Athens Journal of Technology & Engineering 2024, 11: 1-14
https://doi.org/10.30958/ajte.X-Y-Z

A Methodological Proposal for the Characterization of Building Heritage from the Second Twentieth Century for Renovation Purposes

By Teodoro Georgiadis[*], Letizia Cremonini[±], Daniela Famulari[°], Marianna Nardino[•], Federica Rossi[♦], Cristina Siligardi[♣], Erika Iveth Cedillo-González[♠], Simone Bandini[♥] & Matteo Nasci[×]

With the signing of the SECAPs, European cities and municipalities are taking steps to respond to an energy problem deriving from the demand for summer air conditioning, which, since the early 2000s, has exceeded the demand for winter heating. Sustainable urban regeneration requires action by applying an integrated approach between the sectors and professional figures involved, following the principles of sustainable development. Sustainable construction focuses on reducing the environmental impact of the building industry using renewable and recyclable materials, reducing energy consumption and embodied energy of building materials. The recycling and reusing of waste materials can lead to energy savings, cost reductions, potentially improved products, and reduced waste generation-related hazards to the environment. However, an important consideration when using green construction materials as alternative raw materials is having a thorough understanding of their chemical, mineralogical, and physical properties. This knowledge is essential to ensure that recycled materials can be effectively integrated into materials production without negatively impacting the final product quality or production efficiency. We present here processes developing existing materials which are substantial to ensure the maintenance of that heritage recognized, experienced and enjoyed by the people living a given territory.

Keywords: *global change, urban environment, building materials, building heritage and renovation*

Introduction

The building heritage of the Second Twentieth Century, although recognized as being of cultural interest by the urban planning instrument in force, remains at risk of tampering or demolition as the community of citizens, and particularly the

---

[*]Senior Research Associate, Institute for the BioEconomy CNR, Italy.
[±]Researcher, Institute for the BioEconomy CNR, Italy.
[°]Researcher, Institute for the BioEconomy CNR, Italy.
[•]Researcher, Institute for the BioEconomy CNR, Italy.
[♦]Senior Research Associate, Institute for the BioEconomy CNR, Italy.
[♣]Full Professor, University of Modena and Reggio Emilia, Italy.
[♠]Researcher, University of Modena and Reggio Emilia, Italy.
[♥]Researcher, CERTIMAC, Italy.
[×]Researcher, CERTIMAC, Italy.

properties, do not recognize its cultural value and identity. The main objective of this study is to design the possibility of intervention in this protected heritage, to increase the energy consumption mitigation and environmental adaptation character while respecting the architectural and stylistic language that distinguishes it.

The building restoration should ensure the structural and aesthetic integrity of the existing plasters to maintain their original appearance and chemical-physical characteristics. The mixture and color of the material used must be compatible with the existing ones, so it is necessary to identify an ideal mixture of plaster that does not differ from the original.

The Municipality of Bologna' Building Regulations, approved in the context of the General Urban Plan (PUG), in the "Approfondimenti conoscitivi" - Tavole dei Vincoli (and by the previous RUE in the "Disciplina dei materiali urbani" - art.57). Bologna General Urban Plan recognizes, among the existing building architectural Heritage, the "buildings of interest from the Second Half of the Twentieth Century" in order to take into consideration the material and cultural Heritage matured over the last century. The cataloging has divided the built Heritage of the Twentieth Century based on a chronological criterion: the manufacts built in the period between 1915 and 1949 have been collected in the category of buildings of historical-architectural interest of the Modern, the manufacts after 1949 made up the category of buildings of cultural and testimonial interest of the Second Half of the Twentieth Century. The criterion that led to considering only a few buildings from the last century was based on the classification previously made by the PSC and on the existence of files concerning the buildings drawn up by the MiC (Ministry of Cultural Heritage of Italy) and the IBC (Institute of Cultural Heritage of Italy), which decreed their architectural quality. Furthermore, the buildings restricted by the Superintendency were added after verifying that they had been built in the reference period. It should be noted that since the construction is recent, the danger of tampering and/or demolition is particularly high, as awareness and sensitivity in this regard is left to the owners, as a regulatory limit of intervention does not currently support them. Legislative Decree 42/2004 explicitly excludes from its protection works by living authors or whose execution does not go back more than fifty years (Article 10 paragraph 5), however it seems that it can be protected through the copyright law in as a work of art, but if this law protects a subjective right. It does not seem easily usable in the context of the public interest. It is a question of activating a reflection, also of a legal-regulatory type, as well as on the definition and delimitation of the objects to be protected, on the regulatory instruments to be put in place, possibly exploring new forms that the autonomy of the local authority. This Heritage is recognized but there is no cultural perception of its presence, nor of its cultural relevance, and there is the risk of losing part of it. In fact, in this period of major interventions on the building Heritage, which generally focuses on buildings dating from the 1960s up to today, there is the risk of proceeding with "not respectful" interventions only to increase energy performance in order to respond to mitigating needs of today's city.

To address this issue, we are conducting a study in the Bolognina District (Municipality of Bologna, Italy) an analysis of the materials of the exterior vertical walls of one building identified as of interest from the Second Twentieth Century, characterized by plaster and tiles covering. The objective is to develop cooling materials that, in addition to ensuring higher reflectivity (albedo), can respect the style and architectural language while improving the indoor and outdoor well-being. Such new coatings will not inhibit but rather enhance the thermo-hygrometric exchange between indoor and outdoor, ensuring the physiological well-being of the individual. A methodology is proposed below for the application of new materials with the primary objective of increasing the energy and adaptation performance of the protected building heritage of the second half of the twentieth century, guaranteeing respect for the characterizing architectural/stylistic elements and stimulating the sensitivity of the community to regard. The cool materials were studied to guarantee the high reflexivity (albedo) that characterizes them, can respect the architectural style and language and improve the outdoor well-being of buildings, and improve, if not at least keep unchanged, the indoor one. About indoors, it is understood that these new vertical packages do not alter, but rather tend to improve the thermo-hygrometric exchange between indoor and outdoor environments, guaranteeing the physiological well-being of citizens, with particular attention to the weakest groups.

Materials and Methods

Ceramic Tiles Characterization

Ceramic tiles are building materials that can be easily modified to become solar reflective surfaces because of their high intrinsic thermal emissivity (ε = 0.90), excellent durability over time, and resistance to dirt and fouling due to a topcoat ceramic glaze. Another advantage of ceramic materials is the possibility of obtaining coloured products by ink-jet printing, allowing the fabrication of solar reflective ceramic materials with improved aesthetic characteristics (the so-called cool colours) (Cedillo-González et al. 2022, 2023). These materials present a coloured response in the visible wavelength range and higher SR values than conventional materials of the same colour. Moreover, ink-jet-derived solar reflective tiles increase customization capabilities, making it possible to restore historical buildings without compromising their architectural value.

Conventional solar reflective products are constituted by a support, a reflective basecoat, and an IR-transparent topcoat to protect the basecoat. This configuration recalls the layout of porcelain stoneware tiles, which are fabricated by a layer configuration: the ceramic support (1st layer), the engobe (2nd layer), the digital colouration (3rd layer), and the glaze (4th layer). Following this premise, several authors have designed ceramic tiles with high solar reflectance. For instance, Ferrari et al. (2013) designed glazed ceramic tiles with high solar reflectance (SR = 0.90) by adding $ZrSiO_4$ and TiO_2 to the engobe's formulation. As authors found that the ceramic engobe plays a crucial role in enhancing the solar reflective properties of tiles, Governatori et al. (2021) focused their attention on designing high-reflectance glass-ceramic frits, which are a critical component of the engobe's formulation. In a second work, the same authors investigated the obtainment of solar-reflective ceramic tiles by modifying the engobe's formulation, finding that when a glass-ceramic frit with a high intrinsic SR value is incorporated into the formulation of an industrial engobe, it can raise its albedo (Governatori et al. 2022).

An additional advantage of developing white and coloured solar reflective porcelain stoneware ceramic tiles is that their production allows the incorporation of secondary raw materials (SRMs) in all of their elements: support, engobe and glaze. The use of SRM will lead to additional energy savings during the production process and a reduction of the environmental impact of the final products. However, it is known that ink-jet decoration negatively affects the albedo of tiles prepared with reflective engobes due to its coverage by the inks and their mineralogical composition (Cedillo-González et al. 2022, 2023). For this reason, the albedo of the engobe should be as high as possible to compensate for this reduction by ink-jet decoration. This work produced a set of functional solar reflective engobes using several SRMs such as recycled glasses (four types), chamotte, granite waste, and waste yttria-stabilized zirconia from term spraying processes. The obtained engobes were characterized by CIELab colour (colorimetric model), gloss, optical dilatometry and solar reflectance. Their properties were compared with a conventional engobe of similar chemical composition.

The preparation of functional solar reflective engobes was investigated in three steps using several SRMs such as recycled glasses (photovoltaic glass, screen glass, and two types of urban-derived recycled glass), chamotte, granite waste, and waste yttria-stabilized zirconia (YSZ) from thermal-spraying processes. This study aimed to develop an engobe formulation with enhanced SR property, containing at least 30 wt. % of SRM. First, we conducted a preliminary study where a conventional frit-containing engobe (labelled here as "ESTD") made of conventional raw materials (RM) was modified by replacing 100% of the frit with several types of recycled glass. Additionally, 100% of the quartz and the K feldspar were substituted by chamotte and granite waste, respectively. The second step consisted of the modification of the previous engobe's formulations to reduce as much as possible the total molar content of TiO_2 and Fe_2O_3, as these oxides promote the development of yellow colouration, negatively affecting the SR property. Modifications were performed only for two formulations (as the others were already set at the minimum possible TiO_2 and Fe_2O_3 content) using the software Glaze Master® (Expert System Solutions, Modena, Italy). The third step consisted of adding 5 wt.% or 10 wt.% of a whitening agent in the engobe's formulations that presented the best colour (L^* = brightness), high SR property, and an adequate content of SRM. The aim was to further enhance the SR in anticipation of a reduction of this property when the ink-jet inks cover the engobe during the production of porcelain stoneware tiles (support + engobe + ink-jet decoration + glaze). The whitening agent is an SRM composed of waste YSZ from thermal-spraying processes. Here, the formulations of two selected engobes (those with the best properties) are presented in Table 1, where the number in the formulation's name represents the molar % of TiO_2 and Fe_2O_3 (the sum of the two oxides) that was reduced. The number after the term "Zr" in the formulation's name represents the wt. % of waste YSZ that was added.

Table 1. *Formulations (Expressed as wt.%) of the Selected Functional Solar Reflective Engobes*

RM or SRM	ESTD	EGW27Zr10 (Formulation 1)	EMG14Zr5 (Formulation 2)
Na feldspar	20.00	18.17	41.65
K feldspar	20.00	-	-
Clay 1	15.00	-	-
Whitening 1	8.00	3.91	6.05
Clay 2	7.00	-	7.93
Kaolin	14.00	31.96	22.99
Whitening 2	8.00	7.33	7.92
Quartz	4.00	0.82	0.78
Frit	4.00	4.75	-
Granite waste	-	23.05	5.04
Mixed glass	-	-	2.63
Waste YSZ	-	10.00	5.00

All engobes were prepared according to a standard laboratory protocol. For each formulation, a mixture of 200 g of dry raw and secondary raw materials was placed in a 300 mL porcelain jar, along with 250 g of sintered alumina grinding bodies, 0.3 g of tripolyphosphate, 0.3 g of slurry modifier, and 84 g of tap water. A rapid mill was used to create a consistent slurry from the mixture, with a milling duration of 40 minutes. Two types of specimens were prepared: engobed porcelain stoneware tiles and 40 mm (Ø)-disks of pure engobes. The engobed tiles were used to measure the solar reflectance, gloss and colour (CIELab) properties of the engobes, while the disks-shaped specimens were useful to determine the thermal expansion coefficient ($\boldsymbol{\alpha}$) by optical dilatometry and the shrinkage. To prepare the engobed tiles, the density of the slurry was measured using a 100 mL steel pycnometer and adjusted to a value of 1.65 g/ml. The slurry was then precisely deposited on conventional and fired porcelain stoneware substrate, humidified using an airbrush, with a 0.6mm engobe thickness. The engobed tiles were fired in an industrial kiln utilizing a 50-min cold-to-cold firing cycle suitable for porcelain stoneware, with a maximum temperature of 1205 °C. The remaining mixture was dried at 110 °C for 12 h and ground with a porcelain mortar. The powdered engobes were humidified to 6 wt. % in a closed system for at least 24 h and then pressed at 30 bar to obtain the disk-shaped pressed specimens. After drying at 110 °C for 1 h, the pressed engobes were thermally treated in a laboratory furnace at 10 °C/min up to 1205 °C. An isotherm of 10 min was performed, and the engobes were naturally cooled inside the furnace. The shrinkage of the fired-pressed engobes was measured using a calliper with 0.01 mm resolution.

The brightness parameter (L*) is a significant value that can be related to the SR property: high values usually correspond to high SR. Figure 1 presents the solar reflectance spectra of the selected engobes (3 specimens were measured) from which the solar reflectance (SR) values (presented in Table 2) were calculated.

Figure 1. *Solar Reflectance Spectra of the Selected Engobes from which the Solar Reflectance (SR) Values Were Calculated. (a) Formulation 1 (EGW27Zr10). (b) Formulation 2 (EMG14Zr5)*

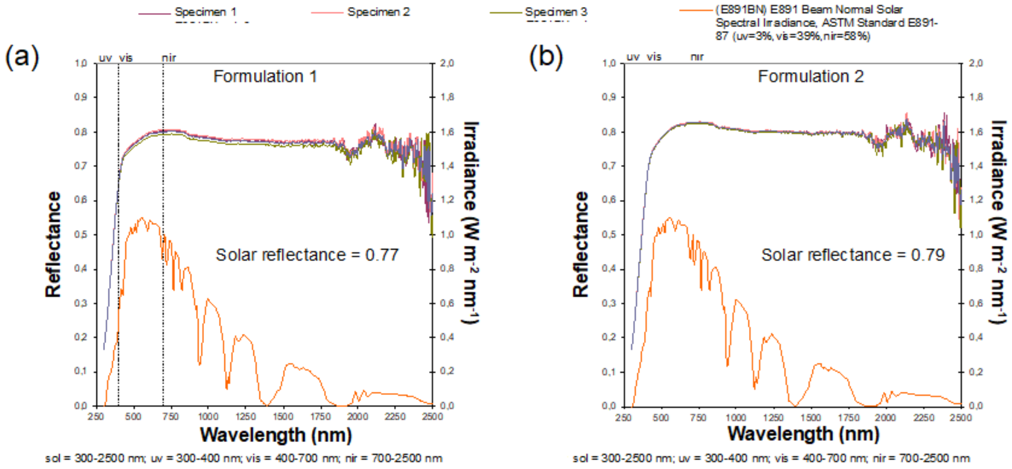


Table 2. *Technological and Aesthetic Properties of the Standard and Selected Engobes*

Formulation	% SRM	Shrinkage (%)	α/1 × 10^7	Gloss (60°)	Colour			SR
					*L**	*a**	*b**	
ESTD	0.0	9.52 ± 0.01	41.36	2.50 ± 0.00	89.3 ± 0.1	0.39 ± 0.04	5.58 ± 0.04	0.769 ± 0.001
Formulation 1	33.1	8.8 ± 0.2	44.15	2.43 ± 0.06	89.7 ± 0.3	0.13 ± 0.04	2.18 ± 0.07	0.771 ± 0.007
Formulation 2	12.7	8.65 ± 0.09	45.11	2.40 ± 0.00	88.9 ± 0.3	0.61 ± 0.02	5.09 ± 0.05	0.794 ± 0.002

The selected engobe formulations with reduced molar % of TiO_2 and Fe_2O_3 and containing 5 and 10 wt. % of the SRM waste YSZ (EGW27Zr10 and EMG14Zr5) present a slightly higher solar reflectance than the standard engobe. This reduced increase in the SR property is likely due to the use of SRM, which intrinsically contains some impurities in their chemical compositions, and those impurities can act as solar radiation absorbers in the final material. Additionally, it is worth mentioning that these formulations can be further improved to increase both the SR and the wt.% of SRM, as the conventional whitening agent and the zirconia raw materials can be further replaced using waste YSZ.

Table 2 presents a selection of the most significant technological and aesthetic properties of the engobes produced in this work. Shrinkage and thermal expansion properties are essential to setting the proper firing conditions for porcelain stoneware tiles. The materials' thermal properties should be compatible with ceramic support and the glaze to avoid deformation or crack formation. On the other hand, gloss and colour are two essential properties that increase the possibilities of industrial application and commercialization of the produced engobes in zero environmental impact buildings and constructions. Notably, in the era of ceramic ink-jet printing, high-quality decorations require engobes with high whiteness and opacity to allow the advantages of ink-jet decoration: the modification in real-time of the decoration patterns, the use of shorter times to change drawings and colours, the opportunity to perform easier testing at lower costs, the increased ability of customization options, the possibility to perform edge-to-edge prints or decorate relief surfaces and a drastic reduction of the amounts of inks compared with the quantities used by traditional decoration systems (Cedillo-González et al. 2022). Table 2 shows that most of the selected engobes present a lower shrinkage value than the standard engobe. The engobes' thermal expansion coefficient ($\boldsymbol{\alpha}$) in the 50 °C – 400 °C interval was measured using the pressed samples. It was found that the produced engobes present $\boldsymbol{\alpha}$ values comparable to that of the standard engobe. The gloss of the engobes was measured on the fired tiles. It is worth noticing that incorporating several SRMs in the engobe formulation does not significantly affect the opacity of the engobes, as the samples presented gloss values comparable to those presented by the standard engobe. The colour was also measured on the fired tiles using the CIELab colour space. As in the case of gloss, incorporating several SRM in the engobe formulation does not significantly affect the colour of the engobes, as most of the samples present L^*, a^* and b^* values comparable to those presented by the standard engobe. Therefore, from the previous results, an important conclusion was derived: an urban-derived mixed recycled glass, granite waste and waste YSZ can be used to modify industrial ceramic engobes formulated with conventional RM without losing the aesthetic characteristics of the engobe.

Built Environment Characterization

The building under study (44°30’50.9” N, 11°20’49.7” E) was the former neighbourhood library (Biblioteca Pelagalli), then nursery school until 2012 – current headquarters of Hex, a coworking association, privately owned and was designed in the year ‘70 by the Architect designer Lorenzino Cremonini (1939-2014) (Figure 2). A microclimate and fluid dynamics analysis of the current context carried out with the ENVImet model during a day characterized by a heat wave, to understand the vulnerabilities present in the vicinity of the building under study. ENVI-met is a three-dimensional non-hydrostatic microclimate model designed to simulate the surface-plant-air interactions within daily cycles in the urban environment with a typical resolution of 0.5 to 10 m in space and 10 sec in time. Several variables can be simulated, included flow around and between building, exchange processes of heat and vapor at the ground surface and at the walls, turbulence exchanges, vegetation parameters, bioclimatology and particle dispersion (ENVI-met, Bruse and Fleer 1998).

Figure 2. *Architect Lorenzino Cremonini (Private Collection)*

A collection of data regarding the construction methods and previous interventions on the historic building and a survey in situ to collect samplings of the coatings (ceramic tiles and plaster) of the vertical masonry packages have been performed. Subsequently, a chemical analysis and mineralogical characterization of the collected material that makes up the package, with particular attention to the external coating was conducted by University of Modena and Reggio Emilia and CERTIMAC.

The new type of coating was studied to guarantee high reflectivity (cool material) and a good response to urban air pollution, even at this stage of the study limited to an increase of 10% of the surface albedo property. Thus, the new building project was characterized by an external vertical cladding made of ceramic tiles highly performing both in terms of reflectivity, sustainability, and resistance to atmospheric pollution.

A microclimate and fluid dynamics analysis of the project status of the building with the ENVImet model, with 1x1 m^2 horizontal resolution, has been conducted to assess in detail the foreseen effects of the new materials.

Figure 3 reports the actual configuration and condition of the investigated building. It is possible to note that the structure has a public or private commercial destination, but not as residential housing. As previously described, the construction period will see in the housing policies of the city of Bologna the need to combine the availability of housing with that of the development of buildings that act as a point of aggregation and socialization of the population.

This building, due to its particular architectural composition, was the object of admiration or strong criticism in those years, because it inserted a strong innovative drive into the city landscape by drawing on other European experiences. This was not an isolated episode, with the passage of time also in other places (for example

Milan, Italy) this new building method became increasingly established, and today it constitutes a large part of the cultural heritage of the entire nation's buildings.

Figure 3. *The Former Neighbourhood Library (Biblioteca Pelagalli), then Nursery School until 2012 – Current Headquarters of Hex, a Coworking Association, Privately Owned*

Table 3 reports the model input data of physical properties for the real tiles (Ex Ante, EA), the simulation performed by changing only the albedo values of tiles incrementing it by a 10% (Ex Post only Albedo, EPA), and the input data of the expected physical characteristics of the new tiles also incremented of 10% in the albedo values and imposed the new emissivity values at 0.90 for all the tiles of various colours (Ex Post Potential, PEP).

This numerical experiment was conducted to verify whether the modification of the albedo alone, which could be carried out with a mere surface treatment, can lead to differences of significant value for the surface temperature, or whether deeper modifications to the structure of the tiles are essential to obtain the desired effects.

Table 3. *Physical Properties Characterizing the External Walls of Biblioteca Pelagalli for Ex Ante (EA), Ex Post Only Albedo (EPA), and Potential Ex Post (PEP) Configurations*

EA	Red	Yellow	Orange	Green	Blue	White
Absorption (shortwave)	0.575	0.420	0.510	0.680	0.800	0.236
Reflection (shortwave)	0.425	0.580	0.490	0.320	0.200	0.764
Emissivity	0.906	0.889	0.900	0.887	0.906	0.879
Specific heat [J/(kg*K)]	770	770	770	770	770	770

Thermal conductivity [W/(m*K)]	1.072	1.072	1.072	1.072	1.072	1.072
Density [kg/m3]	2277.30005	2169.89990	2207.30005	2070.89990	2284.00000	2198.89990
EPA	**Red**	**Yellow**	**Orange**	**Green**	**Blue**	**White**
Absorption (shortwave)	0.532	0.360	0.460	0.640	0.770	0.160
Reflection (shortwave)	0.468	0.640	0.540	0.360	0.230	0.840
Emissivity	0.906	0.889	0.900	0.887	0.906	0.879
Specific heat [J/(kg*K)]	770	770	770	770	770	770
Thermal conductivity [W/(m*K)]	1.072	1.072	1.072	1.072	1.072	1.072
Density [kg/m3]	2277.30005	2169.89990	2207.30005	2070.89990	2284.00000	2198.89990
PEP	**Red**	**Yellow**	**Orange**	**Green**	**Blue**	**White**
Absorption (shortwave)	0.532	0.360	0.460	0.640	0.770	0.160
Reflection (shortwave)	0.468	0.640	0.540	0.360	0.230	0.840
Emissivity	0.900	0.900	0.900	0.900	0.900	0.900
Specific heat [J/(kg*K)]	600	600	600	600	600	600
Thermal conductivity [W/(m*K)]	1.100	1.100	1.100	1.100	1.100	1.100
Density [kg/m3]	2250	2250	2250	2250	2250	2250

Results and Discussion

The building was represented, in the three cases (EA, EPA, PEP) (EA), without the buildings actually present in its surroundings in order to see the maximum effect of the albedo variation. It was decided to maintain the vegetation close to the north façade in order to verify its possible influence. The most detailed cell resolution in ENVI-met is 1x1 m^2. Because of the complex chromatic design developed with the tiles that characterizes the building's facades, a simplification was necessary also to represents all the colours present in each single façade.

In Table 4 are reported the values of the wall temperatures obtained in EA, EPA, and PEP simulations for each colour tile in south façades. In the specific case of our simulation, a wish-list was adopted on the physical properties of the materials which unified the density values at 2250 kg/m^3 and increased the thermal conductivity for all from 1,072 to 1,100 W/mK. Furthermore, the emissivity values were standardized to 0.9.

Table 4. *Outside Wall Temperature Values Obtained by Envi-met Simulation for Ex Ante, ex post Only Albedo, and Potential Ex Post Scenarios for Each Colored Tile*

Hour	Parameter	Facade and color tile	EA	EPA	Comparison EA-EPA	PEP	Comparison EA-PEP
2:00 p.m.	T wall outside	Sud-blue (1)	61.71 °C	60.74 °C	- 0.97 °C	64.29 °C	2.58 °C
2:00 p.m.	T wall outside	Sud-blue (2)	58.32 °C	57.41 °C	-0.91 °C	60.58 °C	2.25 °C
2:00 p.m.	T wall outside	Sud-white (3)	40.78 °C	38.41 °C	-2.37 °C	39.19 °C	-1.59 °C
2:00 p.m.	T wall outside	Sud-white (4)	45.10 °C	42.61 °C	-2.49 °C	43.89 °C	-1.21 °C
2:00 p.m.	T wall outside	Sud-green (5)	56.74 °C	56.64 °C	-0.10 °C	56.80 °C	0.06 °C
2:00 p.m.	T wall outside	Sud-red (6)	53.55 °C	52.22 °C	-1.33 °C	54.78 °C	1.22 °C
2:00 p.m.	T wall outside	Sud-orange (7)	49.99 °C	48.49 °C	-1.50 °C	50.23 °C	0.24 °C

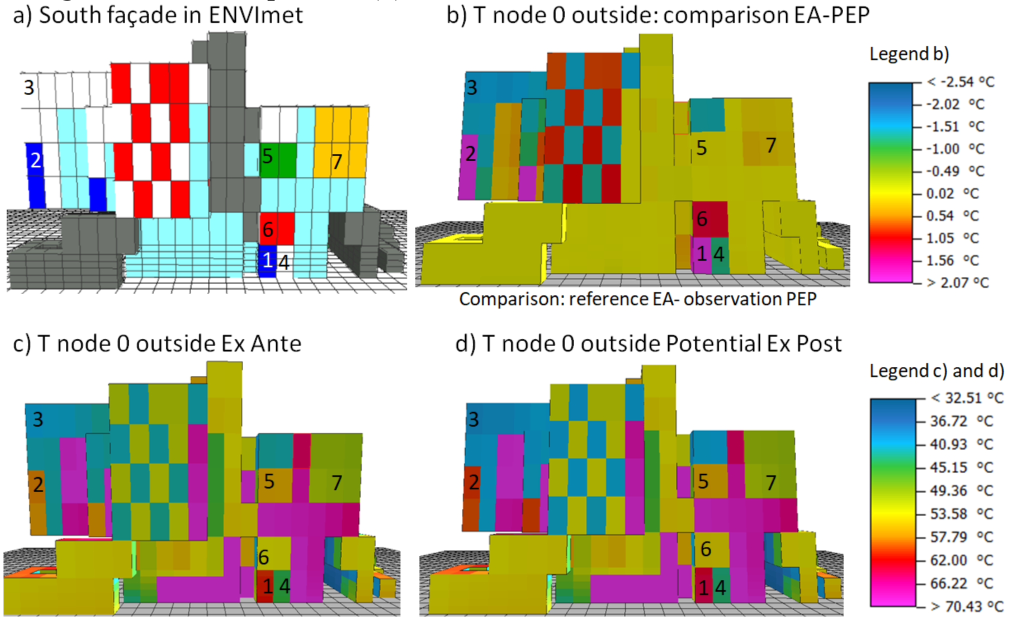
While maintaining the same structural characteristics for the tiles, and changing only the albedo increasing it by 10%, the decrease in the surface temperatures is well evidenced for all the various colours, for the simulation where the physical properties were changed a very different behaviour have been obtained.

The outside wall temperature of improved blue tile at 2 p.m. shows a higher surface temperature (up to 2.58 °C). This can be explained throughout Figure 4 that shows that the tile 1 is very close to the surface so, probably, it is influenced by the radiant temperature emitted by the floor. The other blue tile (2 at 6m height) shows an increment of 2.25°C.

The white tile is the only one that shows an effective cooling of the wall of about -1.59°C near the walking surface and -1.21 °C at about 11 m height. The green tile does not show differences in the wall temperature (0.06 °C) while the red tile shows a warming of the wall surface (1.22 °C).

Some of these results for EA and PEP comparison appear to be counterfactual, that is, the current result appears to conflict with what was reasonably expected. In Figure 4 is reported the complexity of the facade in terms of tile colouring is reported. However, in our modelling simplification we have included the characteristics on the ground coverage and, therefore, the simulation is also affected by this contribution, which differs at different heights of the building. This turns out to be a confounding effect on the results which would require an analysis in the laboratory, in controlled conditions, a turning point developed tiles trying to magnify the effects without however exceeding in the performances the current limitations foreseen by the urban regulations, such as for example those linked to potential glare effects at the street level. Thus, the evaluation work is still ongoing in parallel to the lab development of the new materials and will be followed through other deliverables within ECOSISTER Programme. From the same case study, the ageing effects of the ceramic tiles will be evaluated, to aid advising the industrial production on increasing materials resilience for weathering and air pollution in an urban context.

Figure 4. *Composition of the South Façade of the Building (a) and the Outside Wall Temperature Obtained by the Model for EA (c) and PEP (d) Simulations Along with their Comparison (b)*



What clearly emerges from the simulation is that the renovation of the tiles in buildings belonging to the cultural heritage needs detailed studies on the structural composition of the materials, as their physical properties, if not carefully calibrated, can give rise to effects that conflict with the desired results.

Conclusions

From the comparison made, the thermal excursion of PEP tiles in the temperature on the facade leads to a range of approximately 4.5 °C. The change in the albedo of the material can influence the thermal regime of the building but is not possible to evidence an effect on the well-being outdoor, except for possible glare phenomena which can cause high albedo values of the surfaces, including walls. Furthermore, it was found that the variation of the albedo alone produces very small effects already at a superficial level and, therefore, significant effects on the outdoor environment is reasonable to exclude, even possible research developments may concern new simulations in ENVI-met gradually increasing the albedo to understand the most performing threshold values for each colour, to be able to give indications to the production sector.

At present, utilising the simulated values for the potential new tiles a limitation to only 10% in the albedo value it is debatable it can influence significantly the outdoor environment, as other authors already pointed out, even more studies are necessary to understand if the internal building energy consumption will be positively affected by the innovation (Fabbri et al. 2020, Lopez-Cabeza et al. 2022). As Lee and Mayer (2018) clearly outlined, higher albedo of the building walls causes an increase of mean air temperature and mean irradiance temperature, influencing the PET (Physiologically Equivalent Temperature) values, thus reflecting in a certain decrease of outdoor comfort (Matzarakis et al. 1999). While the increase in indoor thermal comfort is uncontroversial, the effects on the outdoor thermal values has to be specifically investigated case by case.

In our modelling experiment, some limitations to the performed modelling study are due to the oversimplification of the external fabric texture (i.e. surrounding buildings and pavements). As reported in Fabbri et al. (2020), the role of paved surfaces has a much more relevant influence on external comfort compared to the one due to the facades. However, the latter must be part of an overall review of the entire urban regeneration system, because it can provide a contribution, even if limited but, above all, it can contribute to preserving the identity of the places and the value system of the cultural heritage of the resident population.

Acknowledgments

This study was funded by Ecosystem for Sustainable Transition in Emilia-Romagna (Ecosister). Progetto PNRR Programma di Ricerca e Innovazione – CODE ECS0000003 NextGenerationEU, Piano Nazionale di Ripresa e Resilienza (PNRR) – Missione 4 Componente 2.

References

Bologna General Urban Plan. Available at: http://dru.iperbole.bologna.it/pianificazione/profilo-e-conoscenze-approfondimenti-conoscitivi. [Accessed 4June 2024]. (In Italian).

Bruse M, Fleer H (1998) Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model. *Environmental Modelling and Software* 13(3–4): 373–384.

Cedillo-González EI, Governatori M, Ferrari C, Siligardi C (2022) Solar reflective ink-jet printed porcelain stoneware tiles as an alternative for Urban Heat Island mitigation. *Journal of European Ceramic Society* 42: 707–715.

Cedillo-González EI, Governatori M, Siligardi C (2023) Highly reflective engobes for ink-jet printed coloured porcelain stoneware tiles (CO-2:L05). *Ceramics International* 49(14-PART B): 24259–24267.

ENVI-met. Available at: http://www.envi-met.com/. [Accessed 4 June 2024].

Fabbri K, Gaspari J, Bartoletti S, Antonini E (2020) Effect of facade reflectance on outdoor microclimate: an Italian case study. *Sustainable Cities and Society* 54: 101984.

Ferrari C, Libbra A, Muscio A, Siligardi C (2013) Design of ceramic tiles with high solar reflectance through the development of a functional engobe. *Ceramics International* 39(8): 9583–9590.

Governatori M, Ferrari C, Manfredini T, Siligardi C (2021) Preparation and characterization of glass ceramic frits with high solar reflectance. *Open Ceramics* 6(Jun): 100091.

Governatori M, Cedillo-González EI, Manfredini T, Siligardi C (2022) Solar reflective properties of porcelain tiles for UHI mitigation: effect of highly reflective frits in the engobe's formulation. *Materials Today Sustainability* 20(Dec): 100255.

Lee H, Mayer H (2018) Thermal comfort of pedestrians in an urban street canyon is affected by increasing albedo of building walls. *International Journal of Biometeorology* 62(7): 1199–1209.

Legislative Decree 42/2004. Available at: https://www.bosettiegatti.eu/info/norme/statali/2004_00 42.htm. [Accessed 4 June 2024]. (In Italian).

Lopez-Cabeza VP, Alzate-Gaviria S, Diz-Mellado E, Rivera-Gomez C, Galan-Marin C (2022) Albedo influence on the microclimate and thermal comfort of courtyards under Mediterranean hot summer climate conditions. *Sustainable Cities and Society* 81: 103872.

Matzarakis A, Mayer H, Iziomon M (1999) Applications of a universal thermal index: physiological equivalent temperature. *International Journal of Biometeorology* 43: 76–84.