized by hot summer and cold winter conditions.

The results of this study could contribute to further interesting research progress in the investigation about cool materials also in traditional building applications.

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