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The methods for creating energy efficient cool gray building coatings—Part I: Preparation from white and black pigments

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ABSTRACT

We describe the method for creating nominally cool gray coatings by mixing titanium dioxide rutile and black pigments that include chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple. Although the solar reflectance of the gray coatings prepared by adding chromite iron nickel black and manganese ferrite black spinel pastes separately into a white coating are higher than that of the standard gray coating of colors of similarly lightness with the mixtures of carbon black and titanium dioxide rutile, they are actually not qualified cool gray coatings. The light gray coatings colored with a mixture of perylene black and titanium dioxide rutile are eligible cool gray coatings with a green shade. The gray coatings produced by mixing titanium dioxide rutile and dioxazine purple and chrome titanium yellow are also real cool coatings with a violet shade.

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1. Introduction

White solar reflective coatings are the building surface materials that enable the most cooling effect because they reflect not only most of the visible light (VIS, 400–700 nm) but also an overwhelming majority of the near infrared light (NIR, 700–2500 nm). However, white solar reflective coatings are generally not accepted by owners of homes with pitched roofs as a means of energy efficiency because they lack the aesthetics of darker colored coatings [1–3] and result in potential glare problems [4,5]. In addition, white coatings are prone to contamination that attenuates their solar reflectance. These problems can, to some extent, be alleviated by use of cool gray coatings. Therefore, gray is one of the most preferred colors for roofs and exterior walls of buildings in China, especially in the downtown area of Beijing.

The standard gray coatings are generally pigmented with carbon black and titanium dioxide rutile. Carbon black absorbs strongly throughout the solar spectrum. As described below, even when used in very small amounts, carbon black is effective in decreasing the solar reflectance of the resultant gray coating. Consequently, painting the envelope of the buildings with the standard gray coating necessarily results in higher building surface temperatures, which increases the building heat gain and the cooling power demand in summer. From the standpoint of building energy efficiency, it is imperative to develop cool gray coatings. Although several previous studies involved cool gray roof materials [6,7], they did not mention the methods to prepare cool gray coatings. To the best of our knowledge, in all of the published literature available so far, there appears to be only one review paper that described the technique to create cool gray coatings used on the hulls and superstructures of warships in an ocean environment [8].

The above-mentioned paper implies two methods to create cool gray coatings. Method 1 involves the replacement of carbon black with organic perylene black, which absorbs strongly in the VIS region but is quite transparent over the entire NIR region [8,9]. Compared to the standard gray coating that reflects 33% of solar radiation at 800 nm, the obtained light gray coating reflects 77%. Method 2 involves the introduction of a pigment into a coating with complementary colorants and titanium dioxide rutile white to yield a cool gray coating. The resultant color of the gray coating is metameric to the color of the standard gray coating, and its NIR reflectance is approximately twice that of the standard gray coating [8].

To address the lack of information regarding the preparation of cool gray coatings and to provide more insight into the research area of cool coatings for building energy efficiency, we explore the method to manufacture cool gray coatings by mixing black pigments with weak NIR absorptance with titanium dioxide rutile. The optical and thermal properties of the formed gray coatings were systematically investigated and compared. In a companion paper [10], we further study the method to prepare cool gray coatings via blending pairs of NIR-transmitting pigments with complementary colors and titanium dioxide rutile.

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2. Experimental measurements

2.1. Selection of materials

To prepare the pigment pastes of black colorants and the gray coatings, a pure acrylic emulsion and commercially available carbon black (C. I. Pigment black 7), copper chromite black (C. I. Pigment black 28), 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), dioxazine purple (C. I. Pigment violet 23) and chrome titanium yellow (C. I. Pigment Brown 24) pigments were selected. To improve the quality of the pigment pastes and coatings, a wetting agent, a dispersant, an antifoaming agent and a coalescent, were also selected. In addition, a cool white coating developed in our laboratory was selected to be mixed with the pigment pastes of the black colorants. The composition and optical properties of the white coating were described in detail in previous publications [11–13].

2.2. Preparation of conventional and cool gray coatings

The weight contents of the pigment pastes of carbon black and the other black pigments were 10 wt% and 60 wt%, respectively. The weight concentrations of the pigment pastes of dioxazine purple and chrome titanium yellow was 20 wt% (dioxazine purple: chrome titanium yellow = 7:3). The preparation of the pastes of the black pigments proceeded as follows: the water was first added into the mixing setup, followed by the addition of the pigments, wetting agent and dispersant. The mixture was stirred at high speeds for 20 min and the pigment pastes were obtained. Different amounts of pigment pastes were then added into the prefabricated white coating. At this stage, the antifoaming agent and coalescent were added, and then, the mixture was continuously mixed at high speed for 20 min.

To study the optical and thermal properties of the conventional and cool gray coatings, they were sprayed onto bare polywoods, bare fiber cement boards and fiber cement boards with white basecoats. The dry film thickness of the black topcoats was approximately 50 μm; the dry film thickness of the white basecoats was approximately 150 μm to keep the substrates formable without breaking the coatings [3]. In addition to the dry coating thickness and the volume fraction of each pigment, the spectral reflectance of the coated system also depends on the spectral reflectance of the backgrounds [3], therefore, the solar and NIR reflectance values of the selected backgrounds, such as polywood (denoted as S_{PW}, S represents sample, *unless otherwise indicated, S has the same meanings below*), fiber cement board (denoted as S_{FC}) and white basecoat (S_w), were also measured and they are tabulated in Table 1.

Table 1
Solar and NIR reflectances for cool white basecoats and uncoated substrates.

Samples	Solar	NIR
White basecoat	0.87	0.86
Fiber cement board	0.47	0.46
Polywood	0.48	0.60

2.3. Spectral reflectance and lightness measurements

The spectral reflectance of conventional and cool gray coatings over 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). Following ASTM Standard E903-12 [14], the broadband reflectances (UV, visible, NIR and solar) were computed by averaging solar spectral reflectance using a global (direct + diffuse) solar spectral irradiance [15,16] as the weighting function.

Following the procedures described in ASTM Standard E308-01 [17], 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. The CIE standard illuminant D_{65} and 10° observer were selected for the device.

2.4. Thermal emittance measurements

A portable differential thermopile emissometer AE1 (Devices & Services Co., Dallas, TX) was used to measure the thermal emittance of the gray coatings according to ASTM C 1371-04 (a) [18]. The instrument was calibrated using both high and low emittance standards placed onto 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 conventional “hot” gray coatings

As shown in a previous study [9], both carbon black and copper chromite black are weakly scattering **“**hot**”** pigments with strong absorption across the entire solar spectrum. When used to prepare gray coatings, they are very effective in decreasing the solar reflectance of the final products.

Fig. 1 shows the spectral reflectance curves, the lightness dependence of the solar and NIR reflectances and the color images of the gray coatings containing different pigment volume concentrations (PVCs) of the carbon black over different backgrounds. For comparison, the spectral reflectance curves of the white coating, the standard black coating pigmented with carbon black (denoted as $S_{c\text{-}b}$) and the substrates are also shown in Fig. 1a(I)–c(I). The gray coatings containing different PVCs of the carbon black of 0.12%, 0.36%, 0.48%, 0.60% and 1.0% were denoted as $S_{c\text{-}b\text{-}g}$-1, $S_{c\text{-}b\text{-}g}$-2, $S_{c\text{-}b\text{-}g}$-3, $S_{c\text{-}b\text{-}g}$-4 and $S_{c\text{-}b\text{-}g}$-5, respectively. As indicated in Fig. 1a(I)–c(I), over the same substrate, the spectral reflectance curves of the gray coatings lie between the spectral reflectance curve of the white coating and that of the black coating. Compared to the white coating, even adding very small amount of carbon black can significantly decreases the VIS, NIR and solar reflectances of the gray coatings. The spectral reflectance curves of the gray coatings shift downward as the PVC of the carbon black increases. Note that there are overshoots in the NIR region between approximately 850 nm and 900 nm for all of the gray coatings and the black coating. The dips that are present in the NIR region of the curve of the white coating cannot be observed in the corresponding NIR regions of the curves of the gray coatings. Among the commercially available white pigments, titanium dioxide rutile has the strongest hiding power and tinting power; however, these powers are weaker than those of carbon black.

As shown in Fig. 1a(II)–c(II), over the same substrate, the lightness and the VIS, NIR and solar reflectances of the gray coatings decrease as the PVC of the carbon black increases. At the same PVC of the carbon black, these four quantities are similar over different backgrounds. The variation trends of lightness can be vividly observed in Fig. 1a(III)–c(III). These phenomena will also be observed below for the gray coatings created by separately mixing copper chromite black, chromite iron nickel black and manganese ferrite black with titanium dioxide rutile. According to the Chinese building industrial standard JG/T 235-2014 [19], for a cool coating with a lightness lower than 40, its NIR

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