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ScienceDirect
Solar Energy Materials & Solar Cells 91 (2007) 304–314
Solar Energy Materials and Solar Cells
www.elsevier.com/locate/solmat

Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials

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Received 2 April 2005; received in revised form 2 September 2005; accepted 15 June 2006
Available online 28 November 2006

Abstract

We describe methods for creating solar-reflective nonwhite surfaces and their application to a wide variety of residential roofing materials, including metal, clay tile, concrete tile, wood, and asphalt shingle. Reflectance in the near-infrared (NIR) spectrum (0.7–2.5 μm) is maximized by coloring a topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, and by adding an NIR-reflective basecoat (e.g., one colored with titanium dioxide rutile white) if both the topcoat and the substrate weakly reflect NIR radiation. Coated steel and glazed clay-tile roofing products achieved NIR reflectances of up to 0.50 and 0.75, respectively, using only cool topcoats. Gray-cement concrete tiles achieved NIR reflectances as high as 0.60 with coatings colored by NIR-scattering pigments. Such tiles could attain NIR reflectances of up to 0.85 by overlaying a white basecoat with a topcoat colored by NIR-transparent organic pigments. Granule-surfaced asphalt shingles achieved NIR reflectances as high as 0.45 when the granules were covered with a white basecoat and a cool color topcoat.

Keywords: Roofing; Residential; Reflective; Solar; Near infrared; Scattering; Absorption; Coating; Pigment; Metal; Clay tile; Concrete tile; Wood; Asphalt shingle; Treatment; Conversion coating

1. Introduction

A roof with high solar reflectance (ability to reflect sunlight) and high thermal emittance (ability to radiate heat) stays cool in the sun, reducing demand for cooling power in conditioned buildings and increasing occupant comfort in unconditioned buildings. Nonmetallic surfaces and most polymer-coated metal surfaces have high thermal emittance. Hence, a cool roofing surface may be described as a nonmetal or polymer-coated metal with high solar reflectance.

Visible light (0.4–0.7 μm)[1] contains 43% of the power in the air-mass 1.5 global solar irradiance spectrum (0.3–2.5 μm) typical of North-American ground-level insolation; the remainder arrives as near-infrared (NIR) radiation (0.7–2.5 μm, 52%) or ultraviolet (UV) radiation (0.3–0.4 μm, 5%) [2]. A clean, smooth, and solar-opaque white surface strongly reflects both visible and NIR radiation, achieving a solar reflectance of about 0.85. This is the coolest type of roofing surface, and is ideal for

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[1]The spectrum of visible light is typically specified as either 0.38–0.78 μm, or 0.40–0.70 μm. We choose the simpler range 0.40–0.70 μm because phototropic responses to light in the tails (0.38–0.40 and 0.70–0.78 μm) are low [1].

0927-0248/$ - see front matter
doi:10.1016/j.solmat.2006.06.062

low-slope roofs visible neither from ground level nor from taller buildings.

The solar reflectance of a roofing surface (especially that on a home) may be constrained by (a) desire for a nonwhite appearance, which limits visible; (b) NIR transparency of a thin and/or sparsely pigmented coating; and/or (c) curvature, which can cause light reflected from one face to be absorbed by another face. Nonwhite surfaces can be made as cool as possible by maximizing reflectance in the NIR spectrum, which does not affect color. Smoothing rough surfaces can increase reflectance at all wavelengths.

This study describes the engineering principles for creating a solar-reflective coated surface, and their application to a wide variety of residential roofing materials, including metal, clay tile, concrete tile, wood, and asphalt shingle.

2. Literature review

Brady and Wake [3] present the basic method for creating a coating with high NIR reflectance: color an otherwise transparent topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, adding an NIR-reflective basecoat (e.g., titanium dioxide rutile white) if both the topcoat and the substrate weakly reflect NIR radiation (Fig. 1). This technique is reprised in whole or in part by US patents and patent applications for creating generic NIR reflectors [4,5] and for creating NIR-reflective granules and/or granule-surfaced asphalt shingles [6,7,20,21].

The authors reviewed current methods of manufacturing metal, clay tile, concrete tile, and asphalt shingle roofing materials in a earlier pair of articles [8,9].

3. Methodology

3.1. Maximizing solar reflectance of a colored surface

The fraction R of solar radiation incident at wavelengths between λ_0 and λ_1 that is reflected by a surface is the irradiance-weighted average of its spectral reflectance $r(\lambda)$. That is,

$$R_{\lambda_0\to\lambda_1} = \left(\int_{\lambda_0}^{\lambda_1} r(\lambda)i(\lambda)\,\mathrm{d}\lambda\right) \Big/ \int_{\lambda_0}^{\lambda_1} i(\lambda)\,\mathrm{d}\lambda, \quad (1)$$

where $i(\lambda)$ is the solar spectral irradiance (power per unit area per unit wavelength). Irradiance-weighted average reflectances of interest include solar reflectance S (0.3–2.5 μm), UV reflectance U (0.3–0.4 μm), visible reflectance V (0.4–0.7 μm), and NIR reflectance N (0.7–2.5 μm).

It follows from Eq. (1) that the solar reflectance of a surface may be computed as the weighted average of its UV, visible, and NIR reflectances. The aforementioned distribution of solar power (5% UV, 43% visible, and 52% NIR) yields

$$S = 0.05U + 0.43V + 0.52N. \quad (2)$$

Strong UV absorption by surface-layer pigments (e.g., titanium dioxide rutile white) or aggregate (e.g., granules) is usually desirable to prevent UV damage to lower components of the roofing product, such as the primer layer in a coated metal system or the asphalt in a granule-surfaced asphalt shingle. High UV reflectance would be even better, but is difficult to achieve with nonmetallic surfaces. Hence, we maximize solar reflectance by establishing high reflectances in the visible and NIR spectra that contain 95% of the incident solar radiation.

Since there is usually more than one visible spectral reflectance curve (reflectance vs. wavelength in the visible spectrum) that will yield a desired color under a particular illuminant, it is possible to maximize visible reflectance by designing to a color, rather than to a visible spectral reflectance curve. However, this may yield metamerism, in which the color of the coated surface matches that of another surface under one illuminant (e.g., early-morning sun) but not another (e.g., noon sun). Maximizing only NIR reflectance avoids this problem.

3.2. Creating a coated surface with high NIR reflectance

When appearance and hence visible reflectance are constrained by design, a "cool" surface is one with high NIR reflectance. Consider a substrate (opaque structural

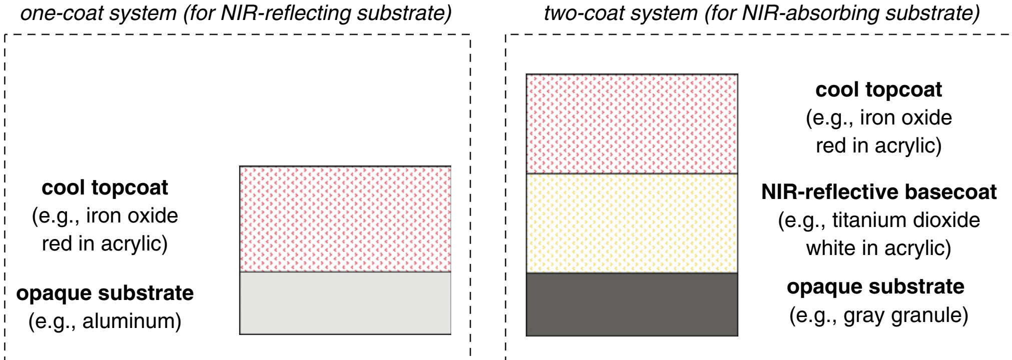

Fig. 1. Schematics of one-coat (substrate + topcoat) and two-coat (substrate + basecoat + topcoat) systems. The one-coat system can also be applied over an NIR-absorbing substrate if the topcoat has at least moderate NIR backscattering and is sufficiently thick.