Acta Polytechnica CTU Proceedings **33**:200–206, 2022
https://doi.org/10.14311/APP.2022.33.0200

Published by the Czech Technical University in Prague

TECHNICAL EFFECTIVENESS OF CEMENT-BASED MORTAR FOR HIGH-REFLECTIVE BUILDING ENVELOPE THROUGH BUILDING ENERGY SIMULATIONS: PRELIMINARY RESULTS

Alessandra Gugliandolo[a,*], Enrico Genova[a], Francesco Baldi[a], Claudia Capone[b], Maria Anna Segreto[a]

[a] *ENEA, Energy Efficiency Unit Department (DUEE), via Martiri di Monte Sole 4, 40129 Bologna, Italy*
[b] *Italcementi SpA, via Stezzano 87, 24126 Bergamo, Italy*
[*] corresponding author: alessandra.gugliandolo@enea.it

Abstract. In areas with high levels of solar radiation, decreasing the amount of solar energy absorbed by the building envelope is useful to reduce the need of air conditioning and "heat island" effects. Most high-reflective products, however, suffer from low durability. The COOL-IT project is developing an innovative high-reflective cement based mortar for precast products to be used as outer layer in buildings for both vertical and horizontal surfaces, or for road pavement. The mix design is aimed at increasing the durability of this cement-based component while retaining high reflectance to solar radiation. This paper presents the preliminary results of the project, based on the simulation of the energy demand of a residential building, intended as a support to optimize the proposed mixes. The model is analysed in three different locations in Italy, for one year of operation. This allows evaluating the trade-off of the energy demand between the winter increase and the summer reduction.

Keywords: Building energy demand, building envelope, cool material, energy efficiency, high reflectance.

1. Introduction

Urban areas are characterized by high density of built surfaces, which generally are low reflective and low permeable. This modification of land surface results in higher air temperature compared to the surrounding rural areas, with differences up to 3°C. This phenomenon, normally referred to as Urban Heat Island (UHI), increases the energy needs and consumption for summer cooling, thus contributing to global warming. The UHI can be countered through the implementation of so-called "cool" technologies. A "cool material" is characterized by high solar reflectance (thereafter denoted also as "albedo") and high infrared emissivity, where the first is the ability to reflect incident solar radiation, and the second allows to return most of the fraction to the atmosphere solar absorbed by thermal radiation. Several technical solutions have been developed for the construction sector, especially in outdoor pavements but also in the building envelope [1–3]. Also in the latter, the most common application field of cool materials is in horizontal surfaces, where the solar radiation peak is reached in the summer season.

2. State of Art

The large use of cement-based pavement products highlights that increasing their solar reflectance may result in a significant mitigation of the heat island effect and in the improvement of urban comfort. Furthermore, the diffusion of cement-based products in building roofs and walls, namely tiles and concrete façades, suggests that the solar reflectance of cement-based components can play a relevant role in reducing the energy demand for building cooling. Mainly related to pavements, researches in this field characterize the albedo of concretes and their constituents or focus on developing methods and technologies to obtain high reflective cement-based products.

Solar reflectance values of 0.35 − 0.40 and 0.25 − 0.30 are considered typical for new and weathered concretes respectively, if conventional mixes are used [4].

Levinson and Akbari [5] studied the effects that composition and exposure of Portland cement concrete have on its solar reflectance. They noticed that concrete albedo grows during the cement hydration reaction but stabilizes after six weeks from casting. The concretes were on average more reflective if produced by means of white than grey cement. The authors also observed a correlation between the composition of concrete and its solar reflectance, which was influenced by cement albedo, fine aggregate albedo and, after abrasion, also by the solar reflectance of coarse aggregates.

Marceau and VanGeem [6] widened the base of available data by measuring the solar reflectance of concrete constituent materials (Portland and slag cements, fly ash, fine aggregates) and concrete specimens comparable to those commonly used in exterior flatwork. Designed with combinations expected to result in low albedo, the concrete specimens showed a minimum solar reflectance of 0.34 and a maximum of 0.64 up to 0.69, with an average value of 0.47. The authors highlight that the influence on concrete albedo is more relevant for cement than for the other constituents and confirm that the higher the solar reflectance of cement, the higher that of concrete.

Since albedo is related to the product surface, a way to increase this property in cement-based components consists in surface treatments of conventional mix designs, generally by the addition of pigments or the application of coatings. Several solutions have been developed for the building sector, generally related to roof tiles and shingles [7, 8]. In the refurbishment of existing constructions, acting on the finishing is appropriate to reduce costs and technical barriers to the boost of albedo. However, the enhancement of solar reflectance can be irreversibly decreased by aging processes, especially in case of abrasion and surface damages. The effects of ageing on the solar reflectance of building envelope materials are object of investigation [9–11].

On the other hand, different studies aim at increasing the solar reflectance of concrete by acting on its composition. For this purpose, the partial substitution of the binder, the use of white cement and the incorporation of lightly coloured aggregates are mainly investigated. It has been observed that fly ash reduces albedo with respect to conventional mixes, without a consistent trend [4]. On the contrary, the solar reflectance of concrete increases consistently with the content of ground-granulated blast furnace slag, which appears to be even more effective than the use of white sand and latex [4].

Besides the ratio of binder replacement, the type of aggregates and the surface finish, also curing conditions influence the solar reflectance of hardened concretes. Recent research has observed that solar reflectance increases if the moist level of curing conditions is higher, with more marked difference if the water-to-cement ratio increases [12].

3. Objective

The research herewith discussed investigates the use of building and urban simulations as a support tool to design innovative high-reflective cementitious mortars to be used on the building envelope. More in detail, the aim is optimizing the use of "cool materials" as constituents of cementitious mixtures. Different from surface treatments and curing treatments, this solution affects the building product, namely a precast tile or panel, in all its thickness. Consequently, the solar reflectance, which is a surface property, is kept in the long term.

Optimization is necessary because not only the "cool material" but also the other constituents of the mix influence the albedo. Furthermore, combination with the effects of mix design strategies described in the literature should be explored, in order to amplify the enhancement of solar reflectance.

The focus of the preliminary investigation presented in this paper, based on building simulations, is on assessing benefits and criticalities of the developed products - whose albedo varies in a range - in terms of building energy demand for heating and cooling, depending on geographic location, climatic conditions and urban density.

4. Materials and method

4.1. Design and characterization of cementitious "cool" mortars

Innovative precast tiles (40 × 40 or 40 × 60 cm, 2 or 3 cm thick), suitable for both horizontal and vertical application on the building envelope, were produced using high-reflective cementitious mortars. The mixes included "cool" binders or "cool" additions, both based on commercial static cool materials (CM). These CMs increase the attitude of the mortars to reflect radiations in the total solar spectrum, with high efficacy in near-infrared region (NIR, with wavelengths between 700 and 2500nm), where about 50 % of solar radiation falls. The compatibility of these inorganic CMs with the alkaline pH of cementitious matrix was verified.

White and coloured traditional mortar tiles surfaces were prepared by means of a high-fluidity matrix, made of white cement CEM I 52.5R, calcareous sands 0 − 2 mm, superplasticizer, shrinking-reducing and water-proofing agents. For the cool cementitious tiles manufacture, a cool binder, made up of selected cement and cool materials proportions, is premixed, before the addition to the other recipe ingredients. After mixing in a planetary−type mixer, the cementitious mortar is cast in vertical moulds. After 24h−demoulding, the tile is kept in a conditioned room at 20°C and 55 % RH.

At fresh state, rheological behaviour of different preparations was mainly monitored through the fluidity characterization over time (EN 7044 standard), e.g. higher than 280 mm up to 30 min. At hardened state, compressive (> 54 MPa at 28 days) and flexural strengths (> 9 MPa at 28 days) were characterized according to EN 196-1. Hydraulic shrinkage resulted in $-500\,\mu$m/m after 28 days (EN 12617 standard). Preliminary promising durability tests were performed in compliance with EN 12380-8, EN 13295, EN 11164, EN 13687-1 standards.

Solar reflectance was measured according to the standards ASTM E903-12 and ASTM G173-03, by means of a UV-Vis-NIR spectrophotometer with 150 mm integrating sphere. Improved optical properties were assessed calculating the increase in solar reflectance of cool cementitious tiles compared with white/coloured control samples, ranging from 0.10 − 0.40(grey surfaces) to 0.60 − 0.81 (white surfaces). By way of demonstration, Figure 1 shows typical solar reflectance spectrum of experimental cool mortars compared with relative white and grey ref-

Reflectance	Cool Surface	Neighbouring buildings
0.30 – 0.80	Walls	No
0.30 – 0.80	Walls	Yes
0.30 – 0.80	Roof	No
0.30 – 0.80	Roof	Yes
0.30 – 0.80	Walls + Roof	No
0.30 – 0.80	Walls + Roof	Yes
0.40	Walls + Roof	Yes
0.50	Walls + Roof	Yes
0.72	Walls + Roof	Yes
0.76	Walls + Roof	Yes

TABLE 1. List of building simulations for each location.

erences w/wo CM. It is worth noting that the cementitious solutions with cool materials enlarge the current possibilities of application for coloured/grey surfaces more significantly than for the white ones: the former improve the solar reflectance of the relevant reference in the entire wavelength range, with high benefits in NIR region; the latter show more limited enhancement margins, despite the CM addition, being themselves high-reflective surfaces.

Accelerated and natural aging tests are in progress.

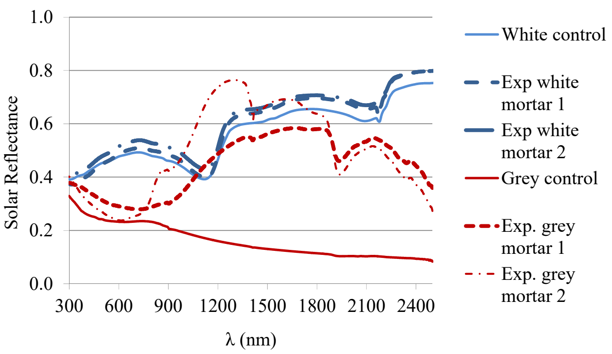

FIGURE 1. Solar reflectance of experimental white and coloured high-reflective mortars compared with the relevant matrix without cool materials.

4.2. METHODOLOGICAL APPROACH

The analysis of the effects that the use of the proposed cementitious products has on the energy performance of residential buildings is based on the numerical modelling and simulation of a reference building. The use of a numerical approach allowed performing an in-depth study of the different performance indicators of interest for the subject, and applying it to different locations, and to different material properties.

The performance of the material is assessed based on the following performance indicators:

- increase in winter energy demand;
- decrease in summer energy demand;
- total energy balance, after conversion to tonnes of oil equivalent (toe);
- difference in operational costs, which also takes into account the different tariffs for electricity (main energy vector for summer cooling systems) and natural gas (energy vector for winter heating systems in the reference building).

The present study is focused on the impact of the technology at building level, hence excluding the impact of the proposed material on the local climate. As the shading effect generated by neighbouring buildings can have a relevant size [9], the difference between the cases with, and without, neighbouring buildings is considered.

The following procedure was designed: first, the performance of the building was simulated with generic, increasing values for the surface reflectance of the building surface material, allowing to get a better understanding of the effects of surface reflectance (r) on the building's energy performance. To this scope, different simulations were performed to consider the effects of applying the material on the roof only, on vertical opaque surfaces only, or on both. Then, the analysis focused on two main scenarios: the use of a relatively dark material ($r = 0.4$), and of a white material ($r = 0.72$); in both scenarios, the performance of the "standard" material was compared to that of the proposed one, characterized by a higher surface reflectance ($r = 0.5$ for the dark material, $r = 0.76$ for the white one). These values were provided by the material manufacturer, based on internal laboratory tests. The full list of simulations performed for each location considered in this study is provided in Table 1.

The study was performed using EnergyPlus [13] together with DesignBuilder [14] as graphical user interface (Figure 2). The description of the building and of the inputs to the model is provided in the following section. The main parameter that varied across the different simulations is the "solar absorbance", which controls the share of solar radiation that is absorbed by the material surface. As the material under study is opaque, it was assumed that $r + a = 1$.

4.3. Reference building

Morphology, size and construction features of the reference residential building were based on the 2011 Italian general census on population and housing [15]. From this data, it emerges that the most representative period of the national residential stock is the decade 1971 − 1980. In the top ten Italian towns for population, the census shows that residential buildings are generally made of at least four storeys and sixteen dwellings. To define the building model, therefore, it was assumed that:

- the building has 6 floors and is equipped with a single staircase, serving three building units per floor;
- the dimensions of the building are 30 m × 12 m;
- each housing unit has a usable area of 90 m^2, while the stairwell has an area of 30 m^2; including walls, the gross floor area of each storey is 360 m^2; the internal height is 2.70 m;
- the roof is flat.

It was assumed that the two minor façades of the building face North and South respectively; the stairwell faces East and is considered to be an "unconditioned" thermal zone (Z1). For each floor, every apartment is considered as a single thermal zone (Z2, Z3, Z4). The external walls don't have overhangs and shielding.

According to the UNI 10339 standard, evaluations were conducted to ensure appropriate thermo-hygrometric conditions, air changes and comfortable occupational conditions. Two density values of different occupations were assigned between the apartments and the stairwell.

From the point of view of the model construction, the building is composed of 6 overlapping blocks (30 m × 12 m). Each block is divided into four parts, representing the three floor housing units and the stairwell.

The building model is referred to the building techniques commonly used in Italy in the 1971 − 1980 decade (UNI/TR 11552:2014). It was assumed that the building structure is a reinforced concrete frame, that is, the most widespread solution in Italian residential construction after the Second World War. The external walls of the reference building consist of a single layer of perforated bricks (medium perforation), plastered on both sides, with a total thickness of 35 cm. The floor slabs, made of concrete beams and clay blocks, are 30 cm thick.

The windows have an aluminum frame without thermal break and a 4−mm double glass with 12−mm air gap. Roller shutters (with a box emerging from the inner side of the wall) are used as shielding system. For each building unit, the window area is equal to 1/8 of the floor area, which is the minimum allowed by the Italian building regulation.

The energy systems of the reference building chosen for this study were defined with reference to a "standard" building built in the 1970s. The systems in the building are, therefore, the following:

- centralized heating system (natural gas boiler) with radiators;
- centralized hot water generation system (DHW, natural gas boiler);
- decentralized systems for summer air conditioning, based on a compression refrigeration cycle.

The energy performance of the reference building was simulated in dynamic conditions in three Italian cities, located in the Northern (Bologna), Central (Rome) and Southern (Palermo) part of the country. The energy demand of the building was simulated over the time of one year. The weather data (in the form of an .EPW file) used in the simulation was a representative average of climatic data gathered in the 2003 − 2017 period.

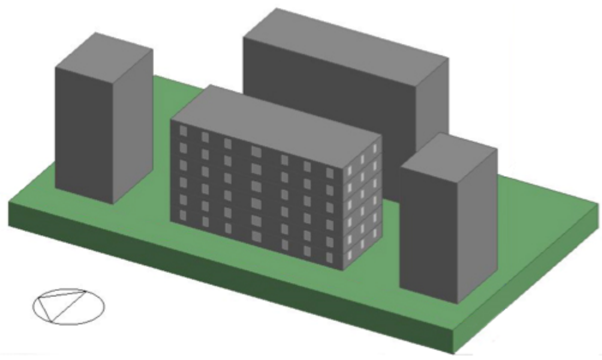

Figure 2. Building model and neighbouring buildings in the graphical user interface. Orientation is specified on the lower left.

5. Results and discussion

The results of the parametric analysis carried out in this research, collected in Table, show the influence that increasing the solar reflectance of different envelope components has on the overall building energy demand for heating and cooling. From this energy perspective, only the application to the case of Palermo appears to be beneficial, as it is the only one where the benefits during the cooling season outweigh the losses during the heating season. The reason behind this effect can be better understood looking at Figure 3, where the yearly energy demand for winter heating and summer cooling is shown for the three locations: both in Bologna and in Rome, the gas demand for heating is much higher than the electricity demand for cooling in summer, while difference shrinks in the case of Palermo. The tendency for the costs is similar to that for energy demand, as expected; as a general trend, the cost per toe is lower for electricity than for natural gas (840 EUR/toe and 1030 EUR/toe, respectively). This works against the use of high-reflectance surface materials, as it increases the weight of the natural gas

	Reflectance	NG (winter)			EL (summer)			Total	
	[-]	[kWh/y]	[toe/y]	[€/y]	[kWh/y]	[toe/y]	[€/y]	[toe/y]	[€/y]
Bologna	0.40	173208	12.58	12962	5823	1.46	1223	14.04	14185
	0.50	175466	12.75	13131	5270	1.32	1107	14.06	14238
	0.72	180548	13.11	13512	4043	1.01	849	14.13	14361
	0.76	181505	13.18	13583	3832	0.96	805	14.14	14388
Roma	0.40	114342	8.31	8557	5155	1.29	1083	9.59	9640
	0.50	116872	8.49	8746	4528	1.13	951	9.62	9697
	0.72	122660	8.91	9179	3182	0.80	668	9.71	9848
	0.76	123747	8.99	9261	2949	0.74	619	9.73	9880
Palermo	0.40	44164	3.21	3305	6994	1.75	1469	4.96	4774
	0.50	45569	3.31	3410	6102	1.53	1281	4.84	4692
	0.72	48858	3.55	3656	4230	1.06	888	4.61	4545
	0.76	49485	3.59	3703	3906	0.98	820	4.57	4524

Table 2. Results of simulation: primary energy demand (NG = natural gas; EL = electricity).

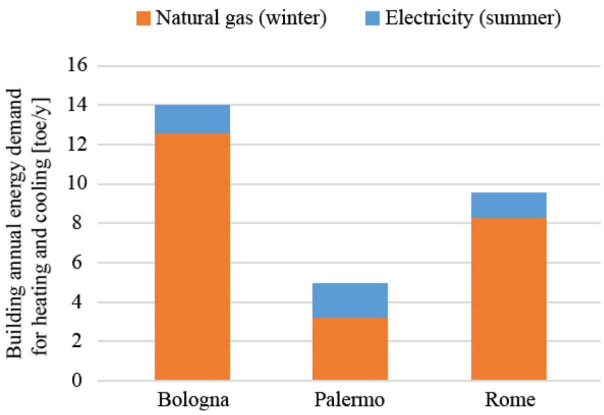

Figure 3. Annual energy demand for winter heating and summer cooling of the reference building, without "cool" cementitious tiles, for the three simulated locations.

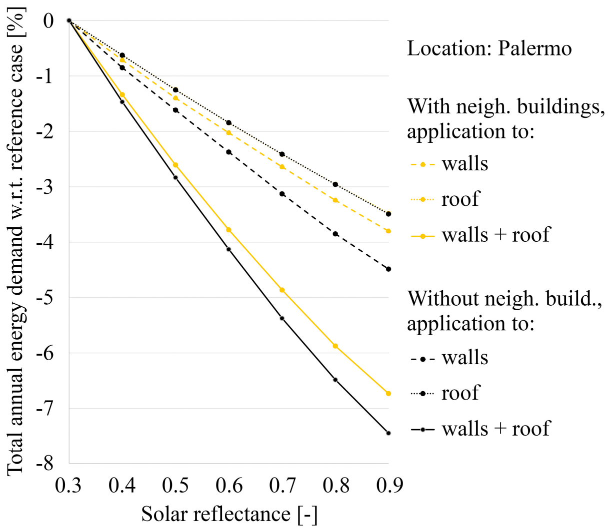

Figure 4. Influence of neighbouring buildings on the effects that the "cool" cementitious tiles would have on the annual energy demand of the reference building in Palermo.

demand, which increases when using these materials. Consequently, the results of the simulations carried out on the reference building highlight that the use of high-reflective products, such as those developed in this research, might be more successfully implemented in hot-summer climate conditions.

Figure 4 shows the effect of the presence of neighbouring buildings in the case of Palermo. As expected, differences are negligible if the "cool" product is used as roof covering, while the shades casted by neighbouring buildings reduce the benefits of the high-reflective wall, thus making it less effective. Furthermore, in case the "cool" product is used on the vertical envelope, the overall energy demand increases in presence of neighbouring buildings. For the reference building, they appear to enhance the criticalities of high reflectance during the heating period than the benefits during the cooling season. The results for the specific application to the four "realistic" scenarios chosen for this study are shown in Figure 5, which confirms the same tendency: increasing the surface reflectance is only convenient for the case of Palermo, where the natural gas demand for winter heating is low (close to one fourth of the demand in Bologna). Moving from a "standard" dark cover to a "high-reflective" one, the electricity demand for cooling is reduced by approximately 13 %, while the total energy demand (expressed in toe) is reduced by 2.5 %.

6. Conclusions and further developments

In this work, dynamic energy simulations of a building model were used to develop a support tool, with the aim of optimizing the design and testing of precast tiles for the building envelope based on new high-reflective (i.e. with enhanced NIR-reflective characteristics) cementitious constituents. The effects of different tiles on the energy demand of a reference building were evaluated in three Italian locations. The preliminary results showed that the use of high-

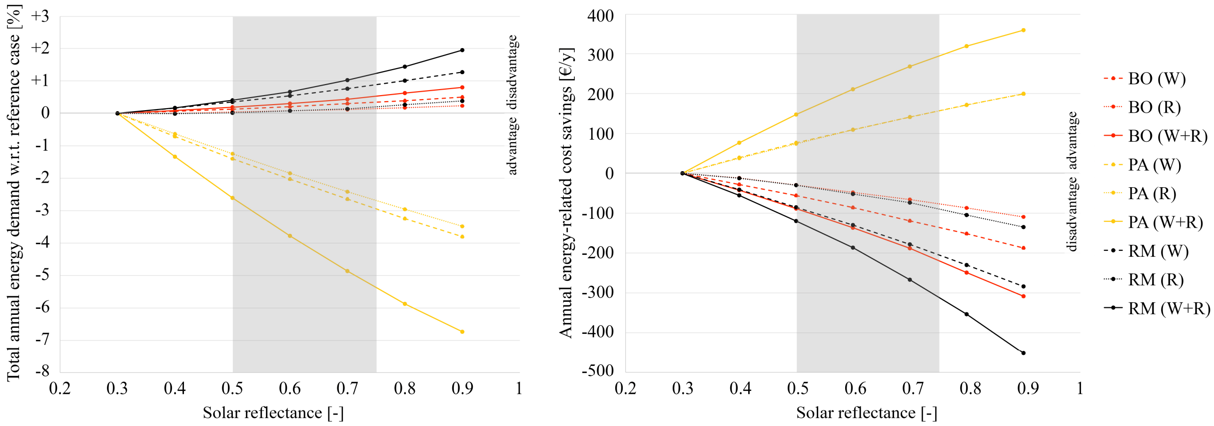

Figure 5. Annual energy demand of the reference building and related cost savings according to location (BO = Bologna, PA = Palermo, RM = Rome), treated envelope components (W if only walls, R if only roof, W+R for both) and solar reflectance of the "cool" product. In grey the range between the albedo of the high-reflective dark material ($r = 0.5$) and that of the white one ($r = 0.76$).

reflective cementitious products might be more successfully implemented in hot-summer climate conditions, where natural gas demand in winter season does not offset the electrical energy saving in building air conditioning expenditures. In the simulations performed for this work, this corresponded to the case of Palermo.

Future analysis needs to be broadened in terms of location and building features. On the one side, locations representative of a wider variety of climate conditions (within Italy and in other Mediterranean countries) will be considered. On the other side, building orientation will be included as a parameter for simulations. Furthermore, different building types must be investigated, since the building use affects the morphology of the envelope (especially the ratio between roof and wall surfaces) and the energy demand for heating and cooling.

Improving the building model could support the cost-benefit analysis of cooling materials in order to design more performing cementitious mortars. Not carried out in this early stage of this research, the economic assessment should take into account both the investment cost of the "cool" material to be used in the mix and the variation in the operational costs for the building use. From this perspective, the parametric curves based on the building model will help in integrating the economic evaluation of the developed products with the effects of long-term aging on their solar reflectance.

Acknowledgements

This paper is related to the industrial research and the experimental development performed in the framework of the Italian project COOL-IT, funded by the Italian Ministry of Economic Development (Ricerca di Sistema Elettrico Nazionale).

The authors thank Eng. A. Cacciatore from Italcementi for the valuable contribution to the research and application activities carried out in the Innovation Laboratories.

References

[1] M. Santamouris. Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments. *Renewable and Sustainable Energy Reviews* **26**:224-40, 2013. `https://doi.org/10.1016/j.rser.2013.05.047`.

[2] A. Pisello, F. Rossi, F. Cotana. Summer and Winter Effect of Innovative Cool Roof Tiles on the Dynamic Thermal Behavior of Buildings. *Energies* **7**(4):2343-61, 2014. `https://doi.org/10.3390/en7042343`.

[3] I. Hernández-Pérez, G. Álvarez, J. Xamán, et al. Thermal performance of reflective materials applied to exterior building components - A review. *Energy and Buildings* **80**:81-105, 2014. `https://doi.org/10.1016/j.enbuild.2014.05.008`.

[4] K. Boriboonsomsin, F. Reza. Mix Design and Benefit Evaluation of High Solar Reflectance Concrete for Pavements. *Transportation Research Record: Journal of the Transportation Research Board* **2011**(1):11-20, 2007. `https://doi.org/10.3141/2011-02`.

[5] R. Levinson, H. Akbari. Effects of composition and exposure on the solar reflectance of portland cement concrete. *Cement and Concrete Research* **32**(11):1679-98, 2002. `https://doi.org/10.1016/s0008-8846(02)00835-9`.

[6] M. L. Marceau, M. G. Vangeem. Solar reflectance values for concrete. *Concrete International* **30**(8):52-8, 2008. `https://www.cement.org/docs/default-source/fc_concrete_technology/sn2982a-solar-reflectance-values-of-concrete.pdf`.

[7] R. Levinson, P. Berdahl, H. Akbari, et al. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. *Solar Energy Materials and Solar Cells* **91**(4):304-14, 2007. `https://doi.org/10.1016/j.solmat.2006.06.062`.

[8] R. Levinson, H. Akbari, P. Berdahl, et al. A novel technique for the production of cool colored concrete tile and asphalt shingle roofing products. *Solar Energy Materials and Solar Cells* **94**(6):946-54, 2010. https://doi.org/10.1016/j.solmat.2009.12.012.

[9] R. Paolini, M. Zinzi, T. Poli, et al. Effect of ageing on solar spectral reflectance of roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs of commercial buildings. *Energy and Buildings* **84**:333-43, 2014. https://doi.org/10.1016/j.enbuild.2014.08.008.

[10] R. Paolini, G. Terraneo, C. Ferrari, et al. Effects of soiling and weathering on the albedo of building envelope materials: Lessons learned from natural exposure in two European cities and tuning of a laboratory simulation practice. *Solar Energy Materials and Solar Cells* **205**, 2020. https://doi.org/10.1016/j.solmat.2019.110264.

[11] N. Xie, H. Li, W. Zhao, et al. Optical and durability performance of near-infrared reflective coatings for cool pavement: Laboratorial investigation. *Building and Environment* **163**, 2019. https://doi.org/10.1016/j.buildenv.2019.106334.

[12] Y. Qin, Y. Zhao, X. Chen, et al. Moist curing increases the solar reflectance of concrete. *Construction and Building Materials* **215**:114-8, 2019. https://doi.org/10.1016/j.conbuildmat.2019.04.164.

[13] D. B. Crawley, L. K. Lawrie, F. C. Winkelmann, et al. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings* **33**(4):319-31, 2001. https://doi.org/10.1016/s0378-7788(00)00114-6.

[14] DesignBuilder. DesignBuilder Software v 4.7.0.027, 2021. www.designbuilder.co.uk.

[15] CensimentoPopolazione. http://dati-censimentopopolazione.istat.it/.