A study on the thermo-optical behaviour of phosphorescent coatings for passive cooling applications

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Abstract. Climate change intensifies the Urban Heat Islands (UHI) in hundreds of cities around the globe. Even though tests on traditional cool materials have shown promising results in terms of UHI mitigation, novel advanced solutions are deemed necessary for strategically counteracting UHI. Unlike traditional materials, phosphorescent materials can not only reflect incident shortwave radiation but also reemit it back, i.e. the phenomenon of phosphorescence. Even though this unique reflection-reemission mechanism known as effective solar reflectance (ESR), has been widely tested for sustainable lightning applications, its cooling potential has been surprisingly overlooked. Here, we examine, in-lab, and numerically, the thermo-optical properties of several phosphorescent coatings of different colours and we evaluate their effective cooling potential. Results reveal that the phosphorescence mechanism could be effectively optimized for obtaining phosphorescent-based coatings with an improved optical performance and hence substantially mitigate surface overheating in the built environment.

1 Introduction

Within recent decades, rural areas are turning to urban ones due to the rapid evolution of urbanization [1]. As a result, the corresponding surface energy balance is substantially modified, leading in many cases, to a high surface and air temperature values within cities [2]. This phenomenon known as Urban Heat Island (UHI) is typically magnified during the hot months of the year and has been widely reported as responsible for detrimental effects, such as morbidity and mortality, increased green-house gasses emission, and increased energy consumption [2, 3].

Under this scenario, several passive strategies have been proposed and tested for counteracting UHI. The application of Cool Materials (CMs) on urban surfaces, such as pavements and buildings facades, is among the most popular UHI mitigation techniques. [4]. The main property of CMs is the high reflection of shortwave radiation especially within the near-infrared wave-range [5]. Hence, they can maintain lower surface temperature than conventional materials and consequently contribute towards lower values of air temperature above them. CMs can be divided into several subcategories, such as classic white [6], coloured [7], phase change [8], photoluminescent [9, 10] and thermochromic [11] ones. Recently, CMs with photoluminescent properties are regarded as the next generation of CMs due to their enhanced rejection of incident solar radiation [12]. In fact, photoluminescent materials can not only reflect the incident solar radiation but also re-emit it back within the visible and/or infrared spectrum [9, 10]. This twofold solar rejection mechanism is known as Effective Solar Reflectance (ESR) [9].

Photoluminescence is typically divided into two main subcategories, i.e. fluorescence and phosphorescence. Even though both subcategories result to re-emission of light, phosphorescence can last substantially longer than fluorescence [13]. For that reason, phosphorescent pigments have been widely used for alternative lightning applications [14]. Surprisingly, notwithstanding the intrinsic property of ESR, only a couple of studies have examined the cooling potential of photoluminescent-based solutions. For instance, fluorescent-based materials were the first photoluminescent materials implemented for counteracting UHI by Berdahl et al. [9]. In their study, they developed CMs with fluorescent ruby crystals and showed that the novel fluorescent CMs could maintain up to 6.5 °C lower surface temperature as compared to a conventional reference. Kousis et al. [10] developed phosphorescent-based paving fields and monitored them in terms of thermos-optical performance. The outcomes of the monitoring campaign showed that phosphorescent-based surfaces can reduce the superficial temperature of cool concrete up to 3.3 °C
During the hottest hours of a typical summer day and simultaneously delay the corresponding temperature peaks. Moreover, it was reported that further addition of phosphorescent components could result to even higher temperature reductions.

Under this framework, further investigation of the radiative properties of photoluminescent materials on theoretical level is needed for their optimization in terms of real-life applications. Here, at first, we performed an in-lab investigation concerning the optical performance of several developed phosphorescent coatings. Subsequently, we performed dynamic simulations of phosphorescent materials in terms of thermo-optical performance. Each phosphorescent coating has different colour and therefore different phosphorescent wave-range. Concerning the simulations, each phosphorescent coating was considered as placed above a conventional concrete surface. Their cooling potential was evaluated by comparing them with (i) a conventional concrete surface and (ii) a cool concrete surface, i.e. with a concrete surface characterised by high solar reflectance.

2 Methodology

In this study, the optical performance in terms of solar reflectance and the corresponding thermal performance of phosphorescent coatings were investigated in-lab and numerically respectively. The performance of each phosphorescent coating was benchmarked with (i) a conventional concrete surface and (ii) a cool concrete surface. Case studies were chosen with respect to the colour of the emitted light, i.e. the phosphorescent wave-range.

2.1 Theoretical background

The energy balance of phosphorescent materials is distinguished from the conventional materials. In more detail, the thermal behaviour of both conventional and cool materials is determined by Eq. (1):

\[
R_{n} = S_{↓} + L_{↓} + S_{↑} + L_{↑}
\]  

(1)

where \(R_{n}\) is the net radiation gains of the material, S and L are the shortwave and longwave radiation components respectively, while upward and downward arrows denote the corresponding directions of radiation. Eq. (1) can be re-written including reflection and emission components as:

\[
R_{n} = S_{↓} + L_{↓} - (α_{SW} \cdot S_{↓}) - ((α_{LW} \cdot L_{↓} + εσT^{4})
\]  

(2)

where \(α_{SW}\) is the reflectance of the material related to the shortwave range of radiation, \(α_{LW}\) is the reflectance related to the longwave range, \(ε\) is the thermal emittance of the material, \(σ\) is the Stefan–Boltzmann constant and \(T\) is the temperature of the material. With regards to phosphorescent materials, Eq. (2) can be re-written including an extra factor of emissivity in both shortwave and near infrared wave-range as:

\[
R_{n} = S_{↓} + L_{↓} - (α_{SW} \cdot S_{↓} + ε_{SW}σT^{4}) - ((α_{LW} \cdot L_{↓} + (εL_{W} + ε)σT^{4})
\]  

(3)

where \(ε_{SW}\) and \(εL_{W}\) are the additional re-emission of shortwave and/or longwave radiation due to the phosphorescent effect and represent the ESR of the material.

2.2 In-lab optical analysis

The developed phosphorescent coatings were examined in terms of optical behaviour by utilising a UV/VIS/NIR spectrophotometer (SolidSpec-3700). Its function is based on an integrated sphere with a 60 mm-diameter and a wavelength accuracy equal to 0.1 nm. The solar reflectance of investigated coatings was assessed with respect to the ASTM Standard E903-96 [15]. It should be noted, that as reported by Levinson et al. [16], accurate measurement of solar reflectance concerning photoluminescent materials is not trivial. Instead, since photoluminescence takes place typically within short wave range, the detector of the spectrophotometer misinterprets the detected light due to photoluminescence as reflected. For that reason, the presented analysis was performed by “bombarding” the sample with incident light of 2500 nm which was progressively decreasing up to 300 nm. This approach, minimized the corresponding error since all investigated coatings get excited below 365 nm. Therefore, samples’ solar reflectance was defined from 400 to 2500 nm.

Finally, thermal emittance of the developed phosphorescent coating was measured by means of an infrared camera.

2.3 Numerical analysis in terms of thermal performance

Dynamic simulations for each coating were performed for evaluating their thermal performance in terms of surface temperature with respect to varied magnitude of emissivity/phosphorescence. All coatings were considered as placed above a very thin (thickness=0.1 m) conventional concrete surface, and eventually compared with (i) a typical uncovered concrete surface and (ii) a cool-concrete surface. The main properties and dimensions of the typical and cool concrete surfaces can be found on Table 1 and Figure 1 respectively.

![Fig. 1. Cross-section and main dimensions of modelled surfaces.](image)
Table 1. Properties of concrete surface

| Variable          | Value | Units         |
|-------------------|-------|---------------|
| Density           | 2300  | [kg/m$^3$]    |
| Thermal conductivity | 1.8  | [W/m·K]      |
| Heat capacity     | 880   | [J/kg·K]      |
| Thermal emittance | 0.95  | [arb. un.]    |

The aim of the present study was a preliminary investigation of phosphorescent coatings under different boundary conditions. Hence, the problem was considered stationary, i.e. time-independent. Additionally, two main initial conditions were assumed (Table 2). In order to approximate a heat source as the sun, we assumed that the incident power was 1000 W/m$^2$ which corresponds to a typical solar irradiance value during the hottest hours of a typical summer day [10]. The initial surface temperature of the coatings was assumed equal to 293.2 K, which corresponds to a typical value of a concrete surface during the early morning hours of a typical summer day [10].

Table 2. Initial conditions

| Variable          | Value | Unit          |
|-------------------|-------|---------------|
| $T_{\text{surface}}$ | 293.2 | [K]           |
| Incident power    | 1000  | [W/m$^2$]     |

Consequently, numerical simulations were performed by progressively increasing emissivity/phosphorescence magnitude by 0.1 for each coating, starting from 0.5 (moderate phosphorescent effect) to 0.9 (high phosphorescent effect).

3 Results

In this section, the results from the (i) in-lab investigation and (ii) dynamic simulations regarding the thermo-optical performance of different types of phosphorescent coatings placed above a thin concrete surface are presented. Consequently, the performance of phosphorescent coatings is benchmarked with (i) a conventional concrete and (ii) a cool concrete surface.

3.1 In-lab investigation of reflectance/thermal emittance

At first, the reflectance profiles of each phosphorescent coating were in-lab investigated with a UV/VIS/NIR spectrophotometer. The resulted average values of reflectance coefficient ($r$) concerning incident short-wave radiation (300-2500 nm) can be seen on Table 3. Violet and green coatings were found to have the highest reflectance, i.e. 0.6, while the lowest was found for orange and yellow ones, i.e. 0.3. Also, the thermal emittance of each phosphorescent coating was measured with an infrared camera and found equal to 0.84 for all coatings.

Table 3. Average reflectance ($r$) of phosphorescent coatings within 300-2500 nm.

| Colour | $r$ |
|--------|-----|
| Blue   | 0.5 |
| Yellow | 0.3 |
| Violet | 0.6 |
| Red    | 0.4 |
| Green  | 0.6 |
| Orange | 0.3 |
| Cyan   | 0.5 |

3.2 Simulations

As it can be seen on Figure 2 there is a negative relationship in-between surface temperature of all coatings with emissivity/phosphorescence magnitude. In fact, this almost linear relationship showed that significant surface temperature reductions can be achieved concerning all phosphorescent coatings. For instance, the highest reductions calculated for cyan and yellow, i.e. 13.9 K and 13.6 K respectively, and were followed by orange and blue coatings, both with a reduction up to 13 K. The lowest reduction was calculated for violet, green and red, i.e. 11.5 K, 11.5 K and 9.9 K.

Fig. 2. Surface temperature of samples with progressively increased intensity of phosphorescence/emissivity: (a) 0.5, (b) 0.6, (c) 0.7, (d) 0.8 and (e) 0.9.

On Figures 3 and 4, a comparison analysis can be seen concerning surface temperature of phosphorescent
coatings for each emissivity/phosphorescence magnitude and surface temperature of a conventional concrete and a cool concrete surface, respectively.

The surface temperature of a typical concrete was found equal to 328.3 K. A comparison with the phosphorescent coatings showed that phosphorescent coatings with 0.5 emissivity/phosphorescence can maintain from 1.8 K (blue coating) up to 3.9 K (cyan coating) lower surface temperature. The temperature difference with the conventional concrete significantly increases with the increase of emissivity/phosphorescence and can reach up to 17.8 K for the cyan coating with an emissivity/phosphorescence equal to 0.9.

Fig. 3. Phosphorescent coating vs. typical concrete.

The surface temperature of a cool concrete under the same boundary conditions was found equal to 323.8 K. As expected, the difference in-between the surface temperature of a cool concrete surface and phosphorescent coatings was smaller compared to ones with conventional concrete. In fact, when emissivity/phosphorescence value is considered equal to 0.5, all phosphorescent coatings, were found to have higher surface temperature than cool concrete, e.g. cyan and red coatings were 0.7 and 4 K, respectively, hotter than cool reference. However, as emissivity/phosphorescence magnitude is increasing, phosphorescent coatings maintain lower surface temperature than cool reference. For example, when the intensity of emissivity/phosphorescence was relatively moderate (=0.6), the yellow coating was found 3 K cooler than cool concrete. Further enhancement of emissivity/phosphorescence intensity led to substantially lower surface temperatures. For example, the orange coating was found 5.5 K cooler than the cool reference when emissivity/phosphorescence was considered equal to 0.7. Temperature reduction as compared to the cool concrete reached up to 13.3 K when emissivity/phosphorescence was considered equal to 0.9.

Fig. 4. Phosphorescent coating vs. cool concrete.

4 Concluding remarks

Here, novel cool solutions for implementation into urban surfaces are proposed for the mitigation of UHI. The thermo-optical performance of phosphorescent coatings of different colour, and hence different phosphorescent wave-range, was in-lab and numerically investigated.

In-lab investigation showed that phosphorescent coating can succeed reflectance of incident radiation within the short-wave spectrum, i.e. up to 0.6 as an average value. With regards to the numerical investigation, an increasing magnitude of emissivity/phosphorescence was assumed for each coating. Results showed that significant decrease of superficial temperature can be achieved. Phosphorescent coatings were found capable to maintain lower temperature than a conventional and a cool concrete up to 17.8 K, and 13.3 K, respectively.

Notwithstanding the assumptions made, it is reported that significant enhancement of emissivity/phosphorescence of a material can be achieved depending on the desire of the manufacturer. Therefore, this preliminary analysis showed a significant cooling potential of phosphorescent coatings placed above a typical concrete surface.

Thus, further investigation concerning optimization of emissivity/phosphorescence may lead to a novel urban component that can effectively maintain low temperature and hence contribute towards the mitigation of UHI.

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