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The methods for creating building energy efficient cool black coatings

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ABSTRACT

The optical and thermal properties of black coatings pigmented with different black colorants were systematically investigated, and their surface temperature reduction values and cooling energy savings were estimated relative to the black coating pigmented with carbon black in Shanghai, China. The black coatings separately pigmented with NIR-transmitting perylene black and dioxazine purple colorants were identified to be real cool black coatings. The addition of chrome titanium yellow to the black coating pigmented with dioxazine purple re-establishes the true black coatings. Over white basecoats, the estimated surface temperature reduction values and annual cooling energy savings in Shanghai are 13.8 °C and 3.9 kW h m^{-2} yr^{-1}, respectively, for the black coating pigmented with perylene black colorant; these two values are 10.2 °C and 2.24 kW h m^{-2} yr^{-1}, respectively, for the black coating pigmented with dioxazine purple colorant.

1. Introduction

Sunlight incident on a horizontal surface illuminated by a zenith sun arrives at wavelengths between 250 and 2500 nm [1]. Ultraviolet (UV, 250–400 nm), visible light (VIS, 400–700 nm) and near infrared light (NIR, 700–2500 nm) account for 5%, 43% and 52% of the energy in the air-mass 1.5 global solar irradiance spectrum (250–2500 nm), respectively [2]. The prerequisites for cool materials are that they must have both high reflectance over the entire solar spectrum and high thermal emittance [3]. The former decreases solar heating, whereas the latter enhances radiative cooling [4,5]. White solar reflective coatings completely meet this requirement. Therefore, they are cool materials and generally applied to the envelope of buildings in cooling-dominated regions. However, light colored coatings have the following disadvantages: lack the aesthetics of darker colored coatings [6–8]; result in a high glare that is offensive to the eye [3,9,10]; are prone to contamination that reduces their solar reflectance [11].

Therefore, although white solar reflective coatings are the coolest building surface materials, they are not conventionally accepted by owners of homes with pitched roofs, who often prefer non-white roofs for aesthetic and visual considerations [3,6–14]. The black coating is a popular option for roofs in the Yangtze River Delta Region in China. The majority of the building sector throughout the U.S. is also made up of black or dark-colored roofs [15]. The conventional use of black roofs on buildings in a lot of places most likely because they have the following advantages: black is always elegent and meets the esthetic requirement [10]; black roofs always perform with lower moisture than white roofs and thus have a low risk of moisture damage [16]; unlike light colored roofs, the albedo of black roofs does not decrease because of aging, but it increases over time to its maximum value [17]. However, a coating must at least absorb all the visible light to show a black appearance. In some circumstances, black coatings, such as those pigmented with carbon black and copper chromite black, not only absorb almost the entire spectrum of visible light but also nearly the entire near-infrared spectrum, which significantly increases the roof surface temperature and the cooling energy consumption in summer [12].

This phenomenon begs the following question: can black be cool? The answer is definitely yes. Generally speaking, two methods are used to prepare cool black coatings. Method one consists of preparing a black thin topcoat pigmented with NIR-transmitting black colorants and a white basecoat with high NIR reflectance, which are then applied to substrates with low NIR reflectance (e.g. gray concretes). This so-called “two-layered technique” was initially proposed by Brady and Wake [18] for creating cool colored coatings [2,7,8,11,18–21]. Method two consists of directly applying a NIR-transmitting black coating to substrates with high NIR reflectance (e.g. shiny metals, woods or clay tiles) [2,8,21].

After determining the methods to prepare cool black coatings, one only needs to select the appropriate NIR-transmitting black

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Table 1
The composition of the conventional and cool black coatings.

Component	Content by weight (%)
Pure acrylic emulsion	80
Black pigment[*]	2
Talcum	15
Wetting agent	0.7
Dispersant	0.8
Antifoaming agent	0.5
Leveling agent	0.5
Coalescent	0.5

[*] The black pigment might be carbon black, copper chromite black, chromite iron nickel black, manganese ferrite black spinel, perylene black or dioxazine purple.

pigments and then prepare the coatings following the standard coating preparation procedures. Currently, commercially available NIR-transmitting black pigments include chromite iron nickel black (C. I. pigment black 30), manganese ferrite black spinel (C. I. Pigment black 26), perylene black (C. I. Pigment black 32) and dioxazine purple (C. I. Pigment violet 23). The last three pigments were identified to be NIR-transmitting colorants, showing both strong NIR backscattering and weak NIR absorption in a binder of refractive index 1.5 [22].

In this paper, the optical and thermal properties of cool black coatings pigmented with the above four NIR-transmitting black pigments are investigated and compared with those of black coatings pigmented with carbon black and copper chromite black colorants. Their cooling effects and cooling energy savings in Shanghai (located in the Yangtze River Delta Region of China) are estimated and discussed.

2. Experimental

2.1. Selection of materials

A pure acrylic emulsion and commercially available carbon black, copper chromite black, chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple pigments were selected to prepare conventional and cool black coatings. Talcum was also selected as an extender pigment because it is transparent and non-reflective throughout the visible and near-infrared regions and does not affect the performance of other pigments [23]. In addition, the presence of talcum can reduce the coating cost [24] and improve the coating hardness.

In addition to the above materials, the appropriate paint additives to improve the coating quality and performance were also selected as follows: a wetting agent, a dispersant, an antifoaming agent, a leveling agent and a coalescent. All of the above materials were used as received to prepare the conventional and cool black coatings. The composition of these coatings is tabulated in Table 1.

2.2. Preparation of conventional and cool black coatings

The conventional and cool black coatings were prepared using the following standard process: the acrylic emulsion and talcum were first added into the mixing setup, followed by the addition of the wetting agent, dispersant and leveling agent. The mixture was stirred at high speeds for 20 min, and the prefabricated black pigment dispersion was then pumped into the paint mixing setup. At this stage, the antifoaming agent and coalescent were added, and the mixture was continuously mixed at high speed for 20 min.

2.3. Preparation of conventional and cool black coating samples

To study the optical and thermal properties of the conventional and cool black coatings, the above coatings were sprayed onto aluminum alloy substrates and substrates painted with a self-manufactured cool white basecoat, whose optical and physicochemical properties were described elsewhere in detail [24–26].

2.4. Spectral reflectance and lightness measurements

Following ASTM E903-12 (Standard test method for solar absorbance, reflectance and transmittance of materials using integrating spheres), the spectral reflectance of the conventional and cool black coatings over white basecoats and/or aluminum alloy substrates was measured using a UV/VIS/NIR spectrophotometer (Perkin Elmer Lambda 750) equipped with an integrating sphere (150 mm diameter, Labsphere RSA-PE-19). The solar reflectance was computed by integrating the measured spectral data weighted with the air mass 1.5 beam-normal solar spectral irradiance.

According to the ASTM Standard E308-01 (Standard Practice for Computing the Colors of Objects by Using the CIE System), a color reader (CR-10, Konica Minolta Sensing, Inc) was used to measure the lightness L^*, a^*(red to green scale) and b^* (yellow to blue scale) of the conventional and cool black coatings.

2.5. Thermal emittance measurements

A portable differential thermopile emissometer AE1 (Devices & Services Co., Dallas, TX) was used to measure the thermal emittance of the black coatings according to ASTM C 1371 (Standard test method for determining the emittance of materials near room temperature using portable emissometers). The instrument was calibrated using both high and low emittance standards placed on the flat surface of a heat sink. The emittance of the test specimen was determined via comparison with the emittances of the standards.

3. Results

3.1. The optical properties of black coatings

To obtain the VIS reflectance and brightness of jet-black coatings, the black coatings separately pigmented with carbon black and copper chromite black colorants were prepared and sprayed onto aluminum alloy substrates and cool white basecoats. Their spectral reflectance and brightness were then measured. Fig. 1 presents the spectral reflectance curves for the black coatings separately pigmented with carbon black and copper chromite black colorants over a bare aluminum alloy substrate and a cool white basecoat, whose solar reflectances are approximately 0.79 and 0.89, respectively [16]. The corresponding computed solar and spectral reflectance values, together with the brightness of the coatings, are summarized in Table 2. As indicated in Fig. 1 and Table 2, the spectral reflectance curves of both the two black coatings over an aluminum alloy and that over a cool white basecoat overlap, and they show very low reflectance over the entire solar spectrum (250–2500 nm), indicating that both pigments are completely absorptive solar pigments. As expected, both the coatings were jet-black in appearance, similar in brightness and featured the same solar reflectance (0.05). Unexpectedly, the black coating pigmented with copper chromite black colorant showed slightly lower UV and VIS reflectances but a slightly higher NIR reflectance than those of the black coating pigmented with carbon black. The spectral and solar reflectances of both coatings were independent of the NIR and solar reflectances of the basecoats and/or substrates. According to the two-flux Kubelka–Munk (K–M) theory, the solar reflectance of a two-layer coating system, R_{12}, of incident light is

$$R_{12} = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \tag{1}$$