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# A systematic investigation of the factors affecting the optical properties of near infrared transmitting cool non-white coatings

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ABSTRACT

The factors affecting the optical properties of a cool, brown coating were systematically investigated using a UV/Vis/NIR spectrophotometer to optimize its solar reflectance. Zinc iron chromite brown is a partially near infrared (NIR) transmitting colorant. Over bare substrates, the NIR and solar reflectances of the coatings generally but not always increase when the reflectance of the substrates increases; the roughness of the substrate surface lowers both values. When applied over reflective white basecoats, the NIR and solar reflectances of the coatings increase as the basecoats thicken and saturate above a threshold value. The NIR reflectance and solar reflectance of the cool brown coating system also decrease as the topcoat thickness and the pigment concentration increase. The computed absorptance of the films containing only an acrylic emulsion and zinc iron chromite brown increases as the pigment concentration and film thickness increase.



## 1. Introduction

In general, the coolest energy-efficient white roof coatings are conventionally used on commercial and official buildings with flat or low-sloped roofs [1–2], while owners of homes with sloped roofs visible from the ground often prefer non-white roofs for esthetic and visual reasons [1–8]. However, conventional dark-colored coatings generally absorb the invisible near infrared (NIR) radiation (700–2500 nm), which accounts for 52% of all solar energy, heating the building [2,4,8–9]. Because strong ultraviolet (UV) absorptance is required to shield the coatings and substrates and the visible (Vis) spectral reflectance is fixed to yield a specific color [3], the most effective way to improve solar reflectance is to maximize the NIR reflectance [2–3,9–10].

Pigments affect the optical and near-infrared properties of coatings [10]. Both organic and inorganic cool pigments exhibit weak absorption and/or strong backscattering in the NIR spectrum [11–12]. Therefore, cool pigments can maximize NIR reflectance, reducing heat buildup in the underlying structure [13–14]. Cool pigments may be sub-classified as "NIR-reflecting colorants" or "NIR-transmitting colorants" [9–10,13,15]; most pigments are NIR transmitting [11]. A coating with NIR-reflecting colorants may be applied directly over any substrate to create a cool non-white coating, while a coating with NIR-transmitting colorants requires an NIR-reflecting background [9–10,15]. Therefore, a substrate with high NIR reflectance (e.g., a shiny metal, wood or a clay tile) can be colored with a coat pigmented with NIR-transmitting colorants [3,9], while a substrate with low NIR reflectance (such as gray cement concrete tile, or gray aggregate) requires a white basecoat and a thin topcoat with NIR-transmitting colorants to form a cool colored composite [2–3,8–10,12,15–21]. This two-layered technique was initially proposed by Brady and Wake [10].

Solar reflectance and thermal emittance strongly affect the temperature of a surface [6,22]. Non-metal surfaces and polymer-coated metal surfaces have high thermal emittance values (0.85–0.95) [3,5–7,10] that are not affected by cool pigments [6]. Therefore, NIR reflectance and/or solar reflectance are two key parameters that influence the cooling effect of cool non-white coatings and are the primary focus of this paper. Of the papers reporting on cool non-white roof materials, only two studies describe the effects of topcoat's surface roughness on the solar reflectance of cool colored asphalt shingles [12,21]. They determined that smoothing the rough surfaces increases the reflectance at all wavelengths. In one of these previous works [12], the effects of the thickness and NIR reflectance of a tile's white basecoat were theoretically estimated, and the effects of the topcoat pigment concentration were mentioned without detailed information or explanation [12]. Surprisingly, to our knowledge, no more papers to date have reported the effects of the thickness of the

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topcoat and basecoat, the reflectance of the basecoat and/or substrates or the cool pigment content on the NIR reflectance and solar reflectance of two-layered, cool, non-white coatings.

Consequently, we conducted a systematic fundamental investigation on the above factors affecting the spectral reflectance of cool, non-white coatings to optimize their solar reflectance and improve their performance.

## 2. The Kubelka–Munk theory

The two-flux Kubelka–Munk (K–M) theory is commonly used to approximately describe the one dimensional, bidirectional propagation of diffuse light through a coating and/or film because of its simplicity and close match to the actual experimental situation [9,23]. In the K–M model of diffuse reflectance and transmission from a film with thickness of $d$, downward (perpendicular to the coating and in the direction of incidence) and upward (opposite to the direction of incidence) light beams can be absorbed and/or backscattered as they pass through the film. The computed wavelength-specific, thickness-independent backscattering coefficient ($S$) and absorption coefficient ($K$) may be used to predict the spectral reflectance ($R_f$) and spectral transmittance ($T_f$) of a coating of arbitrary thickness and background by [9]

$$R_f = \frac{1-R_2(a-b\coth bSd)}{a-R_2+b\coth bSd} \quad (1)$$

and

$$T_f = \frac{b}{a\sinh bSd + b\cosh bSd} \quad (2)$$

where

$$a = \frac{S+K}{S} \quad (3)$$

$$b = (a^2-1)^{1/2} \quad (4)$$

and $R_2$ is the reflectance of coating's background. These equations are applicable for a strongly and/or moderately scattering coating illuminated by collimated light from a spectrometer or the sun [9].

Because the topcoat has uniform (thickness-independent) absorption and backscattering coefficients, its reflectance and transmittance are non-directional. For a two-layer coating system, the reflectance $R_{12}$ of incident light is

$$R_{12} = R_1 + \frac{T_1^2 R_2}{1-R_1R_2} \quad (5)$$

where $R_1$ is the top layer's reflectance to incident light, $R_2$ is the lower layer's and/or substrate's reflectance to incident light, and $T_1$ is the topcoat's transmittance of incident light [9].

The reflectance of the two-layer cool coating system depends on the transmittance and reflectance of the NIR-transmitting topcoat and the reflectance of the NIR-reflecting basecoat and/or substrate. For a given topcoat, the reflectance $R_{12}$ increases as the reflectance of basecoat and/or substrate increases. For a given basecoat and/or substrate, the reflectance $R_{12}$ increases as the transmittance and reflectance of the topcoat increase.

For an NIR-transmitting film with weak absorptance ($K \to 0$), then $a \to 1$ and $b \to 0$; Eq. (2) may be evaluated in the limit

$$\lim_{K\to 0} T_f = \frac{1}{1+Sd} \quad (6)$$

For a film with weak backscatter ($S \to 0$), Eq. (2) may be evaluated in the limit

$$\lim_{S\to 0} T_f = \exp^{(-kd)} \quad (7)$$

In both cases, the transmittance of the pigmented films decreases as the films' thickness increases. Therefore, for a partially NIR-transmitting film, its transmittance decreases as it thickens.

## 3. Experimental

### 3.1. Selection of materials

A representative cool, brown coating was selected to study the factors affecting the spectral reflectance of two-layered, cool, non-white coatings. To prepare the cool, brown top coating, a pure acrylic emulsion and zinc iron chromite brown (CI Pigment Brown 33) with density of 4.5–5.3 g/cm$^3$ were selected. Talcum and silicon dioxide were selected as extender pigments because they are transparent and non-reflective throughout the visible and near-infrared regions and do not interfere with the performance of the other pigments [10,13]. In addition, the appropriate paint additives, including a wetting agent, a dispersant, an antifoaming agent, a leveling agent and a coalescent, were also selected to improve the quality and performance of the topcoat. The above materials were used as received to prepare the cool brown topcoat. The composition of the wet topcoat is listed in Table 1.

### 3.2. Preparation of the cool brown top coating

The preparation of the cool, brown topcoat proceeded as follows: the acrylic emulsion, talcum, silicon dioxide and a portion of the total water were pumped into the mixing apparatus, followed by the wetting agent, dispersant and antifoaming agent. The mixture was stirred at high speed for 30 min, and the prefabricated pigment dispersion was pumped into a paint-mixing apparatus. The antifoaming agent, leveling agent and coalescent were added, and the mixture was continuously mixed at high speed for 30 min. Finally, the remainder of the total water was added to adjust the viscosity.

### 3.3. Preparation of cool brown films

To prepare cool brown films, coatings that contained only the acrylic emulsion and zinc iron chromite brown at a weight concentration of 0.5%, 1%, 3%, 5%, 10%, 20%, 30% and 40% (by weight) were sprayed on to glass molds coated with a demolding agent. After the films were dry, they were demolded and rinsed with clean water. To study the effects of the pigment concentration on the cool, non-white coatings, the coatings were also sprayed onto cleaned aluminum alloy substrates and aluminum alloy substrates painted with a self-manufactured cool, white basecoat;

**Table 1**
The composition of the wet cool brown top coating.

| Component | Manufacturer | Content by weight (%) |
|---|---|---|
| Pure acrylic emulsion | Showa Highpolymer Co., Ltd, Shanghai, China | 54.5 |
| Zinc iron chromite brown | Nanjing PMT Pigment Tech. Co., Ltd, China | 2 |
| Talcum | DuPont Chemicals Co., Ltd, China | 15 |
| Silicon dioxide | Haihua Chemicals Co., Ltd, Guangzhou, China | 15 |
| Wetting agent | Adeka Corporation, Tokyo, Japan | 0.7 |
| Dispersant | Adeka Corporation, Tokyo, Japan | 0.7 |
| Antifoaming agent | Adeka Corporation, Tokyo, Japan | 0.5 |
| Leveling agent | Adeka Corporation, Tokyo, Japan | 0.5 |
| Coalescent | Adeka Corporation, Tokyo, Japan | 0.5 |
| Water | – | 11 |