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Smart cool mortar for passive cooling of historical and existing buildings: experimental analysis and dynamic simulation

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Abstract

In order to mitigate Urban Heat Island Effect and global warming, both governments and scientific community are working to reduce energy consumptions. In particular, the construction sector has a high potential in reducing energy demand, by means of both active and passive solutions. The European building stock is mainly composed by existing buildings as well as historical ones, which happens to be the less energy efficient ones. Moreover, retrofit operations are more complex on historical buildings, due to strict regulations for the preservation of such historical and cultural heritage. Considering this challenge, in this work we described and in lab analyzed possible passive solutions specifically designed for historical and existing buildings. In particular, we developed innovative cool colored mortars and tested them in lab, as well as investigated cool colored mortars, cool clay tiles and cool natural gravels performance when applied as envelope and roof elements, by means of dynamic simulation.

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1. Introduction

Buildings account for almost the 40% of total primary energy consumption, being the most energy intensive sector [1–4]. Transportation sector, which is the second one in terms of consumptions, is responsible for the 33% of total consumptions. As from the famous quote by Winston Churchill, “With Great Power Comes Great Responsibility” and, as a direct consequence, governments and scientific community efforts are directed towards the reduction of energy consumptions in the building sector [5]. This is particularly important since energy consumption is directly linked to emissions, which on their turn are among the causes of global warming [6,7] and Urban Heat Island Effect (UHIE) [8].

The operation of reducing energy consumption in buildings can be pursued on many levels, by exploiting different strategies, for example acting on the single construction element [9], or on occupants’ behavior [10] or on the employment of more efficient energy systems [11]. The selected strategy would depend on many factors, in particular on the building type and characteristics.

For this reason, in order to better direct research and energy retrofit activities, it is interesting to consider the characteristics of European building stock, as reported by BPIE [12]. In Europe, buildings constitute 4’324’782 km² of land area and 24 billion m² of floor space. With respect to Italy, around 40 kgCO₂ m² are emitted due to buildings’ energy utilization. Moreover, the 40% of the total number of buildings was built before 1960, while the 49% were constructed between 1961 and 1990 and only the 14% between 1991 and 2010. This is in line with other European countries mean percentages [12], and given the large historic patrimony of many of these countries, part of the constructions labeled as “before 1960” are historic and protected buildings. Studies have evidenced that historical buildings are the less energy-efficient ones [13]. This data demonstrate with incontrovertible evidence that tapping the potential of existing and historical buildings would permit to save a large quantity of energy, reduce emissions and mitigate UHIE and global warming.

However, the energy retrofit of historical buildings is challenging, since interventions need to be in line with preservation aims. Indeed, historical districts and buildings are protected by national regulations, which have the objective of protecting such cultural heritage sites [14]. Standard interventions on envelope (e.g. external insulation, while internal insulation is a viable strategy [15,16]) are not always feasible, while the employment of efficient construction elements depends on the esthetic appearance of the construction element itself. The exteriors of the protected building cannot be modified, since it has to maintain and preserve its original aspect. For existing buildings that are not historical, many retrofit options are instead available [17–20]. The most common interventions on existing and historical buildings comprise windows replacement with more energy efficient ones and energy system update [21–23]. Passive cool materials strategy usually implies the application of light-colored materials on buildings’ envelope [24–26], in order to boost the solar reflectance in the visible part of the spectrum: however, it appears clearly that in historical buildings this is not a common solution, due to color matching issues with the original envelope. By looking at historical cities aspect, while walking on the streets or having an aerial view, the most common colors are red (bricks or plaster), white-cream (plaster or stone), or gray (plaster or stone) for the envelope and brownish-reddish red clay tiles on the roofs, which are often sloped (Fig. 1).



Fig. 1. Views of the historical Rome city center, displaying typical colors, red clay tiles for roofs, reddish, white-cream envelopes.

Previous studies took into account the colored but still cool behavior of construction materials [27–30] by boosting solar reflectance in the infra-red, non visible part of the spectrum. With particular reference to historical districts, cool colored clay tiles were developed to be employed on sloped roof [31], and further analyzed to demonstrate the energy saving potential of the above mentioned material [32,33].

Based on these works, in order to obtain cool colored materials that can be employed in historical districts, we implemented preliminary prototypes of cement-based mortars, which we are developing also as lime-based mortar for increased compatibility with certain historical envelope. Such prototypes are also the subject of a patent deposit from the Authors. This cool colored material has been developed to match the color of the desired building's envelope by just adding to the cement mix a traditional colored pigment and an infra-red reflecting pigments, which is white in color, and can be balanced on site with the colored pigment to achieve the desired saturation. Usually, the addition of infrared-reflecting paints or pigments takes place before buying the construction elements, which arrive on site with its thermal-optical characteristics already determined. In this work, thermal-optical characteristics of the implemented prototypes are measured in lab and then dynamic simulations of different historic buildings scenarios where prototypes are applied are carried out. In addition, cool colored clay tiles, which are viable for historical buildings [31] are considered in combination with cool colored mortars, in order to provide an idea of the effectiveness of the combined application of the two passive strategies for historical buildings. The implemented cool colored mortars are an economic and relatively easy solution to be applied also on existing buildings that are not historical and is able to guarantee architectural variety by permitting to obtain colored but still cool envelopes. Therefore, as additional application, in this work cool colored mortar for existing, non historical building application is considered and tested in lab and by means of dynamic simulations, for a typical horizontal roof building, in combination with another cost-effective passive solution for cool roof application, i.e., cool natural gravels as roof finishing layer [34,35].

2. Materials and methods

In this section, cool materials selected for energy retrofit or historical and existing buildings are described. After materials implementation and/or analyses, two case study buildings were selected and modeled on the dynamic simulation software. Three scenarios for the historic case study and three scenarios for the existing case study were developed, with increasing level of passive solutions as well as the method employed to carry out this research. The method is thoroughly described in section 2.2.

2.1. Materials

Cool colored materials exploit the infra-red part of the solar spectrum to improve their optic characteristics, in the non-visible field. Previous studies were carried out on this topic, about cool colored paints, asphalt shingles, tiles and cool clay tiles [27–31]. Among these studies, Pisello and colleagues focused their attention on finding a solution for applying cool roof strategy in historical districts, where determined requirements about construction element composition and color are mandatory to preserve the historical and cultural heritage identity for generations to come. The cool clay tile is composed by three layers [31]: the clay tile, a white engobe and top pigmented layer. The measured solar reflectance is 67% (measured according to [36]), while thermal emittance is equal to 0.88. With the same objective, for this research cool colored mortars were developed to be employed in historical buildings as energy retrofit solutions for the envelope, as well as in existing buildings to obtain improved thermal-energy performance but still architectural variability in terms of color.

Prototypes were designed in order to be easily realized on site, in order to match the color of the desired part of the construction. For this reason, they are constituted by a cement mix composed by white Portland cement, water and fine glass aggregates and by the addition of a traditional (i.e., non infra-red reflecting) colored pigment and of a white infra-red reflecting pigment [37]. The balance of these two last components permits to achieve the desired color and saturation. Prototypes were developed by using red, white and gray pigments for historical buildings application, and by using also a blue pigment in the case of existing but non historical building envelope (Fig. 2). For comparison purposes, same color but non cool samples with the same exact components except for the infra-red

(IR) pigment were also prepared. The thermal-optical characteristics of both traditional and cool prototypes were measured in lab, and results are reported in the results section.

As an additional passive solution, for the roof of existing building case, cool natural gravels were taken into account as a simple, cost-effective solution. Such roof solution was studied in Castaldo and coauthors [34], where thermal-optical characteristics were assessed by means of in lab and in field analyses. We selected a light gravel type coming from scrap, with a medium dimension (4-12.5 mm of diameter) for maintenance purposes. The solar reflectance corresponded to 50%. Such gravels were studied also with respect of pedestrians' visual and thermal perception, resulting in good thermal comfort [35].

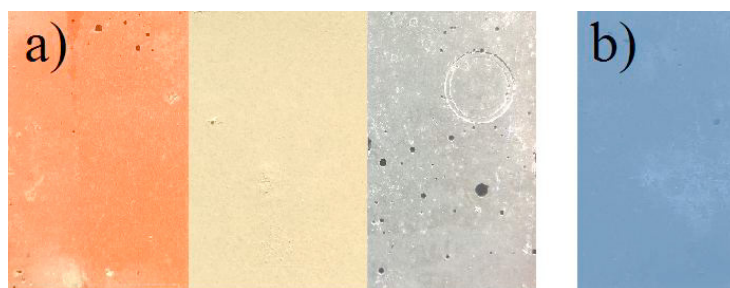


Fig. 2. Cool prototypes implemented: a) for historical and existing applications and for b) existing applications.

2.2. Methods

The cool colored prototypes and the colored samples were developed and tested in laboratory. Optic and thermal characteristics of all the considered materials were measured in lab, following current regulations [36,38]. Then, two case study buildings were selected, one for the historical case study and the other one for the existing one. The case study building was a three story, 117 mq, residential building, with two parallel facades overlooking the street and two facades adjacent to other buildings, as in historical districts (Fig. 1). The two facades adjacent to other buildings are considered as adiabatic. The historical Case study (H) has a sloped roof and a different wall composition (Table 1.a) with respect to the existing (E) building, which was modeled with a horizontal roof (Table 1.b).

For the H Case, three scenarios were considered for comparison purposes (Table 2.a). Case H0 is the reference case, with the building still without any retrofit solution, i.e., traditional colored envelope, traditional clay tiles. Case H0 was tested with all the considered traditional colored mortar red mortar finishing layer on the envelope (H0R), white red mortar (H0W) and gray mortar (H0G). In Case H1, cool innovative colored mortars replaced traditional mortars: the red (H1R), white (H1W) and gray (H1G) prototypes were tested as envelope external layers. Finally, in Case 2H, the maximum level of cool passive solution was applied, with both cool colored mortars envelope and cool colored clay tiles for the roof (H2R, H2W, H2G). Similarly, for existing building analyses, in Case E0, the existing building without any passive solution is considered, while in Case 1E the cool blue envelope is applied. In Case 2E, cool natural gravels were added as finishing roof layer, to obtain the cool roof effect (Table 2.b).

Table 1. Wall composition

a) H case study*	Thickness [mm]	b) E case study*	Thickness [mm]
Colored mortar	0.03	Colored mortar	0.03
Bearing masonry	0.80	Brick	0.25
Mortar	0.02	Insulation	0.12
		Brick	0.08
		Mortar	0.02

* from external layer to internal one

Table 2. Analyzed scenarios.

a) Historical Case study		b) Existing Case study	
Envelope	Roof	Envelope	Roof
H0 Traditional colored, non cool mortar	Traditional clay tiles roof	E0 Traditional colored, non cool mortar	Bitumen finishing layer
H1 Cool colored prototype mortar	Traditional clay tiles roof	E1 Cool colored prototype mortar	Bitumen finishing layer
H2 Cool colored prototype mortar	Cool colored clay tiles	E2 Cool colored prototype mortar	Cool natural gravels

The simulations were carried out by means of the software Design Builder-EnergyPlus simulation tool. The values of thermal-optical characteristics of the considered materials that were previously measured in lab were inserted into the simulation software. The case study buildings were analyzed both with working HVAC system (radiator, natural ventilation and chiller) and with HVAC off, to assess primary energy consumption but also external surface temperatures. Occupants activities and schedule were inputted into the simulation too, following different settings depending on the thermal zone (kitchen, bedroom, bathroom, etc.). Data from the simulations were then collected and analyzed, comparing it to the measured materials' characteristics, in order to comprehend cool passive solutions effectiveness.

3. Results and discussion

3.1. Materials characterization

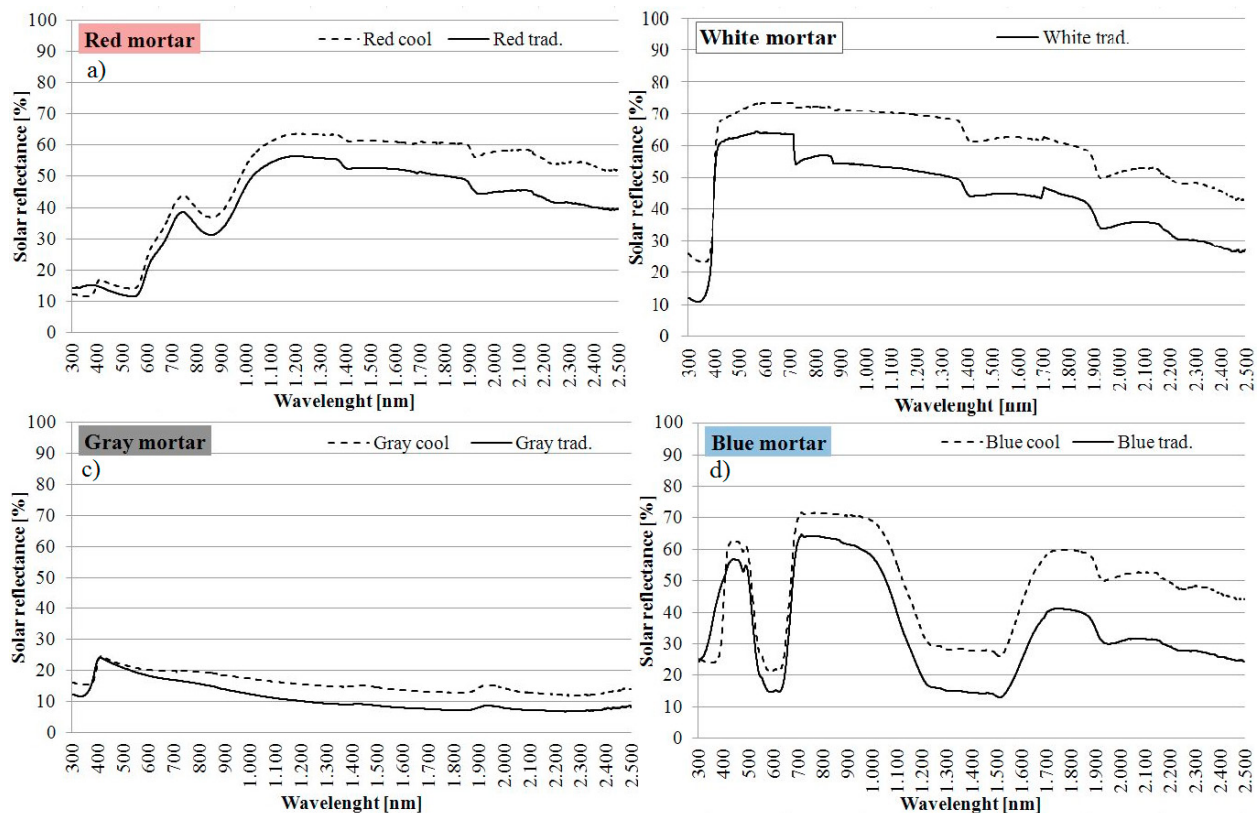


Fig. 3. Cool colored mortars reflectance and comparison with traditional (non IR), same color mortars.

Prototypes samples were tested in lab, by means of spectrophotometer analyses with respect to optical characteristics [36]. The entire spectrum for each sample is visible in Fig. 3, permitting to note the difference in reflectance between cool colored prototypes and traditional, same color samples. This difference is especially visible in the near-infrared part of the spectrum (above 700 nm), while is lower in the visible part, since both cool and traditional samples display the same color. The solar reflectance index (SRI) was then evaluated. For red samples, SRI was equal to 40% for the cool prototype, 28% for the traditional sample. Considering white mortars, cool white samples had a SRI equal to 66%, while same color traditional ones had 53%. Gray mortars showed smaller differences, with cool prototypes SRI equal to 19%, which was 15% for traditional ones. Finally, cool blue samples displayed 50% SRI, traditional ones 45%. With respect to thermal emittance, a portable emissometer was utilized in accordance with standards [38]. There were no significant differences among the samples, which all displayed a 0.88-0.89 thermal emittance.

3.2. Thermal analysis

In order to investigate external surface temperatures due to external environment, a set of simulations ran with HVAC system turned off. 30 and 31st July were selected for the simulation, in order to test the materials in the hottest condition. Results are displayed in Fig. 4, where external surface temperatures were plotted with respect to daily and nightly hours. Each graph allows for the comparison of cool colored and traditional samples, as it was for reflectance analyses in the previous section. In this case, following solar reflectance findings, cool samples were able to maintain lower surface temperatures, especially during the peak hours (13:00-15:00). Differences during the peak were equal to 9.3°C for red samples, 6.2°C for white ones, 2.2°C for gray samples and 1.5°C for blue samples.

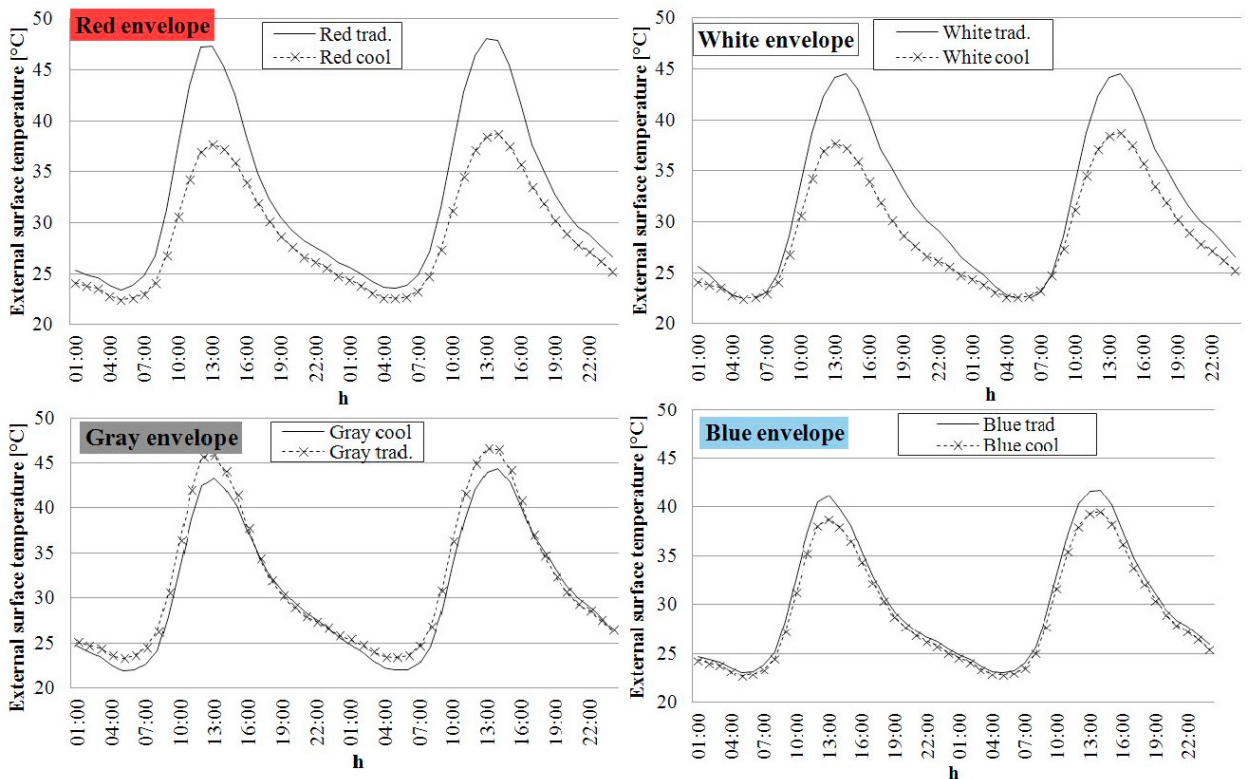


Fig. 4. External surface temperatures for the vertical envelope, 30 and 31st July.

3.3. Energy analysis

To verify case study buildings energy performance, each scenario energy demand was compared with the improved scenarios' ones. Results are reported in Table 3 and Fig. 5 with respect to energy for cooling. For the historical case study (Fig. 5.a), savings vary between 1.7-3.6% depending on the color, when focusing the retrofit only on the envelope (H1). A larger saving is assessed when adding cool tiles on the sloped roof (6.5-8.6%), for scenario H2. Larger savings can be observed for red and white envelopes, since gray mortars are very similar in terms of SRI.

With respect to existing case study (Table 3, Fig. 5), large savings are assessed in E2 scenario, where gravels are applied as cool roof solution (-7.6%), while the reduction in energy consumption due to the replacement of the standard, non-IR doped blue mortar is equal to 0.6% (E1). In this case, as noted for gray mortars, the difference in solar reflectance between standard and optimized mortars was smaller.

Table 3. Energy savings with respect to cooling.

Comparisons	[%]	Comparisons	[%]	Comparisons	[%]	Comparisons	[%]
H1R on H0R	2,5	H1W on H0W	3,6	H1G on H0G	1,7	E1-E0	0,6
H2R on H0R	7,6	H2W on H0W	8,6	H2G on H0G	6,5	E2-E0	7,6
H2R on H1R	5,3	H2W on H1W	5,2	H2G on H1G	4,9	E2-E1	7,1

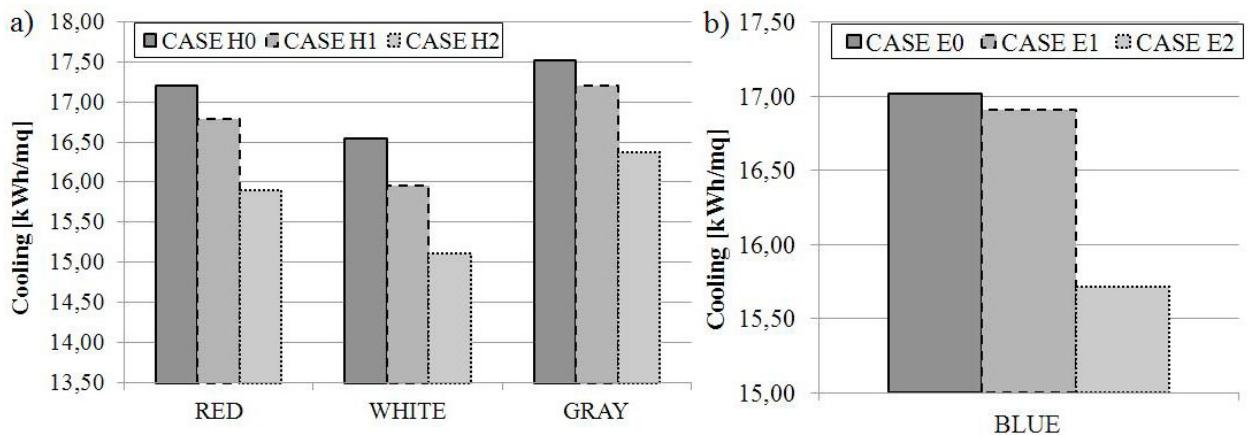


Fig. 5. Cooling energy requirements for each scenario.

4. Conclusions

In this work, cool innovative mortars, developed by the Authors for historical and existing buildings' envelope retrofit, were described. The design process, thermal-optical characteristics and thermal-energy performance when applied both to historical or existing buildings were presented.

The prototypes were compared to same color, non optimized mortars, in order to verify differences in thermal-optical characteristics and consequently in thermal energy performance. In terms of optical characteristics, solar reflectance of optimized samples was significantly higher than same color, traditional samples one, especially in the infra-red spectrum, due to the addition to the mix of infra-red reflecting pigments. In particular, cool red and white samples demonstrated higher solar reflectance than traditional samples, while differences between cool gray and blue and traditional gray and blue samples were lower. This finding was reflected by both the thermal and energy analyses: cool red and white mortar, when applied as historical building envelopes were able to lower energy demand for cooling up to 3.6%. An additional cool passive solution was combined with cool envelope retrofit

strategy, i.e., the application of cool clay tiles replacing traditional tiles. This increased retrofit scenario led to further energy reductions, up to 8.6% with respect to reference scenario.

With respect to existing buildings, the blue cool mortar was applied as first level retrofit option for the envelope, leading to less than 1% energy saving, while cool natural gravels as finishing roof layer, when combined with the cool blue envelope, was able to lower energy for cooling up to 7.6% with respect to reference case.

Therefore, even if behavior as time passes should be verified [9,39], such cool, cost-effective solutions, which are viable for historical and existing buildings, permit to save energy for cooling, while at the same time, as demonstrated by cool materials researches, mitigating UHIE and improving pedestrians thermal comfort when the sky view factor is not limited [35,40].

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