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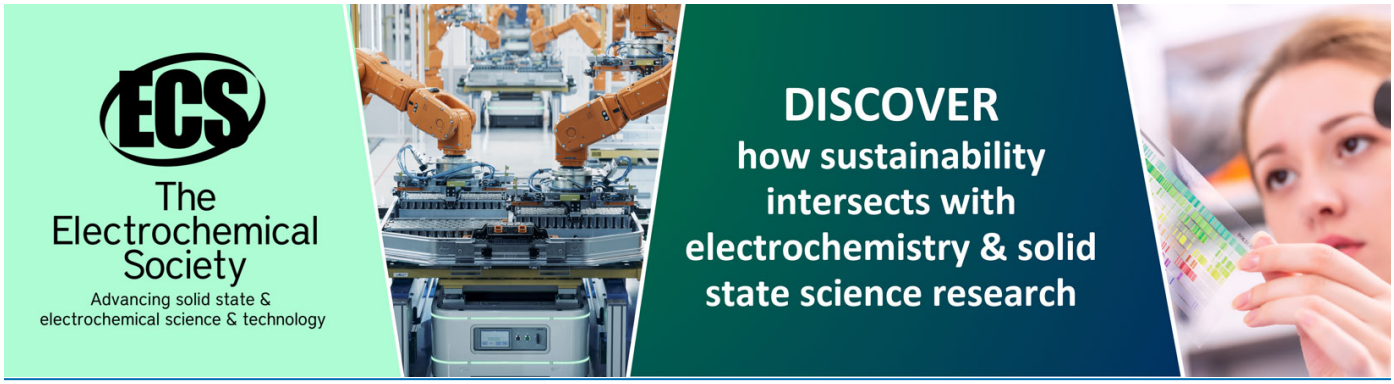

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Cool, photoluminescent paints towards energy consumption reductions in the built environment

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Abstract. Nowadays, passive strategies are identified among the preferred solutions to reduce energy consumption and to increase comfort in the built environment. Indeed, such strategies allow energy saving by exploiting the intrinsic characteristics of materials. In this work, an innovative cool, photoluminescent paint is considered for application in the built environment, as a passive strategy to (i) reduce energy for cooling in the hot season, (ii) maintain lower surface and air temperatures, thus benefiting comfort and (iii) contribute to the lighting of the outdoor public space. The cool, photoluminescent material is first described, then its implementation in the built environment is hypothesized. An experimental, in-lab characterization is conducted to measure the optics characteristics of the samples. Finally, possible implementation of the investigated material in the built environment is investigated by means of dynamic simulation, in terms of thermal- and lighting-energy performance, when applied on the external envelope of a case study building and as an advanced paving solution in a public space. Results from this preliminary study show that the investigated material has promising features, since it can save up to 30% energy for cooling and 27% yearly energy for lighting.

1. Introduction

Nowadays, passive strategies are investigated towards the pressing objectives of energy consumptions and emissions reductions in the built environment [1–4]. Indeed, passive strategies allow exploiting the intrinsic characteristics of the materials composing the built environment, towards energy consumption reduction and performance improvement. Consequently, such solutions consist in the employment of the most adequate materials depending on the specific case, e.g., on the climate, to contribute to the urging call for energy demand reduction.

Greenery and cool materials are among the most studied solutions, since their application on buildings' external envelopes allows for consistent reductions in energy consumptions for heating and cooling [5]. Cool materials are among the most common, non-expensive and easy-to-apply passive strategies [6, 7]. Such materials reflect back the incoming radiation and thus maintain lower surface temperatures and lead to lower air temperatures. Indeed, cool materials were also identified as a possible solution to mitigate the Urban Heat Island phenomenon [8], when extensively employed on horizontal and vertical surfaces in urban areas [7, 9]. Among passive solutions, innovative materials, in particular insulating materials, are being introduced in the construction sector as advanced materials for energy efficiency in buildings. Phase Change Materials (PCMs) are among such innovative materials and are employed as a passive strategy to store energy until it is needed; or they can be employed to reduce heating and cooling needs when changing phase [10, 11]. Indeed, PCMs, when changing phase from

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solid to liquid, prevent heat to enter the ambient. PCMs can be included in a wide variety of ways into the construction element: micro- and macro-encapsulated PCMs, which can be mixed into the concrete mix or mortar layer, wallboards and honeycomb panels. Moreover, the melting temperature varies among different PCMs, and permits to select the most suitable PCM depending on the application and the local climate [11–13]. The concept behind the use of PCMs in the building sector is to store heat and use it later, when it is more needed, instead of having it when it constitutes an issue in the indoor ambient. Based on the same idea, also other forms of energy could be postponed in their utilization, thanks to the specific characteristics of some materials.

In this work, we introduce the novel application in the outdoor built environment of a peculiar cool material, which can be used to diminish energy consumption both with respect to cooling and electricity for lighting. The stored energy, in this case, comes out as light: during the day, when there is enough light, the luminous energy is stored, and then it is released by the material also after the sunset.
The material is a photoluminescent paint, which we developed in-lab and whose components are commercially available. Indeed, the paint is composed of a solvent and photoluminescent pigments, mixed together. The pigment is white when it is "unloaded", while it appears blue colored when the light is emitted from the material itself, once it is "loaded" with energy. The considered material is cool, due to the high solar reflectance, and it can also be considered, similarly to PCMs with thermal energy, a "storage of energy for lighting" (LES), similarly to thermal energy-storage (TES) concept, due to the intrinsic photoluminescence.

The in-lab development of the above-mentioned material is presented here, together with the assessment of its solar reflectance. We developed a plain-paint sample, as a reference case, and a photoluminescent sample. Then, we hypothesized the application of such in-lab developed materials as external paint on the vertical envelope of a case study building located in Central Italy, with varying glazed/opaque ratio, and performed a dynamic energy simulation to assess the yearly energy performance. This peculiar application allows exploiting the properties of the in-lab developed material as a cool paint, i.e., a large part of the incoming solar radiation is reflected due to high solar reflectance, and thus it does not enter the building, lowering energy demand for cooling. Moreover, another advantage consists in the reduction of electricity for lighting: indeed, the material being photoluminescent, it emits light for a certain time-span after absorbing energy. Therefore, in the hypothesis of an application in the built environment, less electricity would be needed in the surroundings to provide lighting, while higher safety for pedestrians is ensured during evening hours. To evaluate the achievable energy savings, we (i) compare a reference case building with a building whose finishing layer is the above described photoluminescent paint, and (ii) the same building with a varying ratio of glazed/opaque envelope. Finally, we consider the advantages in terms of lighting when the photoluminescent material is applied in a public space. Results show that the in-lab developed materials, applied on the external building envelope, are able to lower energy demand for cooling, while at the same time winter penalties are negligible. Moreover, the materials are able to contribute to the outdoor area lighting, reducing electricity consumption.

2. Method

In this work, we developed the photoluminescent samples and characterized them in terms of optics characteristics (solar reflectance index). Then, we selected case studies to be modelled in specific numerical environments. The cases consisted of a case study building and a public square, where the innovative material had been respectively applied on the external envelope (building) and on paving (square). Dynamic simulations were conducted both in terms of thermal energy performance of the building (EnergyPlus) and lighting of the public space, considering respectively the cool intrinsic property (high solar reflectance) of the photoluminescent paint for the cooling energy saving and the emission of light for the energy saving related to lighting. In the next subsections, the procedure is described in greater detail.

2.1 Photoluminescent Materials development and characterization

The photoluminescent paints are ready-to-use paints that can be employed on many different base materials. The color of the paints usually changes when they are "loaded" and emit light and when they

are “unloaded”, due to the different spectrum of light emission. In this case, we selected a white paint that turns fluorescent light-blue during the night. Indeed, the luminescent color is mainly visible when the surroundings are dark. The process behind the photoluminescent phenomenon is due to the absorption of a photon by a molecule: the photon excites an electron and radiates it when the electron returns to lower energy state. The activating phenomenon is electromagnetic radiation hitting the material, e.g., the envelope paint. With respect to the considered photoluminescent paints, the result of the absorbed electromagnetic radiation is the emission of light, with a longer wavelength (thus lower energy) than the absorbed one. The duration of light emission is referred to as “lifetime” of the photoluminescence phenomenon, and it can last for minutes, hours or even days.

The paints are composed by a primer (75% in weight), which is responsible for the fluorescent color, and a hardener (15% in weight). The samples were prepared by applying three coats of paint on a white plastic support, with dimensions 10 cm x10 cm. The resulting sample was tested by means of an integrating sphere spectrophotometer, to measure the solar reflectance of the sample. Indeed, solar reflectance is the intrinsic characteristic of the material that is responsible for the cool behavior and, thus, for the optimized thermal-energy performance during the hot season. The solar reflectance index is equal to 90%. Moreover, the lifetime of the light emission after the loading was observed to be consistent during all the night, by means of luxmeter measurements.

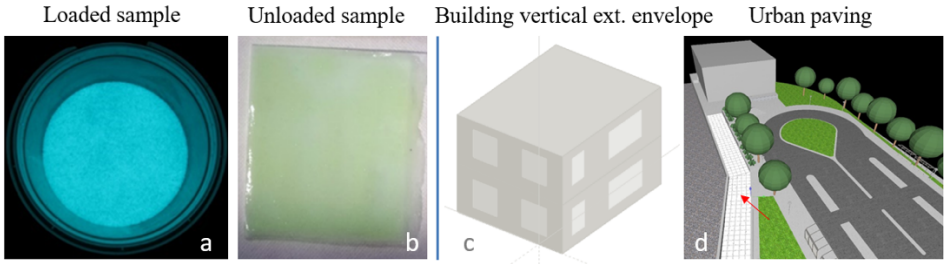

Figure 1. Loaded cool-photoluminescent paint sample in the jar (a); unloaded photoluminescent paint, obtained sample (b). On the right, the simulated case studies: building with paint as external finishing layer (c); and the application of photoluminescent material as urban paving (d).

2.2 Dynamic simulation for thermal-energy performance

The effectiveness of passive strategies towards energy saving is tested by means of dynamic simulations, with respect to the thermal-energy performance of the building. The case study is a single-family, residential building, composed by two floors for a total of 160 m^2 of surface. The building is parallelepiped-shaped, as showed in Fig. 1, with sides of 8 m and 10 m length. With respect to orientation, the 10 m sides are north and south oriented. To more precisely control the efficacy of the cool, photoluminescent paint, we modelled and simulated two buildings, with different glazed/opaque wall ratio but otherwise identical in terms of the other characteristics. For the first case, we selected the minimum glazed surface, equal to 1/8 of indoor area surface, i.e., 20 m^2 of glazed surface on the façade of the whole building (W_{min}). Then, in the second case study building we considered the same exact windows for each room, to maintain the same exposition to the sun for each window, but with a larger windows area. In this case (W_{max}), the total glazed surface of the building was equal to 55.4 m^2, more than the double with respect to the W_{min} case. In W_{max}, the surface for the cool, photoluminescent paint is much reduced (195 m^2) than in W_{min} (230 m^2), thus we hypothesized that the passive strategy related to the cool envelope is reduced. Indeed, cool materials allow to maintain lower surface temperatures, as acknowledged in literature: a wider cool surface on the external envelope (as in W_{min} with respect to W_{max}) has a higher potential in lowering envelope temperatures. For both W_{min} and W_{max}, we performed two simulations, one with the reference paint (Ref, considering a solar reflectance index equal to 0.5, for a light plaster material) and one with the cool, photoluminescent paint (Cool) applied as external envelope finishing layer, with a solar reflectance index equal to 0.85 (measured in lab). A thermal emittance of 0.84 was measured for the samples. In total, four simulations were conducted, measuring energy performance all along an entire year. At the same time, a thermal performance, with HVAC off, was conducted to assess the air temperature indoor, in the living room, during a typical summer hot day,

as influenced by the paint. Each separate thermal zone of the building was characterized in terms of occupancy profiles (as in [15]) and construction characteristics. The wall, whose finishing layer is the cool photoluminescent plaster, has a thermal transmittance equal to 0.32 W/m^{2}K.The whole building is heated (by means of gas power) and cooled (electricity).

2.3 Dynamic simulation for the lighting energy performance

The lighting of public spaces, especially in urban areas, is of paramount importance in terms of safety and comfort for pedestrians, during the night hours [16]. Most often, the presence of adequate lighting is able to discourage violence and crime. Studies demonstrated that improving street lighting is able to reduce crimes by up to 21% [17, 18]. Here we consider a public space, a path for pedestrians near the railway station (as in Figure 1 d), as a case study. According to CIE 115-2010 [19], the reference class for the area in terms of number of users and surroundings is P5, which requires an average horizontal illuminance equal to 3.0 lux, a minimum horizontal illuminance equal to 0.6 lux, a minimum vertical illuminance of 1.0 lux and a minimum semi-cylindrical illuminance of 0.6 lux, the last two illuminance values being additional requirements specifically tailored towards crime reduction. The case study area is modelled by means of the DIALux lighting design program. First, the current situation (Led+lamps), then the solution with the application of the photoluminescent paint (Photo, as showed in Fig.1, d), are modelled, and finally a solution with both photoluminescent material and street lamps (Photo+lamps). All the simulations are performed for the night-time, when lighting is needed. The materials are loaded by the daytime solar radiation. Samples exposed on the University of Perugia building roof were monitored with a luxmeter, so as to measure illuminance. Experiments showed that the lifetime duration for the photoluminescent materials is the whole night, and the guaranteed illuminance is equal to 28 lux, constant for the entire night duration after an initial peak (40 minutes) of 490-570 lux (for a cloudy and sunny day). The current situation depicts a lighting system composed by led light sources on the paving and street lamps along the path; in the photoluminescent materials scenario, only street lamps were maintained in addition to lighting from photoluminescent materials.

3. Results

3.1 Results from the thermal-energy performance analysis of the case study building

Results of the dynamic energy simulation are reported in the figure and table below. Considerations can be done with respect to the comparison between the different scenarios. W_{min} consumes less energy than W_{max}; and the cool solution, even if cool properties of the material are a penalty during winter, is more efficient than the reference case. Moreover, the effectiveness of the cool paint is much higher in W_{min} (-3 kWh/m^2 in Cool with respect to Ref), while in W_{max}, as expected, the reduction is lower, equal to -0.6 kWh/m^2, due to the reduced extension of the cool surface on the external envelope.

Table 1. Yearly energy consumption for the investigated scenarios.

Annual energy	W_{min}		W_{max}	
	Ref	Cool	Ref	Cool
kWh	14255.5	13913.97	15557.13	15479
kWh/m^2	109.59	106.97	119.60	119.00

Cooling energy	W_{min}		W_{max}	
	Ref	Cool	Ref	Cool
kWh	1829.25	1272.68	1934.29	1819.01
kWh/m^2	14.07	9.79	14.88	13.99

The difference between the Ref and Cool scenario is even more visible in Figure 2, where monthly energy consumptions, for heating and for cooling, are reported. Here, during the summer months, especially June, July and August, the Cool case allows saving around 200 kWh for the W_{min} case, while the corresponding savings for W_{max} are as low as 30 kWh.

With respect to thermal performance, the same results can be observed. Without HVAC, W_{min} is able to maintain lower air temperatures (-6°C) in the living room, considered as the reference indoor space, with respect to W_{max}. This result is mirrored by the lower total yearly energy consumption (Table 1) of W_{min}. Moreover, the effect of the cool paint in W_{min} allows to reach lower temperatures (almost -2°C with respect to Ref), while in W_{max} the reduction is equal to -1°C.

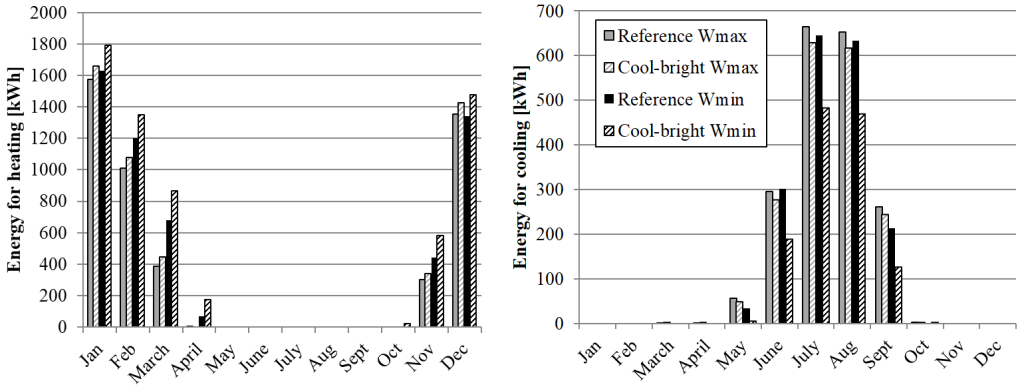

Figure 2. Monthly energy consumption (heating and cooling) for the investigated scenarios.

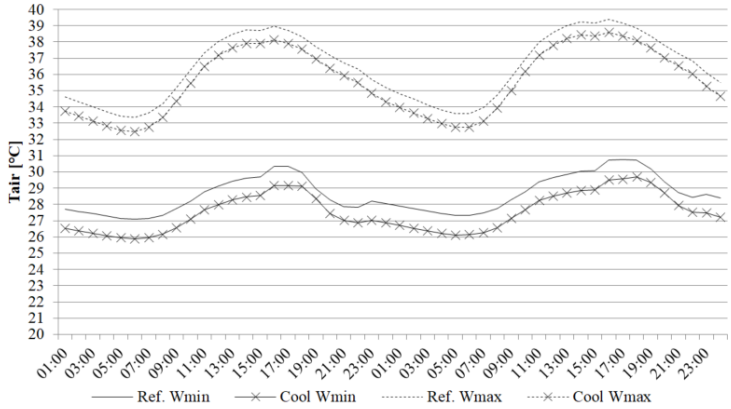

Figure 3. Daily (30th July) air temperature, living room.

3.2 Results from the outdoor energy performance analysis of the public space

With respect to the energy saving for lighting, we considered the above described public space, the path nearby the railway station. In the current scenario, Led+Lamps, the regulation requirements are exceeded. The photoluminescent materials alone are not able to provide the required illuminance levels, while the addition on street lamps allows exceeding the required illuminance values. Considering the total yearly operating hours, consumptions are evaluated. The solution with the photoluminescent material can save an average of 36 W. It has to be considered that the solution with such materials also allows saving in terms of maintenance and substitution of light bulbs.

Table 2. Results of the lighting simulation.

Case	Ehor, av.[lx]	Ehor, min [lx]	Evert [lx]	Evert, sc [lx]	Power [W]
Led+lamps	13,33	1,52	2,01	3.92	**136**
Photo	0.62	0.17	1.97	2.57	**0**
Photo+lamps	4,41	0,71	2,34	4.22	**100**
Regulation	*3.00*	*0.60*	*1.00*	*0.60*	_

Av. Horizontal illuminance (Ehor, av.), Min. Horizontal illuminance (Ehor,min.), Min. vertical illuminance (E,vert), Min. semi-cylindrical illuminance (Evert,sc)

4. Conclusions

In this work, cool, photoluminescent materials are considered for application in the built environment, as passive strategies to reduce energy consumptions. Indeed, in this work we demonstrated that these materials can lower energy consumption when applied as external envelope finishing layer (plaster paint) in buildings, as cool materials, and are also able to lower energy consumption for lighting in public spaces, when applied as paving finishing layer. This preliminary study paves the road for future studies, following our explorative work, that should carefully consider also the architectural aspects of

such a paint, and its potential to be applied in different locations such as cities, parks, historical sites or mountain lodges needs to be explored more in depth.

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