



Evaluation of thermochromic elastomeric roof coatings for low-slope roofs



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ABSTRACT

Thermochromic elastomeric roof coatings for low-slope roofs were prepared by incorporating a commercial thermochromic dye (with transition temperature, $T_c \sim 32^\circ\text{C}$) into a white acrylic elastomer matrix. Freshly applied coatings showed an initial temperature-dependent solar reflectance change of 22–25%, with a maximum solar reflectance of 70% in the colorless state ($T > T_c$). Weathering studies revealed that these thermochromic coatings undergo irreversible photodegradation in as little as 96 h of accelerated aging. Attempts to protect thermochromic dyes with inorganic (nano-ZnO) or organic (Lowilite® 20S) UV absorbers were partially successful but need significant improvements to achieve the required lifetime of at least 10 years. Cost calculations in three different geographies showed that even if the durability of these coatings is greatly improved, the energy savings relative to the incumbent static cool roofs are small and do not currently justify the additional cost of thermochromic pigments and UV absorbers.

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1. Introduction

The impact of large cities on climate change can be reduced through improvements in energy efficiency of buildings and by mitigation of the urban heat island effect [1,2]. Energy conservation through cool roof technology appears to be a promising means to limit this impact on climate change—especially in commercial low-slope roofing as a means to reduce energy usage related to air-conditioning in hot weather [3]. Although this technology is advantaged over traditional black roofs, static cool roofing has the disadvantage of reflecting solar energy in cold weather, increasing heating costs. Current widely deployed cool roofing technologies for commercial low-slope roofs include elastomeric (acrylic latex) coating formulations or thermoplastic polyolefin (TPO), ethylene propylene diene monomer membrane (EPDM), or polyvinyl chloride (PVC) single ply membranes, chloro sulfonated polyethylene (CSPE), or metal roofing [4]. Unlike residential roofing applications, the main driver for adoption of such new technologies in commercial roofing is energy savings with a lower priority given to aesthetics

An alternative approach involves an adaptive technology that changes its optical properties as a function of temperature—a thermochromic technology [5,6]. The prior art for thermochromic coat-

ings is rather limited [7–9]. As of today, no thermochromic roofing membranes or coatings are available on the market. In principle, such a roof would have a low solar reflectance (SR) below a temperature threshold ($T < T_c$) and a high solar reflectance above that threshold ($T > T_c$). Currently, no single material exists that can successfully achieve such a thermochromic change across the entire solar spectrum at ambient temperature. Many thermochromic materials—especially organic thermochromic dyes—switch from an intensely colored (i.e. absorbing) state below T_c to a colorless or nearly colorless state above T_c [5]

Instead, a combination of materials in a multi-layer system (Fig. 1) could provide the desired performance in order to minimize energy usage on both hot and cold days. An ideal thermochromic material would fully match the solar spectrum for absorbance at low temperatures ($T < T_c$) and for reflectance at high temperatures ($T > T_c$). Practically, however, a single material will be incapable of fully covering the broad wavelength range of the solar spectrum. Since the visible region of the solar spectrum (390–700 nm) is relatively narrow and contains about 50% of the solar energy, any solution that operates well over that range would have a useful impact on the energy efficiency of large low-slope commercial buildings. In an ideal smart roof coating system, a large solar reflectance above the transition temperature (preferably $SR_{(T > T_c)} > 70\%$) and a large change in solar reflectance ($\Delta SR = SR_{(T > T_c)} - SR_{(T < T_c)}$) are desired

One such class of materials is organic leuco dyes—multi-component systems that contain a leuco dye, a weak acid, a weak

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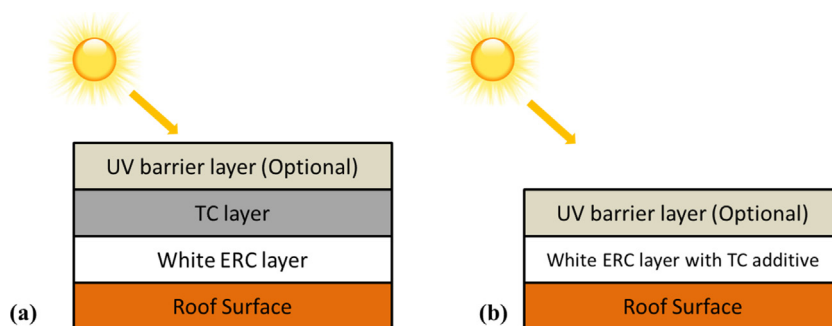


Fig. 1. Schematics of proposed multi-layered thermochromic roof coating systems. (a) Two-layer system with optional UV barrier layer. (b) Single layer system with optional UV barrier layer (ERC: Elastomeric Roof Coating, TC: Thermochromic).

base, and a high melting solvent inside a microcapsule [5]. While these dyes undergo a temperature-dependent color change, they are technically halochromic, i.e. they undergo a color change in response to a change in protonation state. The change in protonation state is brought about by the melting of the encapsulated solvent that results in allowing the interaction of the weak acid with the leuco dye. Upon protonation, the colored dye becomes transparent. As the solvent solidifies upon cooling below T_c , the reaction reverses to return to the dye's colored state

In this report, we have evaluated the performance of a commercially available leuco dye ($T_c \sim 32^\circ\text{C}$) as a thermochromic additive in the fabrication of a multi-layered thermochromic roof coating system. The coatings were also tested for UV stability, and energy savings were performed to determine the commercial viability of such coatings

2. Methodology

Rhoplex™ EC-1791 acrylic polymer with and without TiO_2 was obtained from Dow Construction Chemicals and used as the elastomeric roof coating (ERC) formulation. Hereafter, they will be referred as white and clear ERC, respectively. A black thermochromic slurry (TA031K, QCR Solutions Corp., $T_c = 31^\circ\text{C}$) was used as the organic thermochromic dye (OTD) [10]. For UV barrier layers, nanoparticulate ZnO (Nanophase Technologies Corporation) or Lowilite® 20S (Chemtura Corporation, CAS: 4065-45-6) was dispersed in clear ERC formulations. Lowilite® 20S is a water soluble benzophenone UV absorber.

Coating formulations were prepared by thoroughly mixing the ERC and the relevant additive using a Flacktek SpeedMixer (DAC 150). Coatings were applied to aluminum test panels (Q-Panel A-36, 70 mm \times 150 mm) using a BYK 4" square frame (wet thickness of 5, 15, 25, or 50 mil/coat). UV-vis transmission measurements were carried out on coatings, which were applied to glass microscope slides, using a Perkin Elmer Lambda 35 UV-vis-NIR spectrometer with wavelength range from 200 to 2500 nm. Solar reflectance was measured on a solar spectrum reflectometer (Devices and Services, SSR-ER version 6) calibrated to AM1.5. Solar reflectance measurements were recorded on triplicate samples at the top, middle, and bottom of each sample.

To collect data at elevated temperatures ($T > 40^\circ\text{C} > T_c$), the samples were heated either by a heat gun or placed on a hot plate prior to measurement, and the sample temperature was monitored by an infrared thermometer. Since the thermochromic dye showed a sharp color change above its T_c and remained in its light-colored state for a prolonged period, continuous heating of samples during measurement was not required.

An Atlas Material Testing Ci65 Xenon Arc Weatherometer was used for accelerated solar aging. Up to 504 h of continuous illu-

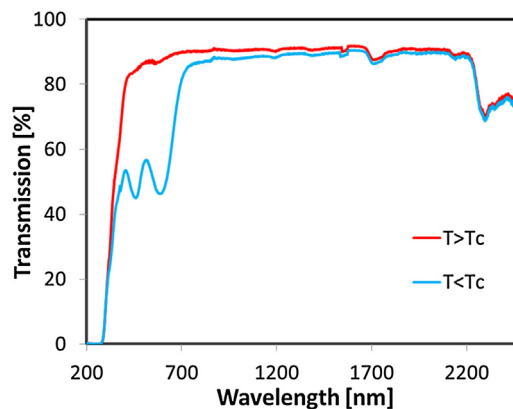


Fig. 2. UV-vis-NIR transmission spectra of the thermochromic layer (10 wt% OTD, 50 μm) below and above the transition temperature ($T_c = 32^\circ\text{C}$).

mination was used to simulate natural sun exposure. The samples were irradiated across a spectrum of the xenon-arc wavelengths achieved by filtering through Type S borosilicate filters.

ASTM D2565 (procedures and test conditions for the exposure of plastics in a test to simulate solar radiation in direct sunlight) was used to evaluate coatings [11]. As per ASTM D2565, the testing was conducted using a modification to Cycle 1 with the black panel temperature controlled at $63 \pm 2^\circ\text{C}$ and relative humidity at $50 \pm 5\%$ without water spray. The xenon arc light source was calibrated to a $0.46 \pm 0.05 \text{ W/m}^2$ output at a wavelength of 340 nm.

3. Results and discussion

3.1. Coating performance

The transmission UV-vis-NIR spectrum of a 50 μm thick thermochromic layer, formed by dispersing 10 wt% of the OTD in a clear ERC formulation, is shown in Fig. 2. The layer showed a maximum change of 40% in its optical transmission, which was accompanied by a change in color from opaque black to nearly colorless and translucent, as temperature was increased above T_c . Minimal changes were observed in the NIR region.

To optimize the loading of thermochromic dye for a single layer system (Fig. 1b), increasing amounts of OTD were dispersed in opaque white ERC formulations, and the solar reflectance (SR) of the applied coatings was measured below and above the transition temperature (T_c). Increasing the concentration of OTD from 1 to 15 wt% increased the change in solar reflectance (ΔSR) from 5 to 15% with negligible improvements in ΔSR above 10 wt% (Fig. 3). Since the absolute value of SR (for $T > T_c$) also decreased with increasing dye content (Fig. 3), 10 wt% was identified as the opti-

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