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The methods for creating building energy efficient cool black coatings

Jie Qin, Jianrong Song, Jian Qu, Xiao Xue, Weidong Zhang*, Zhongnan Song, Yunxing Shi, Lihong Jiang, Jingfang Li, Tao Zhang

Technical Center, China State Construction Engineering Co., Ltd, No. 15 Linhe Street, Beijing 101300, PR China

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A B S T R A C T

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

* Corresponding author. Tel.: +0086 10 89498866; fax: +0086 10 89498030.
E-mail addresses: zhang.weidong@cscec.com, zwdpt@sohu.com (W. Zhang).

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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

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

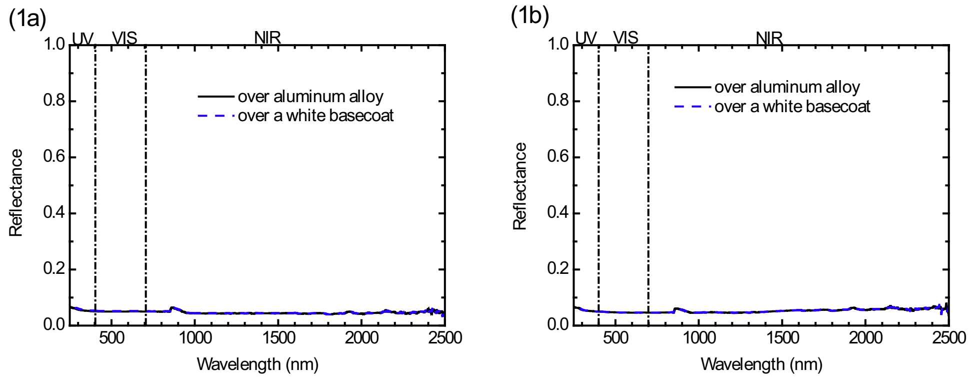

Fig. 1. Spectral reflectance curves for the black coatings separately pigmented with carbon black (a) and copper chromite black (b) colorants over bare aluminum alloy substrates and white basecoats.

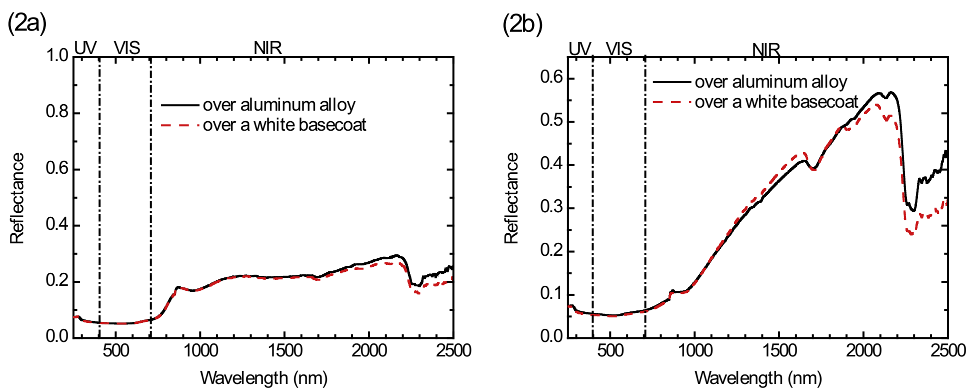

Fig. 2. Spectral reflectance curves for the black coatings separately pigmented with chromite iron nickel black (a) and manganese ferrite black spinel (b) colorants over bare aluminum alloy substrates and white basecoats.

where T_1 and R_1 are the transmittance and the solar reflectance of the top layer, respectively. R_2 is the solar reflectance of the background (basecoat and/or substrate) [21].

The solar reflectance of a two-layer coating system increases as the transmittance and solar reflectance of the top layer and the solar reflectance of the background increase. Because strong ultraviolet (UV) absorptance absorbance is required to shield the coatings and substrates [3] and all visible light is nearly absorbed to yield a black appearance, the NIR reflectance of a two-layer coating system should also increases as the NIR transmittance and NIR reflectance of the top layer and the NIR reflectance of the background increase. As clearly indicated in Eq. (1), the solar reflectance of the two-layer coating system is independent of the solar reflectance of the background for a black topcoat pigmented with non-NIR-transmitting colorants ($T_1 \rightarrow 0$). Because the solar reflectance of the black coatings separately pigmented with carbon black and copper chromite black colorants are nearly independent of the solar reflectance of the background, carbon black and copper chromite black are not NIR-transmitting black pigments.

The spectral reflectance curves for the black coatings separately pigmented with chromite iron nickel black and manganese ferrite black spinel colorants over bare aluminum alloy substrates and white basecoats are presented in Fig. 2. The corresponding computed solar and spectral reflectance values, together with the measured lightness, are listed in Table 3. Several observations can be made from Fig. 2 and Table 3. First, the spectral and solar reflectances of both coatings over the aluminum alloy substrates were similar to those of the coatings over white basecoats. Because the solar reflectance of a NIR-transmitting cool-colored coating system increases as the solar reflectance of the basecoats and/or substrates increases [21], chromite iron nickel black and manganese ferrite black spinel colorants are weakly NIR-transmitting pigments with strong absorption in the VIS and short NIR regions. Second, the solar reflectance of the coating pigmented with manganese ferrite black spinel colorant is higher than that of the coating pigmented with chromite iron nickel black over the same white basecoats and/or substrates. Third, the solar, VIS and NIR reflectances of black coatings pigmented with chromite iron nickel

Table 2
Spectral and solar reflectance values as well as lightness for the black coatings separately pigmented with carbon black and copper chromite black colorants over an aluminum alloy substrate and a white basecoat.

Samples		Reflectance				Lightness		
		Solar	UV	VIS	NIR	L^*	a^*	b^*
Carbon black	Over aluminum	0.049	0.053	0.050	0.048	26.2	−2.4	1.6
	Over white	0.049	0.053	0.050	0.047	25.1	−2.5	1.4
Cu–Cr black	Over aluminum	0.049	0.052	0.047	0.051	25.6	−2.7	1.0
	Over white	0.049	0.052	0.047	0.051	25.7	−2.7	1.0

Table 3
Spectral and solar reflectance values as well as lightness for the black coatings pigmented with chromite iron nickel black and manganese ferrite black spinel colorants over aluminum alloys and white basecoats.

Samples		Reflectance				Lightness		
		Solar	UV	VIS	NIR	L^*	a^*	b^*
Cr–Fe	Over aluminum	0.115	0.058	0.058	0.194	27.0	−1.5	1.3
black	Over white	0.113	0.057	0.058	0.190	27.0	−1.5	1.4
Mn–Fe	Over aluminum	0.124	0.055	0.056	0.219	26.9	−0.8	1.7
black	Over white	0.126	0.058	0.058	0.221	27.6	−0.8	1.5

black and manganese ferrite black spinel black colorants were higher than those of the black coatings separately pigmented with carbon black and copper chromite black colorants. Nevertheless, they cannot be considered as cool black coatings. According to the China building industrial standard JG/T 235-2014 (architectural solar reflective thermal insulation coatings), the NIR reflectance of a qualified cool coating with lightness L^* smaller than 40 should be higher than or equal to 0.4 and its solar reflectance should be higher than or equal to 0.3. As shown in Table 3, the lightess of these two coatings is smaller than 40, and their NIR reflectance and solar reflectance are also much lower than 0.4 and 0.3, respectively.

The spectral reflectance curves of the black coatings pigmented with perylene black colorant over an aluminum alloy and a white basecoat are compared in Fig. 3. The corresponding calculated spectral and solar reflectances, along with the measured lightness, are compared in Table 4. As shown in Fig. 3, the curves of the black coatings pigmented with perylene black over different backgrounds overlap in the UV and VIS region; the curve of the coating over the white basecoat is higher than that of the coating over the aluminum alloy substrate in the NIR region between 700 and 1600 nm; the curve of the coating over the white basecoat is lower than that of the coating over the aluminum alloy substrate in the NIR region between 1600 and 2500 nm. Because half of the NIR solar energy (a quarter of the total solar energy) lies within the shorter NIR wavelengths (700–1000 nm) and 30% lies within 1000–1500 nm [21,22], the NIR and solar reflectances of the coating over the white basecoat are higher than those of the coating over the aluminum alloy substrate (Table 4). Because the lightness of the black coating pigmented with perylene black colorant is smaller than 40 and its NIR reflectance and solar reflectance are much higher than 0.4 and 0.3, respectively, this coating appears to be a cool black coating according to the China building industrial standard JG/T 235-2014.

Fig. 4 and Table 5 show the similar results obtained for the black coating pigmented with dioxazine purple over a white basecoat and an aluminum alloy substrate. Overshoots are visible in the VIS region between 400 and 455 nm (Fig. 4). These overshoots are most likely due to the reflectance of the purple color (390–455 nm). ACIE $L^*a^*b^*$ (CIELAB), which is the most complete color space specified by the International Commission on Illumination (French Commission internationale de l'éclairage), describes all the colors visible to the human eye. The coordinates of CIELAB a^* and b^* represent the color's position between red/magenta and green (a^*, negative values indicate green while positive values indicate magenta) and its position between yellow and blue (b^*, negative values indicate blue and positive values indicate yellow), respectively. As shown in Table 5, the a^* and b^* of the coatings are positive and negative, respectively. The coatings have both a reddish and a bluish shade. According to basic color theory, mixing red and blue colors yields purple color. Therefore, the black coating pigmented dioxazine purple actually shows a violet shade.

Similar to the black coating pigmented with perylene black colorant, the NIR reflectance in the NIR region between 700 and 1600 nm of the black coating pigmented with dioxazine purple over the white basecoat is higher than that of the coating over the aluminum alloy substrate, whereas the opposite phenomenon occurs in the NIR region between 1600 and 2500 nm (Fig. 4). The NIR and solar reflectances of the coating over the white basecoat are higher than those of the coating over the aluminum alloy substrate. The lightness of the black coatings pigmented with dioxazine purple over different backgrounds is lower than 40, and their NIR and solar reflectances are higher than 0.4 and higher than or nearly equal to 0.3, respectively. Thus, the black coating pigmented with dioxazine purple is also a real cool black coating.

Fig. 5 presents the spectral reflectance curves of a bare aluminum alloy substrate and a white basecoat. This figure will be used to explain the following: 1. the lower NIR reflectances of the black coatings separately pigmented with perylene black and dioxazine purple over the aluminum alloy compared to the reflectances of the same coatings over white basecoats in the shorter NIR region and 2. The higher NIR reflectances of these coatings over the aluminum alloy compared to the same coatings over the white basecoats in

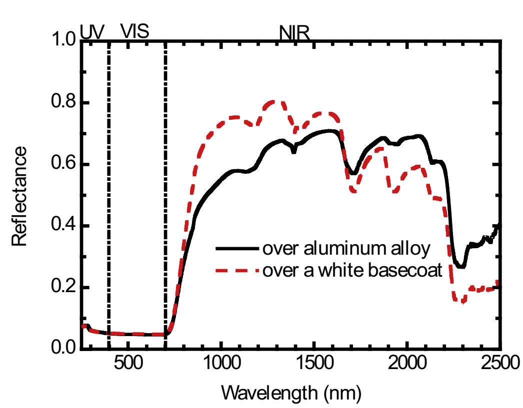

Fig. 3. Spectral reflectance curves for the black coatings pigmented with perylene black colorant over a bare aluminum alloy substrate and a white basecoat.

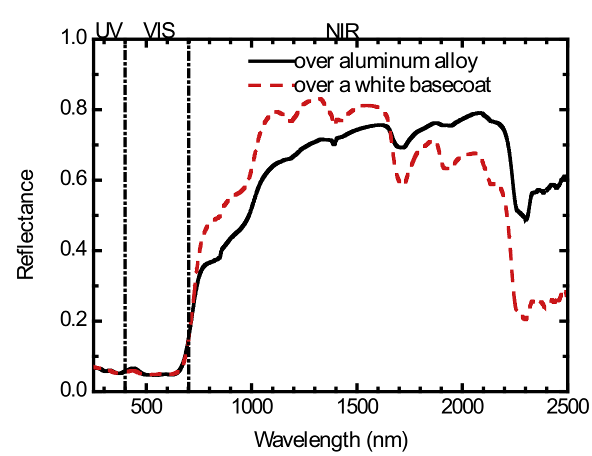

Fig. 4. Spectral reflectance curves for the black coatings pigmented with dioxazine purple colorant over a bare aluminum alloy substrate and a white basecoat.

Table 4
Spectral and solar reflectance values as well as lightness for the black coatings pigmented with perylene black over an aluminum alloy substrate and a white basecoat.

Samples		Reflectance				Lightness		
		Solar	UV	VIS	NIR	L^*	a^*	b^*
Perylene black	Over aluminum	0.335	0.054	0.079	0.686	25.6	−1.9	2.5
	Over white	0.346	0.051	0.075	0.715	25.2	−1.5	1.9

Table 5
Spectral and solar reflectance values as well as lightness for the black coatings pigmented with dioxazine purple colorant over an aluminum alloy substrate and a white basecoat.

Samples		Reflectance				Lightness		
		Solar	UV	VIS	NIR	L^*	a^*	b^*
Dioxazine purple	Over aluminum	0.298	0.054	0.098	0.572	25.6	1.3	−3.4
	Over white	0.334	0.054	0.107	0.644	26.0	0.8	−1.1

the longer NIR region. As shown in Fig. 5, the NIR reflectance of the white basecoat is higher than that of the aluminum alloy in the shorter NIR region, whereas the former is lower than the latter in the longer NIR region. As mentioned above, the NIR reflectance of the NIR-transmitting coating system highly depends on the NIR reflectance of the background. Therefore, the weaker reflectance of the aluminum alloy substrate in the shorter NIR region and its stronger reflectance in the longer NIR region generate the lower NIR reflectance values of the coatings in the shorter NIR region and the higher NIR reflectance values in the longer NIR region, respectively, due to the transparent nature of the perylene black and dioxazine purple colorants.

3.2. Re-establishment of true black coatings

According to the basic color theory, mixing two complementary colored pigments yields a neutral gray–black [27]. Therefore, a yellow colorant should be added to the violet-shaded black coating to re-establish a true black color. In this work, an NIR-transmitting chrome titanium yellow colorant (also known as chrome titanium brown, C. I. Pigment brown 24) was added to the black coating pigmented with dioxazine purple to re-establish true black coatings. The weight content of the yellow colorant ranged from 0.4 to 1.0 wt%. The results obtained for the coatings over a white basecoat are presented in Fig. 6 and Table 6.

When the weight content of the chrome titanium yellow colorant of the black coating is 0.4 wt%, the following phenomina can be observed: compared to the spectral reflectance curve of the black coating simply pigmented with dioxazine purple (Fig. 5), the overshoot in the VIS region of the refletance curve is nearly completely eliminited (Fig. 6); furthermore, the VIS, NIR and accordingly the solar reflectances of the black coating decrease, wheares the lightness of the coating increases (Tables 5 and 6); in addition, a^* changes from 0.8 to −0.9 and the b^* varies from −1.1 to 0.7 (Tables 5 and 6). Clearly, the violet shade was nearly eliminated, and the true black color was nearly re-established, although an exactly non-metameric match to the desired jet black color could not yet be obtained.

Because the weight content of the chrome titanium yellow pigment increases, the overshoots of the reflectance curves of the black coatings are shifted to the higher VIS wavelengths (Fig. 6), and the VIS, NIR and thus the solar reflectances increase (Fig. 6 and Table 6). Concurrently, the lightness, a^* and b^* also increase. Specifically, as the weight content of the chrome titanium yellow pigment increases from 0.4 to 1.0 wt%, the peaks of the overshoots gradually approach the yellow wavelength range (577–597 nm) and b^* increases from 0.7 to 3.3. Clearly, these values exceed the boundary of the desired black color tolerance. Taking into account all these factors, we believe that the appropriate weight content of the chrome titanium yellow pigment is 0.4 wt%. The measured solar reflectance of this modified black coating over a white basecoat (0.259) and over an aluminum alloy substrate (0.25) will be used below to estimate its cooling effect and cooling energy savings in Shanghai.

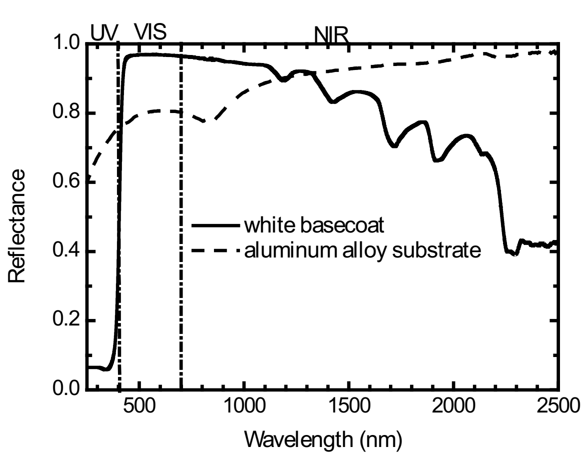

Fig. 5. Comparison of spectral reflectance curves for a bare aluminum alloy substrate and a white basecoat.

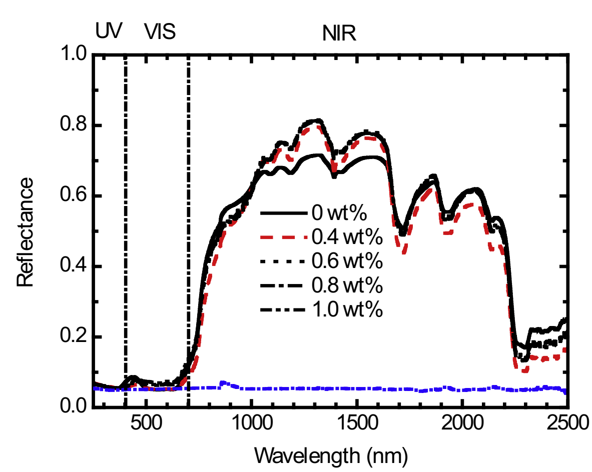

Fig. 6. Comparison of spectral reflectance curves for the black coatings pigmented with dioxazine purple and different weight contents of chrome titanium yellow over a white basecoat. For comparison, the spectral reflectance curve of the black coating pigmented with carbon black (short dash dotted line) is also presented.

Table 6
Spectral and solar reflectance values as well as lightness for the black coatings pigmented with dioxazine purple colorant and different weight contents of chrome titanium yellow colorant over a white basecoat.

Samples (wt%)	Reflectance				Lightness		
	Solar	UV	VIS	NIR	L^*	a^*	b^*
0.4	0.257	0.054	0.087	0.491	28.4	−0.9	0.7
0.6	0.284	0.055	0.099	0.536	30.4	−0.7	1.7
0.8	0.328	0.056	0.109	0.629	31.5	−0.7	2.5
1.0	0.339	0.057	0.115	0.646	32.3	−0.6	3.3

3.3. The measured thermal emittance of the black coatings

To assess the cooling effect and estimate the cooling energy savings in Shanghai, the thermal emittance of the black coatings pigmented with the selected black colorants were measured, and the obtained results are tabulated in Table 7. As anticipated, the thermal emittances of all black coatings pigmented with different colorants are nearly identical. The thermal emittances of non-metal surfaces and polymer-coated metal surfaces are widely accepted to be high, ranging from 0.85 to 0.95 [3,6,8,9,18]. Therefore, the obtained results are reasonable.

3.4. Estimated surface temperatures and cooling effect

Generally speaking, the true cooling effect of a coating can be assessed in two ways: the coating's surface temperature can be measured under the sun on a sunny calm summer day. However, a sunny calm summer day is not always available, and the measurement conditions change over time. Alternatively, the surface temperature of the coating can be estimated following ASTM E 1980-01 (standard practice for calculating solar reflectance index of horizontal and low sloped opaque surfaces) under the following conditions: insolation = 1000 W m^{-2}, sky temperature = 300 K, ambient air temperature = 310 K and convection coefficient (medium wind) = 12 W (m^2 K)$^{-1}$. The estimated surface temperatures of the black coatings and surface temperature reduction values relative to that of the black coating pigmented with carbon black and/or copper chromite black colorants are summarized in Table 8.

As shown in Table 8, the surface temperatures of the black coatings separately pigmented with the other four NIR-transmitting black colorants were lower than those of the black coatings separately pigmented with carbon black and copper chromite black under the standard conditions specified by ASTM E 1980-01. The black coatings pigmented with chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple reduced the temperatures on the aluminum alloy substrates by 3.1, 3.7, 12.0 and 9.8 °C, respectively, compared to the black coatings pigmented with carbon black and copper chromite black colorants; over white basecoats, the corresponding surface temperature reduction values were 3.0, 3.6, 13.8 and 10.2 °C, respectively. The black coatings pigmented perylene black and dioxazine purple colorants are real cool coatings, which agrees well with the above findings.

Table 7
Measured thermal emittance of the black coatings pigmented with different black colorants.

Samples pigmented with different black colorants	Thermal emittance
Carbon black	0.90
Copper chromite	0.89
Chromite iron nickel	0.91
Manganese ferrite black spinel	0.90
Perylene	0.90
Dioxazine purple	0.92

3.5. Estimated cooling energy savings of the coatings in Shanghai

In this section, the most commonly used DOE-2 computations will be used to estimate the cooling energy savings in Shanghai, a representative city in the Yangtze River Delta Region in China, due to the applications of black coatings on low-slope and/or flat roofs. The simulation was based on a simplified model [28] that correlates the cooling energy savings to the annual cooling degree days (base 18 °C, CDD18). The climate data for Shanghai were obtained from the Chinese typical meteorological year (CTMY) database, which was co-developed by Zhang et al. [29] and the Lawrence Berkeley National Laboratory.

Assuming that the average value of the roof insulation of the prototypical model house used in this paper was R-10 (1.74 m^2 kW^{-1}) and that the average coefficient of performance (COP) of the cooling air conditioner was 2.0, the simulated cooling energy savings due to the applications of the black coatings separately pigmented with chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple colorants over white basecoats in Shanghai are compared in Table 9. The simulated annual cooling energy savings in Shanghai for the black coatings separately pigmented with chromite iron nickel black and manganese ferrite black spinel colorants are nearly negligible. The estimated annual cooling energy savings in Shanghai resulting from the application of the black coatings separately pigmented with perylene black and dioxazine purple are 3.90 and 2.24 kW h yr^{-1} m^{-2}, respectively.

Table 8
Estimated surface temperatures of the black coatings and surface temperature reduction values relative to those of the black coating pigmented with carbon black and/or copper chromite black colorants.

Samples		Surface temperature (K)	Temperature reduction (°C)
Carbon black	Over aluminum	355.6	–
	Over white	355.6	–
Cu–Cr black	Over aluminum	355.6	–
	Over white	355.6	–
Cr–Fe black	Over aluminum	352.5	3.1
	Over white	352.6	3.0
Mn–Fe black	Over aluminum	351.9	3.7
	Over white	352.0	3.6
Perylene black	Over aluminum	343.6	12.0
	Over white	341.8	13.8
Dioxazine purple	Over aluminum	345.8	9.8
	Over white	345.4	10.2

Table 9
Estimated cooling energy savings for the cool black roof coatings separately pigmented with chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple colorants over white basecoats in Shanghai.

Coatings	Annual cooling energy savings (kW h m^{-2} yr^{-1})
Cr–Fe black	0.13
Mn–Fe black	0.40
Perylene black	3.90
Dioxazine purple	2.24

Shanghai is located in eastern China at a latitude of approximately 31°N in the sub-tropical monsoon climate zone. For a given low-slope or flat roof with a specific solar reflectance and thermal emittance, the cooling energy savings resulting from the applications of cool roof coatings are commonly known to positively correlate with the ambient temperature, the roof insulation and the COP of the air conditioner. Therefore, a larger cooling energy savings for subtropical monsoon climate zones and tropical monsoon climate zones would be expected, where the monthly average ambient temperatures in the summer are higher than those in Shanghai. In addition, the roof insulation assumed here is an average value. For poorly insulated roofs (e.g. R-5), the estimated annual cooling energy savings in Shanghai resulting from the application of the black coatings separately pigmented with perylene black and dioxazine purple are 6.70 and 4.32 $kW\,h\,yr^{-1}\,m^{-2}$, respectively. Apparently, the use of cool black coatings on the roofs in the Yangtzi River Delta Region in China can greatly reduce the cooling energy consumption in summer, save roof insulation costs for the same cooling energy use or improve the thermal comfort for non-air conditioned buildings in summer.

4. Discussion

For aesthetic and energy efficient considerations, organic and complex inorganic black pigments with good spectral selectivity have attracted some industrial formulators to fundamental and applied researches. Complex inorganic pigments are less expensive and generally exhibit high durability properties-weathering, temperature and chemical resistance, and UV scattering [12,23]. From the standpoints of energy-efficiency, practicality and cost-effectiveness, the ideal black pigments should be inorganic complex that have strong absorption in the VIS to show a black appearance and very weak absorption in the NIR to present good NIR reflectance and/or NIR transmittance. However, the commercially available inorganic chromite iron nickel black pigment only has weaker NIR transmittance (0.26) and NIR reflectance (0.15) [22]. As shown above, the other commercially available inorganic manganese ferrite black spinel pigment cannot endow the coatings with good NIR reflectance either even over a white basecoat. To the best of our knowledge, to date, there appears to be no other commercially available inorganic NIR-transmitting and/or NIR-reflecting black pigments. Although the black coatings separately pigmented with chromite iron nickel black and manganese ferrite black spinel colorants are cooler than those separately pigmented with carbon black and copper chromite black colorants, they are actually not eligible cool black coatings for building energy efficiency in China.

In a previous informative study [22], perylene black and dioxazine purple were identified to be weakly scattering organic pigments. The perylene black colorant exhibits a jet black appearance and has strong absorptance in the VIS (0.93) and very weak absorptance in the NIR (0.05) [22]. It has moderate NIR reflectance (0.21) and exceptionally strong NIR transmittance (0.74) [22]. The dioxazine purple shows a violet-black appearance. Its VIS and NIR absorptance values are 0.72 and 0.03, respectively. Its NIR reflectance and NIR transmittance are 0.1 and 0.87, respectively [22]. Apparently, both pigments have exceptionally high NIR transmittance. As shown above, over the suitable backgrounds (substrates and basecoats) with high solar and NIR reflectances, the black coatings separately pigmented with perylene black and dioxazine purple are qualified cool black coatings.

Although organic perylene and dioxazine purple are subject to the chemical stability, they exhibit excellent lightfastness and weatherfastness and are nearly ideal for formulation of black NIR-transparent layers [22]. When directly applied to a substrate with high NIR reflectance (e.g., a shiny metal, wood or a clay tile), they are qualified cool black coatings. When used on a substrate with low NIR reflectance (such as gray cement concrete tile, or gray aggregate) as the NIR-transparent topcoats, they are also eligible cool black coatings over a white basecoat.

From a cost and profit perspective, the application of black coatings pigmented with perylene black to the roofs of buildings is not realistic, mainly because of the high cost of the perylene black pigment. Dioxazine purple is a common organic pigment and is thus less expensive. Although it is less chemically stable than inorganic black pigments [22], the addition of inorganic yellow pigments to re-establish a true black color helps to improve its chemical stability. When black roofs are preferred to colored roofs, the black coating pigmented with dioxazine purple and yellow colorants likely presents one of the best choices for the building energy efficiency.

5. Conclusions

In this research work, the optical and thermal properties of the black coatings pigmented with different black pigments were investigated. The cooling effect and the energy savings potential of these black coatings were estimated. In addition, the cost and practicality of the black coatings separately pigmented with chromite iron nickel black, manganese ferrite black spinel, perylene black and dioxazine purple were analyzed. Inorganic chromite iron nickel black and manganese ferrite black spinel are not suitable pigments to manufacture qualified cool black coatings for building energy efficiency in China. Organic perylene black and dioxazine purple are nearly ideal to prepare NIR-transmitting black coatings. However, the high cost of the perylene black prevents the pigmented coating from being a good choice for the building energy efficiency. The coating pigmented with dioxazine purple is a practical cool black coating. When applied over a white basecoat, it can effectively reduce the roof surface temperature and the annual cooling energy consumption in summer.

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