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On Innovative Cool-Colored Materials for Building Envelopes: Balancing the Architectural Appearance and the Thermal-Energy Performance in Historical Districts

Federica Rosso [1,*], Anna Laura Pisello [2], Veronica Lucia Castaldo [2], Marco Ferrero [1] and Franco Cotana [2]

[1] Department of Civil, Construction and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy; marco.ferrero@uniroma1.it

[2] Department of Engineering, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy; anna.pisello@unipg.it (A.L.P.); castaldo@crbnet.it (V.L.C.); franco.cotana@unipg.it (F.C.)

* Correspondence: federica.rosso@uniroma1.it; Tel.: +39-06-4458-5665

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Abstract: Architectural expression and energy performance are key decision-drivers in the selection of a particular construction element, with the purpose of Urban Heat Island mitigation, energy-consumption reductions, and cultural heritage preservation in historical centers. In historical centers, the external layer of the envelope and the visible parts of the building are built with traditional materials and technological solutions, such as single-layer walls or brickworks, depending on the country's context, while the energy performance is usually optimized by means of internal insulation layers, or other active and passive solutions. Thermal-energy efficient materials and construction elements for the temperate, warm climate of the Mediterranean area are usually light-colored to reflect the largest part of solar radiation, thus reducing energy demands for cooling and improving thermal comfort conditions for occupants. On the other hand, many historical centers in such areas are characterized by reddish or grayish colors. In this work, we considered Italian historical areas, and other countries in the Mediterranean area with present similar situations. Thus, in this study, innovative, cool-colored, cement-based materials were developed to improve the thermal-energy performance of the external envelope of historical/historic built environments, without altering their appearance. These materials were prepared directly on-site, by mixing two types of pigments to achieve the desired color saturation. Optic and thermal properties were assessed, and yearly dynamic simulations of a historic, listed, case study building were performed, by comparing traditional-colored mortar and the prototype cool mortar envelopes. The research demonstrates that such cool-colored materials can maintain lower surface temperatures (−8 °C), while reducing energy demands for cooling (−3%).

Keywords: cool-colored materials; cement-based materials; historical districts; energy performance; passive solutions; cool envelope; cool roof; dynamic simulation; thermal-optic characteristics

1. Introduction

The Italian national built environment, as well as the European one, is characterized by numerous historical buildings and centers, which are protected, depending on national regulations [1,2], in order to preserve the cultural, architectural and artistic heritage that they provide. Operating in these areas involves paying great attention to both possible retrofit solutions for existing buildings and to construction elements' designs in the case of new buildings. Indeed, many solutions that are commonly applied to achieve energy efficiency in new buildings in non-historical areas cannot be implemented in historical centers. This is because of cultural-heritage constraints that require one to preserve the appearance and identity of the building, which is of historical/historic value, for generations to come. This issue is of primary importance in Italy, due to the large amount of historic and historical building stock [3]. "Historic" and "historical" have two distinct meanings, which need to be defined for the sake of clarity. While historical refers to anything that was built in the past (more than 50 years ago), historic is a definition that entails that the building/district has an influential role in history. As a consequence, "historical" does not always comprehend a historic built environment, but it can be considered as potentially "historic". Depending on the classification, buildings and districts are subject to regulations for any modification that has to be performed on them. The Italian Legislative Decree 42/2004 "Code of Cultural Heritage and Landscape", which is currently in force, includes "buildings, town centers and historical complexes having aesthetic and traditional value" among the cultural and architectural heritage sites.

Considering the large amount of energy consumed by buildings, equal to almost 40% of the total energy demands in Europe [4–6], and the consequent regulations about energy consumptions [7–9], it appears fundamental to exploit the large potential of buildings with the aim of reducing energy consumption. This objective can be reached by means of multiple strategies, both active and passive, to be tested and implemented on new as well as on existing building stock [10,11]. With particular reference to the existing stock (including historical and historic constructions) as mentioned above, improving its energy performance would tap into its huge potential to save energy [12]. In fact, existing buildings are responsible for more than half of the total consumptions of the construction sector, given their low-performing envelopes and energy systems [13]. Numerous studies took into consideration historical and historic constructions, due to the fact that they require more complex analyses with respect to possible retrofit options, due to conservation and architectural constraints [14]. Researchers focused on Italian historical and listed building stock, pertaining to different periods, and analyzed the effects of both passive and active energy retrofitting technologies [1,14–17]. In particular, Ciulla and colleagues [18] evaluated the most common retrofit solutions in Italian historical stock, by specifically focusing on envelopes. They considered the energy and economic impact of the refurbishment in different climatic contexts, concluding that there is not a generic solution that is suitable for all regions. A multi-criteria approach for the refurbishment of a historical building was carried out by means of experimental and numerical studies [16]. Results showed that changing types of windows, increasing thermal insulation, and updating the energy system are the most effective solutions to improving thermal-energy performance. Pisello and colleagues [19] proposed both passive and active solutions for the retrofit of a historic building, and evaluated their impact by means of dynamic simulation. They assessed energy savings equal to 4% for the passive solution.

The passive strategies that are commonly adopted to boost energy efficiency include exploited natural ventilation [20–22], increased thermal insulation [23,24], window types substitution [25], or solar radiation [26–28]. Green roof or roof ponds are less common solutions, due to higher cost of implementation and maintenance [29–31]. However, with reference to historic buildings, it is not viable to intervene with many of the above-mentioned strategies, since the architectural characteristics of the construction and external appearance conservation do not allow such modifications.

New materials have been developed, with the aim of improving the thermal-energy performance of the building and, at the same time, maintaining the architectural constraints. As an example, Pisello and Cotana [32,33] developed an innovative cool clay tile, similar to traditional ones used for a sloped roof. The tile has good thermal-optic characteristics (improved reflectance in the infrared part of the spectrum), which are better than the characteristics of traditional tiles with the same appearance. This is because of its addition of a basecoat, and its ability to blend in with a historical sloped roof, while providing improved energy performance. Indeed, the addition of cool coatings to colored construction elements, or the implementation of cool-colored mixes, opens up many possibilities for the application of energy-efficient materials in historical contexts, as well as to favor architectural variety in the case of new constructions. Cool-colored materials differ from "traditional" cool materials in terms of appearance and composition. In fact, "traditional" cool materials are traditionally light-colored, in order to optimize their reflectance in the visible part (Vis) of the solar spectrum, while cool-colored materials are optimized in the infrared part of the spectrum (IR), which is not visible to the human eye. Therefore, cool-colored materials improve thermal-optic characteristics, and go beyond the reduced variety of colors of traditional cool materials [34–41].

Following this trend, the present work deals with the implementation of innovative cool-colored prototypes of cement-based mortars, which have been deposited as a patent by the authors (Deposit number I0165684), as well as with the assessment of their effectiveness when applied on a case study building. The peculiarity of the developed material is the implementation process, which permits one to choose the required color saturation directly on-site, by adding two types of pigments to the mix. The application of the material is simple, as a traditional mortar, and as a finishing layer of the external building envelope.

In this work, we will refer to both historical and historic building heritage; the considered case study is a historic building, but here, the described envelope retrofit solution would also be suitable for historical buildings' retrofit. Additionally, the cool-colored materials for a building envelope can be employed as an additional strategy to boost the energy efficiency of new buildings in historic/historical districts.

2. Method

The research was developed, by implementing in the lab, cement-based prototypes and then assessing their thermal and optic-characteristics. A historic university building in Perugia, central Italy, was selected as the case study building to test the effectiveness of the investigated materials as retrofit solutions, and aiming at improving the thermal-energy performance of historical/historic buildings. Therefore, the in-lab measured characteristics of the selected prototypes were employed for running the dynamic simulation of the case study building. In particular, three scenarios for the same case study building were simulated in order to compare proposed solution effectiveness with respect to the reference case (Case 0), where no retrofit solution was applied. The scenarios were characterized by increasing levels of cool retrofit. The scenarios were Case E, where the cool prototypes were applied on the vertical envelope (E), and Case E+R, where cool retrofit solutions were applied both on the vertical envelope (E) and on the roof (R). More specifically, in Case E+R, the cooling solution consisted of the cool-colored prototypes for the envelope, and of cool-colored roof tiles for the roof. In previous research, similar prototypes were investigated in terms of thermal-optic characteristics [40], whereas in this work, we concentrated on a single-colored prototype and on deriving the thermal-energy performance of a case study building, with this specific material applied as envelope.

In the following sections, the method employed to carry out this work, as well as the developed material, are described in greater detail.

2.1. Materials Implementation and Characterization

The choice of the materials and the colors of the developed prototypes are based on the analyses of the most common colors in Italian historical centers (Figure 1). In particular, as a preliminary prototype, we decided to develop a cool red-colored mortar.

As mentioned in the Introduction section, in order to optimize colored mortar mix reflectance, which is low in the visible part of the spectrum due to the dark red pigment, IR pigments were added to the mix [42]. More specifically, titanium dioxide pigments from Huntsman Corporation (The Woodlands, TX, USA) (Altiris®, [43]) were employed. Such pigments are light in color, almost white; therefore, their addition to the colored mix implies not only an optimization in the IR part of the spectrum, but also a slight improvement in the visible part. However, in order to make the comparison, we selected a cool red prototype and a traditional red prototype showing the same color and color saturation. The prototype is composed of cement, water, fine aggregates and two pigments (Figure 2): the "traditional" red pigment (red oxide), which provides color, and the white IR pigment, which provides improved thermal-optic characteristics and is responsible for the "coolness" of the proposed material, as well as of color saturation. The components can be mixed directly on-site, in order to more precisely match the desired color saturation of the historical building envelope that needs to be imitated, by balancing the quantity of the two pigments. Even if, in this example, we employed a cement-based mortar, plaster-based mortars can be equally implemented following the same procedure. Therefore, depending on the construction type and the underlying layer, the most suitable cement- or plaster-based mortar can be selected.

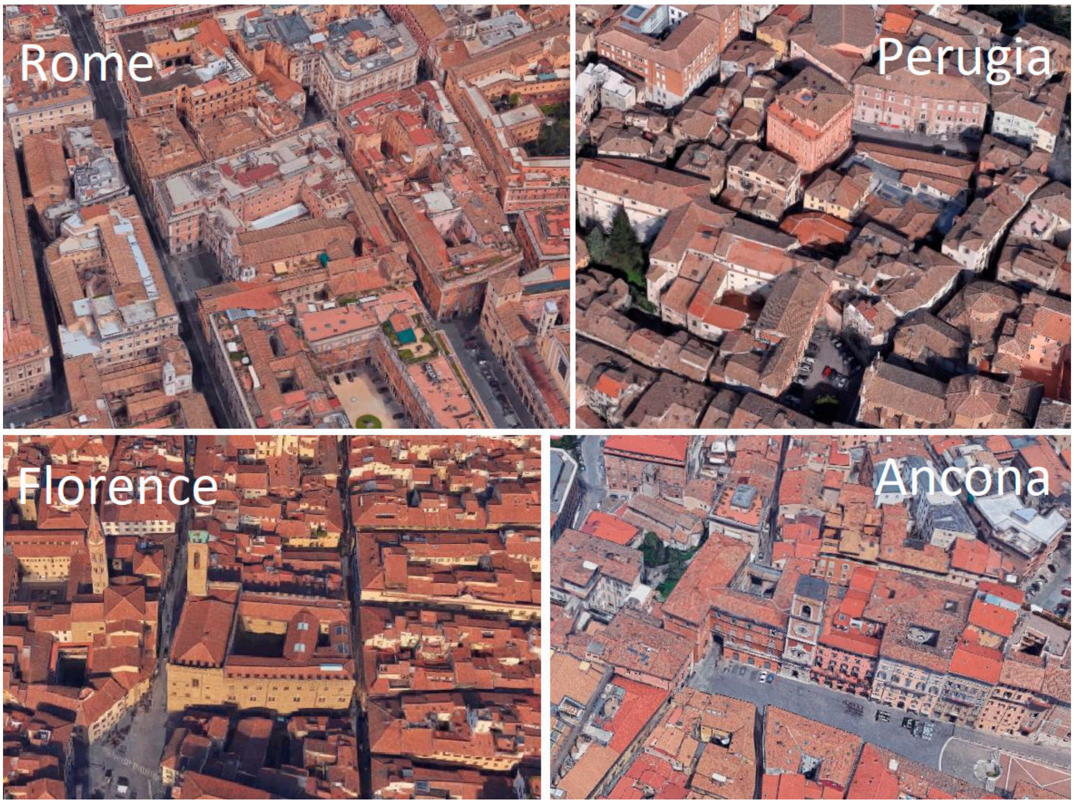

Figure 1. Overview of historic centers and colors of the main envelope, adapted from Google Maps. From top right, Rome, Perugia, Ancona and Florence.

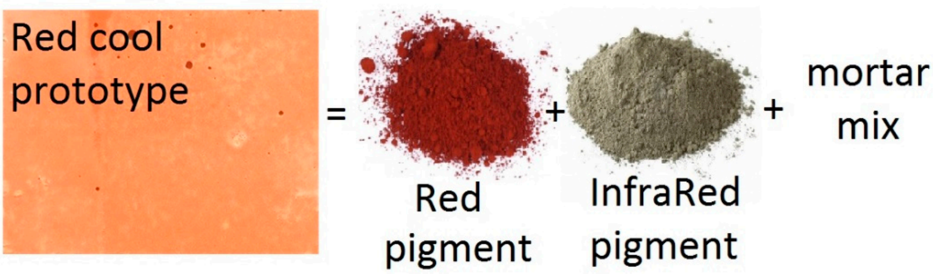

Figure 2. Cool red prototype composition.

Cool materials also bring other advantages when they are employed in the built environment, as reported in previous studies. They help Urban Heat Island mitigation, by lowering the quantity of heat absorbed by cities' surfaces [44], and they improve thermal comfort in the outdoor environment [45], when the sky-view factor is not too limited [39,41,46,47]. These aspects are not considered in this work; however, they have to be taken into account since they constitute additional benefits related to the use of these materials.

Several prototypes of (i) cool red mortars and (ii) traditional red mortars were prepared, with the same colors but different compositions.

After the curing, the samples were characterized in the lab by means of a spectrophotometer (Shimadzu SolidSpec 3700, Shimadzu Corporation, Kyoto, Japan), to assess optic characteristics, by following the instructions of ASTM E-903 [48]. Also, thermal emissivity (Portable Emissometer model AE1, Devices & Services Co., Dallas, TX, USA) and thermal conductivity (TPS 2500S, Hot Disk, Gothenburg, Sweden) were measured, respectively, in accordance with ISO 2207 [49] and ASTM C1371-15 [50]. Red mortar samples were also investigated in terms of surface temperatures by means of a climatic chamber (ATT, Perugia, Italy) equipped with a solar lamp (BF SUN 1200W, BF Engineering, Geretsried, Germany), which were able to simulate solar radiation, and monitored with PT100 thermocouples. Results of the analyses are reported in the Results section below.

2.2. Case Study Building Selection and Dynamic Simulation

In order to evaluate the effectiveness of the proposed prototype mortar, a case study building was selected to run a yearly dynamic simulation. The chosen building is a historic building, Palazzo Gallenga Stuart [51], located in the historic center of Perugia, Italy (Figure 3). It is a university building composed of four floors above the ground and two below the ground, hosting classrooms and laboratories, as well as professors' offices, a conference room, a cafeteria and the entrance hall. The total building area is equal to around 8000 m^2. The building model was developed with the software Design Builder in order to perform annual dynamic simulation. This model was validated in a previous study [19].

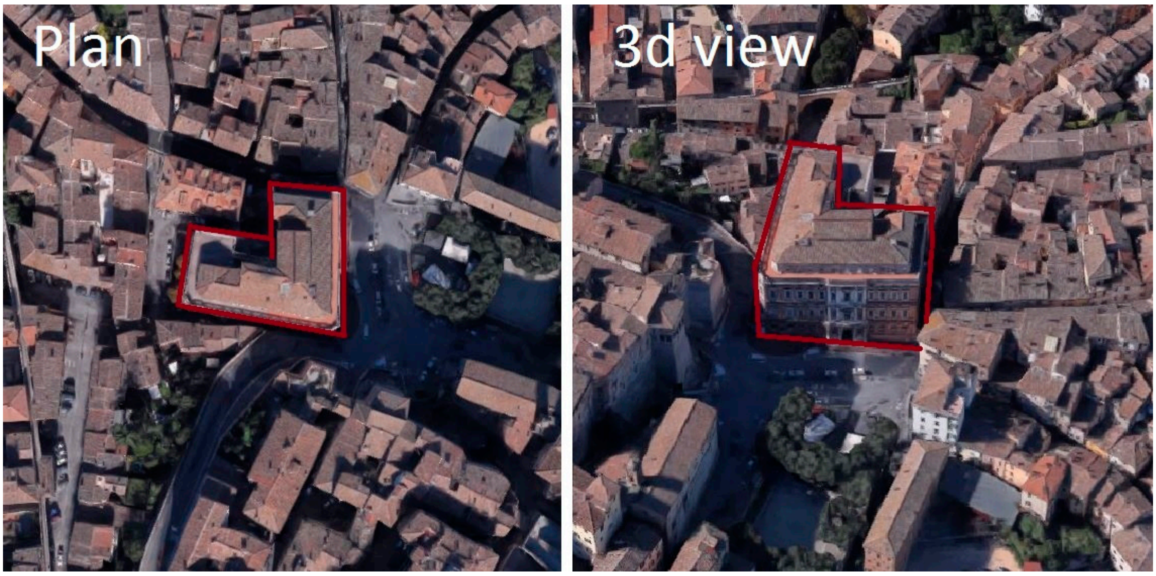

Figure 3. View of Palazzo Gallenga, extracted from Google Maps.

The Palazzo Gallenga dates back to the 18th century. The wall composition is described in Belardi's work [51], as formed by a thick bearing masonry composed of stone and brick elements (around 80 cm thick) and with an external layer of brickwork, characterized by a very compact texture (around 30 cm) (Figure 4), which appears to be a red mortar when looking from a distance. Therefore, even if the envelope is not coated by an additional finishing layer in some of its parts, just for the development of this study, we hypothesized externally covering it with a red mortar layer. The windows are composed of double clear glass panels with internal air (3 + 13 + 3 mm), equipped with internal blinds to control lighting in the day.

We considered the Palazzo as coated with a traditional red mortar in the reference case (Case 0), and we developed two additional scenarios to test the effectiveness of cool-colored solutions.

In Case E, the red IR-optimized mortar developed in the lab was considered as a finishing layer. In Case E+R, the cool clay tiles were also analyzed [19], and were applied on the building model's roof (Figure 4, Table 1), as the maximum level of passive materials' application for the improvement of thermal-energy performance.

Figure 4. Cross-section (elaborated from [51]) and façade view of Palazzo Gallenga.

Table 1. Effectiveness of passive solutions: simulated scenarios.

Scenarios	Passive Solution	Optimized Elements
Case 0	-	-
Case E	Cool-colored mortar	Envelope
Case E+R	Cool-colored mortar and cool-colored clay tiles	Envelope and roof

Then, we developed the Palazzo model for the different scenarios with the software Design Builder (version 4, Gloucestrshire, UK) [52], by inserting the materials' characteristics that were previously assessed in the lab. The installed energy system consists of a hot water radiator distribution for heating, powered by a methane boiler (600 kWh), and a fan-coil with external condensing units spoiling the façade, a common solution which would not be allowed for cooling. The heating system operates from 1 October to 30 April, while the cooling system operates from 1 June to 30 September. The building operates from 8:00 a.m. to 7:00 p.m. for 5 days per week, excluding the weekend.

The set point for cooling is 25 °C, and the set point for heating is 20 °C. Different thermal zones are also characterized by different occupancy levels, higher in classrooms (0.5 people per square meter) and lower in the other areas (0.1 people per square meter), and occupancy schedules. The model was previously validated in Pisello and colleagues' work [19].

3. Results and Discussion

3.1. Materials' Characterization

The cool red mortars prototype was analyzed with respect to thermal-optic characteristics, as described in the Method section above. Also, traditional mortars, which were developed in the lab with the same exact components except for the IR pigments, were characterized in terms of thermal-optic characteristics for comparison purposes, and to provide experimental measurements for the materials' characteristics in the dynamic simulation. The two types of prototypes were the same color, so that the aesthetic performance was the same, while the thermal-energy performance varied due to the composition.

In Figure 5, the solar spectrum, starting from 300 nm up to 2500 nm, was measured with the spectrophotometer. The solar reflectance of the IR sample was higher than its traditional sample, especially in the IR region, while in the visible part of the spectrum, the two were almost identical. This was due to the addition of IR pigments, which increased the IR reflectance of the prototypes, as expected and reported by other studies [42]. In general, solar reflectance of cool red mortars was equal to 0.4, while for traditional red mortars, this value was lower, i.e., 0.3.

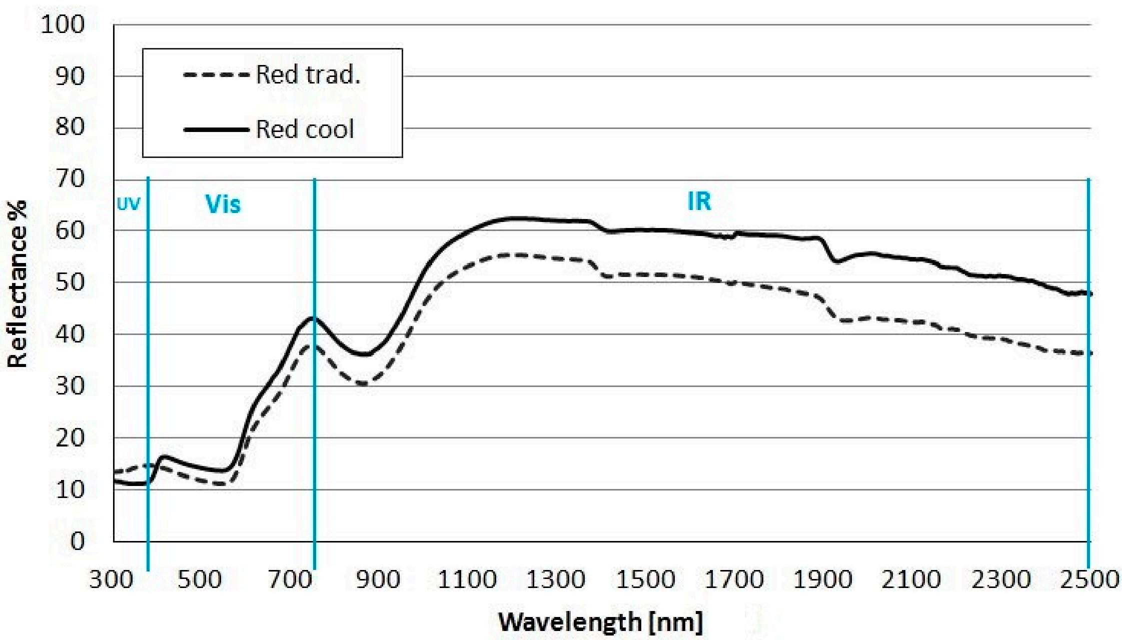

Figure 5. In-lab measured solar reflectance of traditional red samples and cool red prototypes.

With respect to thermal emissivity and thermal conductivity, they were the same in both prototype sets, and they did not change with the addition of IR pigments. Thermal emissivity was equal to 0.9, while thermal conductivity was 1 W/mK.

The different compositions of the two samples analyzed implied different surface temperatures when tested in the climatic chamber. The samples were exposed to the controlled environment for two hours; in particular, the climatic chamber was equipped with a solar lamp, which was able to replicate solar radiation (600–1200 W power range). The temperatures were measured at the end of the exposure time, in order for the samples to show constant temperatures. The cool red concrete displayed a temperature which was around 8 °C lower than the traditional red sample, confirming the effectiveness of the addition of IR pigments to the mix in the same-colored samples. The temperatures were, respectively, 61.5 °C and 69.9 °C.

With respect to the cool-colored tiles, thermal-optic characteristics were measured and thoroughly described in Pisello and colleagues' work [33]. The optimized tiles displayed a thermal emissivity equal to 0.89, while the solar reflectance was around 0.7.

3.2. Thermal-Energy Analyses

The dynamic simulation was performed for the selected case study for all the three considered scenarios (Case 0, E and E+R, displayed in Table 1). In Case 0, the reference case, a traditional red mortar was considered as an external finishing layer, influencing the thermal-energy behavior of the building with its thermal-optic characteristics. In Case E and E+R, increasing levels of passive solutions were applied to the envelope to improve the thermal-energy performance of Palazzo Gallenga. In

Case E, the cool red mortar finishing layer was applied on the vertical envelope, while in Case E+R, representing the maximum level or cool retrofit solution, the combination of the cool red mortar finishing layer for the vertical envelope, and the cool clay tiles [33] for the roof, was simulated.

In order to assess whether there were any energy savings, as well as the amount of energy being saved, due to the reduction of cooling energy demands, the HVAC was operating, and the simulation ran on Design Builder. Results are displayed in Figure 6. Differences between Case 0, E, E+R exist but are not large. Indeed, by comparing Case E with Case 0, the reduction in energy demands for cooling is equal to 1.2%. This percentage represents the energy saved, due to the application of cool-colored prototypes on the vertical envelopes, with respect to traditional, same-aspect envelopes. The reduction is higher when comparing reference case, Case 0, with Case E+R, the scenario with the maximum level of cool envelope optimization. Case E+R allows almost 3% to be saved in terms of energy for cooling. Thus, when applying cool-colored materials on the vertical envelope and on the roof, energy savings equal 3% with respect to traditional, same-aspect vertical and horizontal envelopes.

A second simulation set and comparison was performed on July 31, as an example of a hot summer's day, with non-operating HVAC. This second simulation was performed in order to evaluate an indoor mean radiant temperature, as a consequence of the different thermal-optic characteristics of the external layer of the envelope. While the application of the cool envelope and the cool roof together (Case E+R) was able to lower the indoor mean radiant temperature of around 1.5 °C, the application of cool red mortar (Case E) was not able to provide significant reductions in the indoor mean radiant temperature, when compared with the reference case (Case 0, red traditional mortar) (Figure 7).

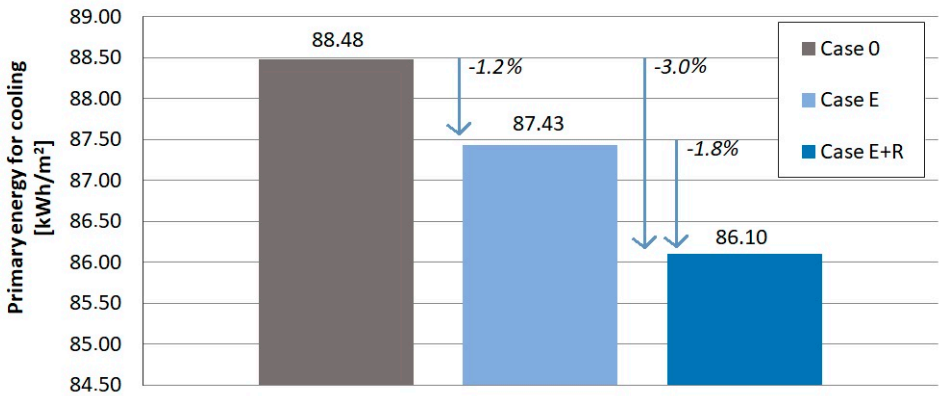

Figure 6. Energy for cooling: demand for each scenario.

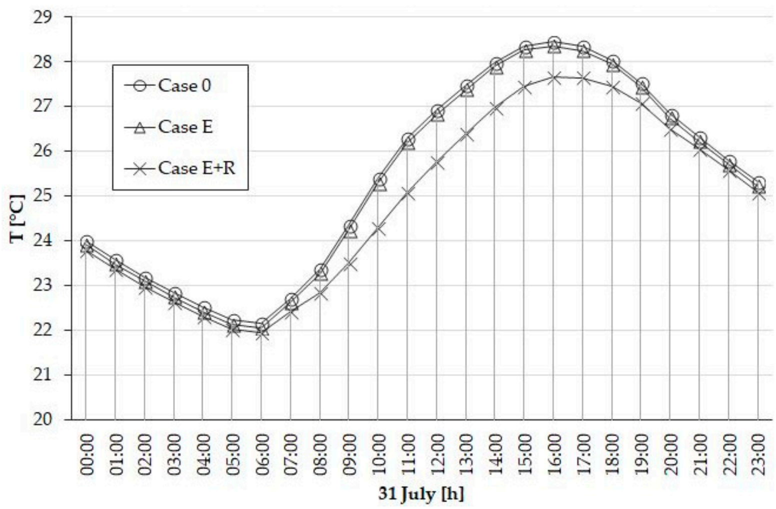

Figure 7. The indoor mean radiant temperature for each scenario on a summer's day (31 July).

4. Discussion and Conclusions

This work took into consideration innovative, cool-colored mortar prototypes, which were developed in the lab, and have been the subject of a patent deposit by the authors. These materials were implemented with the aim of providing a passive, cooling solution which is viable for historical and historic buildings and districts. Indeed, the proposed materials have the same appearance of traditional materials characterizing historical envelopes, but are optimized with respect to their thermal-optic intrinsic characteristics due to the addition of infrared reflecting pigments. Moreover, the production process is simple, and can be performed on-site in order to choose the color saturation that matches that of the desired site. Only the main components of the cement-based mortar mix have to be acquired, with the addition of the colored pigment and the infrared pigment, which is almost white in color.

The in-lab characterization of the prototypes demonstrated that the addition of infrared pigments allows solar reflectance to be increased, especially in the infrared part of the spectrum, by considering same-colored samples with a different mix. Instead, thermal emissivity and conductivity did not vary by optimizing the mix with the IR pigments. The exposure of the samples to a climatic chamber with a solar lamp and a controlled environment confirmed the efficacy of IR pigments in the mix. In comparison to cool red and traditional red mortars, they lowered surface temperatures by up to 8 °C.

These results only partially translated into advantages for the thermal-energy performance of the selected historic case study building, Palazzo Gallenga in Perugia. Three scenarios of the same case study were taken into consideration for comparison purposes, with increasing levels of cool, passive solutions implemented on the building envelope: Case 0, the reference case with no retrofit solution; Case E, with the cool red mortar on the vertical envelope, and finally Case E+R, with both cool red mortar as the envelope finishing layer and cool clay tiles [33] as roof elements. By comparing the energy demands for cooling, Case E was able to reduce demands by 1.2%, when compared with Case 0, while Case E+C allowed 3% energy to be saved for cooling with respect to Case 0, combining both the benefits of the vertical and horizontal envelope. The above-mentioned savings were not so large; however, it has to be considered that surrounding constructions were taken into account, which partially shaded the building's façade from solar radiation, and thus limited the effectiveness of cooling solutions, whose effectiveness was based on the materials' reaction to solar radiation.

In terms of indoor temperatures decreasing due to the radiative properties of cooling solutions, only E+R displayed lower indoor mean radiant temperatures (−1.5 °C), when compared to Case 0, while Case E reductions were almost nonexistent. A discussion about these results can be started here, while the hypotheses should be tested in future studies. The low effectiveness of the cool vertical envelope solution, in terms of energy saving, could be due to the surface-plan extension of the considered case study building and the role of thermal inertia. It is interesting to note that the results, in terms of surface temperature reductions due to the cool-colored envelope implementation, are noticeable, and are equal to −8 °C, when compared to traditional-colored envelopes; this is not mirrored by energy demand reductions. By considering previous studies [53], which took into account cool envelope effectiveness with respect to other case studies, and while results in mean radiant temperatures are comparable, results in terms of cooling and primary energy saving are higher in these works (−18% in cooling energy demands for a similar increase in reflectance). Taking into account the solar reflectance differences between this work and the above cited one, the values are comparable; the wall composition of the case study building is different, with the latter being a thin, double-glazed envelope of a new building. As demonstrated in Piselli and colleagues' work [54], many factors and variables can influence the effectiveness and optimization of cooling solutions. Piselli and colleagues' work focused specifically on cool roofs. Results of their work demonstrated that among the variables influencing cool roof effectiveness were roof insulation, local climate, building typology and end-use. Therefore, further analyses should be conducted on each specific building where refurbishment is needed, in order to select the solar reflectance of the envelope material according to the optimal value for the specific case, and to adjust the desired solar reflectance of the cool-colored envelope by balancing the components' mix. The prototypes proposed here allow for this solution, as the production process permits one to select the desired color and adjust the solar reflectance accordingly, based on the specific need.

Moreover, it is important to underline that cool materials have other important benefits for urban districts where they are applied, which are not assessed in this study. In fact, they contribute in Urban Heat Island mitigation, by lowering external surfaces and air temperatures [55], and they also improve outdoor thermal comfort for pedestrians, depending on the sky-view factor. Therefore, the proposed prototypes are promising materials to be employed in historical district energy retrofitting, and future studies could analyze more in-depth the above-mentioned advantages. Moreover, it is also important to consider the performance and the appearance of the cool mortars as time passes, since the interaction with the external environment could modify optic-characteristics [56] and consequently, also their thermal-energy performance [26].

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Author Contributions: All the Authors conceived the study; Federica Rosso, Veronica Lucia Castaldo and Anna Laura Pisello carried out the experimental activities and dynamic simulations and analyzed the results; Franco Cotana and Marco Ferrero are the full professors who supervised the energy and the architectural analyses, respectively.

Conflicts of Interest: The authors declare no conflict of interest.

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