

Cool Colored Materials for Roofs

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ABSTRACT

Raising the solar reflectance of a roof from a typical value of 0.1 – 0.2 to an achievable 0.6 can reduce cooling-energy use in buildings by more than 20%. Cool roofs also reduce ambient outside air temperature, thus further decreasing the need for air conditioning and retarding smog formation.

We are collaborating with pigment manufacturers to characterize colorants, and with manufacturers of roofing materials to produce cool colored products, including asphalt shingles, tiles, metal roofing, wood shakes, membranes, and coatings. Significant efforts are being devoted to the identification and characterization of pigments suitable for cool-colored coatings, and to the development of engineering methods for applying cool coatings to roofing materials. We are also measuring and documenting the laboratory and in-situ performances of roofing products. Demonstration of energy savings can accelerate the market penetration of cool-colored roofing materials. Early results from this program have yielded colored concrete, clay, and metal roofing products with solar reflectances exceeding 0.4. Obtaining equally high reflectances for roofing shingles is more challenging, but we expect manufacturers to soon have several cost-effective colored shingles with reflectances of at least 0.25.

Introduction

Benefits of Cool Roofs

Building-energy monitoring studies in California and Florida have demonstrated cooling-energy savings in excess of 20% upon raising the solar reflectance of a roof to 0.6 from a prior value of 0.1 - 0.2 (Konopacki and Akbari, 2001; Konopacki *et al.*, 1998; Parker *et al.*, 2002). Energy savings are particularly pronounced in older houses that have little or no attic insulation, especially if the attic contains the air distribution ducts. Our research estimates U.S. potential energy savings in excess of \$750 million per year in net annual energy bills (cooling-energy savings minus heating-energy penalties) (Akbari *et al.*, 1999). Cool roofs also significantly reduce peak electric demand in summer (Akbari *et al.*, 1996; Levinson *et al.*, 2004a). The widespread installation of cool roofs can lower the ambient air temperature in a neighborhood or city, decreasing the need for air conditioning, retarding smog formation, and improving environmental comfort. These “indirect” benefits of reduced ambient air temperatures have roughly the same economic value as the direct energy savings (Rosenfeld *et al.*, 1997).

Lower surface temperatures may also increase the lifetime of roofing products (particularly asphalt shingles), reducing replacement and disposal costs. Our preliminary analysis suggests that there may be a surcost of up to \$1 per square meter for cool roofing materials. This represents 2 to 5% of the cost of installing a new residential roof.

Availability of Cool Roofing Materials

Cool (solar-reflective) roofing products currently available in the market, such as single-ply membranes and elastomeric coatings, are applied almost exclusively to commercial buildings with low-sloped roofs. Cool products for pitched residential roofs are generally limited to tile and metal. Asphalt shingles dominate the residential roofing market, comprising 47% of 2004 sales in the western state residential market (Western Roofing, 2004). Assuming that the cost per unit roof area of asphalt shingles is about half that of other residential roofing products, we estimate the fraction by surface area is over 60%. Most commercially available asphalt shingles are optically dark, with solar reflectance ranging from 0.05 to 0.25, depending on color. With the exception of one “ultra-white” product, even nominally “white” shingles appear gray, and have a solar reflectance of about 0.25—much lower than the solar reflectance of 0.7 achieved by a white tile or a white metal panel. It is possible to produce a truly white shingle with a solar reflectance of about 0.55 by increasing the amount of white pigment (titanium dioxide rutile) on its granules. However, since many homeowners desire nonwhite roofs, we seek to develop and promote cool colored roofing products, especially shingles.

Development of Nonwhite Cool Roofing Materials

Currently, suitable cool *white* materials are available for most roofing products, with the notable exception of asphalt shingles. Cool nonwhite materials are needed for all types of roofing. Industry researchers have developed complex inorganic color pigments that are dark in color but highly reflective in the infrared portion of the solar spectrum. The high near-infrared reflectance of coatings formulated with these and other “cool” pigments—e.g., chromium oxide green, cobalt blue, phthalocyanine blue, Hansa yellow—can be exploited to manufacture roofing materials that reflect more sunlight than conventionally pigmented roofing products.

The California Energy Commission (CEC) has engaged Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) on a three-year project to (a) work with the roofing industry to develop and produce colored roofing products with high solar reflectance, and (b) encourage the homebuilding industry to use these products. The intended outcome of this project is to make nonwhite cool roofing materials commercially available within three to five years. Specifically, we aim to produce nonwhite shingles with solar reflectances not less than 0.3, and other types of nonwhite roofing products (e.g., tiles) with solar reflectances not less than 0.45. The reflectance goal for shingles is lower than that for other products because (a) the roughness of a shingle’s surface reduces its reflectance, and (b) manufacturing constraints typically limit the reflectance of coatings applied to granules.

We are collaborating with pigment manufacturers to characterize colorants, and with manufacturers of roofing materials to produce cool colored products, including asphalt shingles, tiles, metal roofing, wood shakes, membranes, and coatings. Significant efforts are being devoted to the identification and characterization of pigments suitable for cool-colored coatings, and to the development of engineering methods for applying cool coatings to roofing materials. We are also measuring and documenting the laboratory and in-situ performance of roofing products. The latter, including demonstrations of building energy savings, can accelerate the market penetration of cool-colored roofing materials.

Research & Marketing Issues

Our activities are designed to address the following six topics.

1. *Formulation of Cool Colored Coatings.* How can we maximize the total solar reflectance of a pigmented coating while matching a desired color?
2. *Development of Cool Colored Roofing Prototypes.* What is the relationship between the optical properties of a simple pigmented coating and the optical properties of a pigmented coating applied to roofing materials (e.g., granules, tiles)?
3. *Durability of Cool Colored Coatings.* How do cool colored coatings weather and age?
4. *Longevity of Cool Colored Roofing Materials.* Does higher solar reflectance increase the lifetime of cool colored roofing materials?
5. *Demonstration of Energy Savings.* What are the building-energy savings yielded by use of cool colored roofing materials?
6. *Market Introduction.* How can we promote the use of cool colored roofing materials?

Formulation of Cool Colored Coatings

In order to determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to that of a standard material, we (a) have identified and characterized the optical properties of over 100 pigmented coatings; (b) have created a preliminary database of pigment characteristics; and (c) are developing a computer model to maximize the solar reflectance of roofing materials for a choice of visible color.

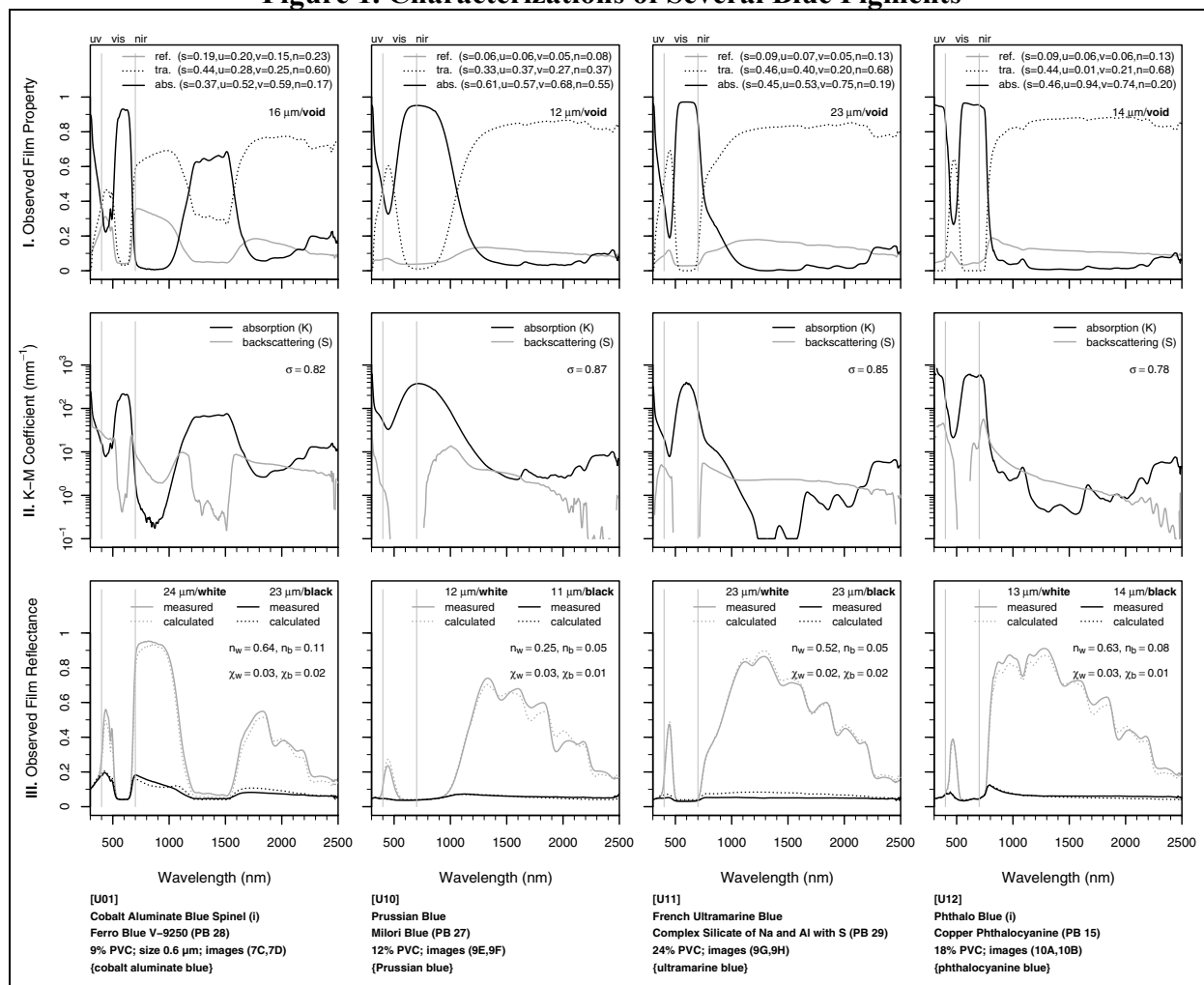
Pigment Characterization

We have measured the spectral optical properties of many individual pigments and have used these data to develop a method to predict the spectral radiative properties of materials fabricated with these pigments (Levinson *et al.*, 2004b,c).

We illustrate our characterization efforts by presenting results for four blue pigments (see Figure 1). Each pigment is described by a column of three solar spectral charts. The first chart shows the measured transmittance, measured reflectance, and calculated absorptance of a pigmented film; the second, its computed absorption coefficient K and backscattering coefficient S ; and the third, its measured and computed reflectances over black and white backgrounds, which serve as checks on the mathematical consistency of the results. The absorption coefficient K should be large in parts of the visible spectral range, to permit the attainment of desired colors, and should be small in the near infrared (NIR). The backscattering coefficient S should be small (or large) in the visible spectral range for formulating dark (or light) colors, and is preferably large in the NIR.

Cobalt aluminate blue (CoAl_2O_4 ; U01) derives its appearance from modest scattering ($S \sim 30 \text{ mm}^{-1}$) in the blue (400 - 500 nm) and strong absorption ($K \sim 150 \text{ mm}^{-1}$) in the rest of the visible spectrum. It has very low absorption in the short NIR (700 - 1000 nm, containing 50% of the NIR energy), but exhibits an undesirable absorption band in the 1200 - 1600 nm range, which contains 17% of the NIR energy. A white background dramatically increases NIR reflectance but makes it lighter in color.

Figure 1. Characterizations of Several Blue Pigments



Each pigment is described by a column of three solar spectral charts. The first chart shows the transmittance, reflectance, and absorbance of a pigmented film; the second, its absorption coefficient K and backscattering coefficient S ; and the third, its measured and computed reflectances over black and white backgrounds, which serve as checks on the mathematical consistency of the results.

Iron (a.k.a. Prussian or Milori) blue (U10) is a weakly scattering pigment with strong absorption in the visible and short NIR, and weak absorption at longer wavelengths. It appears black and has little NIR reflectance over a black background, but looks blue and achieves a modest NIR reflectance (0.25) over a white background. It should be avoided in cool coatings.

Ultramarine blue (U11), a complex silicate of sodium and aluminum with sulfur, is a weakly scattering pigment with some absorption in the short NIR. If sparingly used, it can impart absorption in the yellow spectral region without introducing a great deal of NIR absorption. This is a durable inorganic pigment with some sensitivity to acid. While most colored inorganic pigments contain a transition metal such as Fe, Cr, Ni, Mn, and Co, ultramarine blue is unusual. It is a mixed oxide of Na, Si, and Al, with a small amount of sulfur. The metal oxide skeleton forms an open clathrate structure that stabilizes S_3 ions in cages to form the chromophores. Thus isolated S_3 molecules with an attached unpaired electron cause the light absorption in the 500-700 nm range, producing the blue color.

Copper phthalocyanine blue (“phthalo” blue) (U12) is a weakly scattering, dyelike pigment with strong absorption in the 500 - 800 nm range and weak absorption in the rest of the visible and NIR. Phthalo blue appears black and has minimal NIR reflectance over a black background, but looks blue and achieves a high NIR reflectance (0.63) over a white background. It is durable and lightfast, but as an organic pigment it is less chemically stable than (high temperature) calcined mixed metal oxides such as cobalt aluminate.

Pigment Property Database

We have developed a preliminary database summarizing our characterizations of about 100 pigments. The database describes each pigment with a tab-delimited plaintext file that includes identification (name, color, and chemistry); mechanical properties (film thicknesses); spectral optical properties (measured reflectance, transmittance, and absorptance; derived absorption and backscattering coefficients; predicted reflectances over various backgrounds); and ancillary parameters generated in the derivation of absorption and backscattering coefficients. We have shared this database with our industrial partners to help them develop cool colored coatings and roofing products.

Cool-Color Formulation Software

We are developing a model that estimates the spectral solar reflectance of coatings from (a) pigment properties (spectral absorption and backscattering coefficients); (b) coating composition (pigments, vehicle, and filler); and (c) coating geometry (thickness and roughness). This model will be implemented in software that suggests recipes to maximize the solar reflectance of a colored coating. The software will be available to pigment, coating, and roofing manufacturers.

Development of Cool Colored Roofing Prototypes

We have surveyed methods of manufacturing various roofing materials, and are working with roofing manufacturers to design innovative techniques for producing cool-colored materials.

Survey of Manufacturing Methods

We estimate that roofing shingles, tiles, and metal panels comprise over 80% (by roof area) of the western state residential roofing market. We contacted representative manufacturers of asphalt shingles, concrete and clay tiles, metal panels, and wood shakes to obtain information on the processes used to color their products. We also reviewed patent and other literature on the fabrication and coloration of roofing materials, with particular emphasis on asphalt roofing shingles.

Shingles. The solar reflectance of a new shingle is dominated by the solar reflectance of its granules, since by design, the surface of a shingle is well covered with granules. Hence, we focus on the production of cool granules.

Until recently, the way to produce granules with high solar reflectance has been to use titanium dioxide (TiO₂) rutile, a white pigment. Since a thin layer of TiO₂ is reflective but not opaque, multiple layers are needed to obtain the desired solar reflectance. This technique has been used to produce “super-white” (meaning truly white, rather than gray) granulated shingles with solar reflectances exceeding 0.5. Manufacturers have also tried to produce colored granules with high solar reflectance by using nonwhite pigments with high NIR reflectance. However, like TiO₂, cool-colored pigments are also partly transparent to NIR light; thus, any NIR light not reflected by the cool pigment is transmitted to the (typically dark) granule underneath, where it can be absorbed. To increase the solar reflectance of colored granules with cool pigments, multiple color layers, a reflective undercoating, and/or reflective aggregate should be used. Obviously, each additional coating increases the cost of production.

The application of pigmented coatings to roofing granules appears to be the critical process step. Several layers of silicate coatings can be involved, and may include not just one or more pigments, but the use of clay additives to control viscosity, biocides to prevent staining, and process chemistry controls to avoid unreacted dust on the product.

One way to reduce the cost is to produce cool-colored granules via a two-step, two-layer process. In the first step, the granule is pre-coated with an inexpensive pigment that is highly reflective to NIR light. In the second step, the cool-colored pigment is applied to the pre-coated granules.

Tiles. For colored tiles, there are three ways to improve the solar reflectance: (1) use of raw clay materials with low concentrations of iron oxides and elemental carbon; (2) use of cool pigments in the coating; and (3) application of the two-layered coating technique using pigmented materials with high solar reflectance as an underlayer. Although all these options are in principle easy to implement, they may require changes in the current production techniques that may add to cost of the finished products. Colorants can be included throughout the body of the tile, or used in a surface coating. Both methods need to be addressed.

Metal panels. Application of cool-colored pigments in metal roofing materials may require the fewest number of changes to the existing production processes. As in the cases of tile and asphalt shingle, cool pigments can be applied to metal via a single or a double-layered technique. If the raw metal is highly reflective, a single-layered technique may suffice. The coatings for metal shingles are thin, durable polymer materials. These thin layers use materials efficiently, but limit the maximum amount of pigment present. However, the metal substrate can provide some NIR reflectance if the coating is transparent in the NIR.

Wood shakes. We will survey methods of manufacturing wood shakes in the near future.

Innovative Methods for Application of Cool Coatings to Roofing Materials

We have collaborated with 12 companies that manufacture roofing materials, including shingles, roofing granules, clay tiles, concrete tiles, tile coatings, metal panels, metal coatings, and pigments. To date, over 50 prototype cool shingles, 30 tiles or tile coatings, and 20 metal roofing prototypes have been developed and tested. The development work with our industrial partners has been iterative and has included selection of cool pigments, choice of base coats for the two-layer applications, and identification of pigments to avoid.

Figure 2 shows the iterative development of a cool black shingle. A conventional black roof shingle has a reflectance of about 0.04. On the first try to increase the solar reflectance of the shingle, we replaced the standard black pigment on the granules with one that is NIR reflective. That increased the reflectance of the granule to 0.12. On the second try, we used a two-layered technique where we first applied a layer of TiO₂ white base (increasing the solar reflectance of the base granule to 0.28) and then a layer of NIR-reflective black pigment. This increased the reflectance of the black granule to 0.16. On our third prototype, the base granule was coated in ultra-white (reflectance 0.44) and then with an NIR-reflective black pigment. This increased the solar reflectance to 0.18. Figure 2 also shows the performance limit (reflectance 0.25) where a 25- μ m thick layer of NIR-reflective black coating is applied on an opaque white background.

Figure 2. Development of a Cool Black Shingle

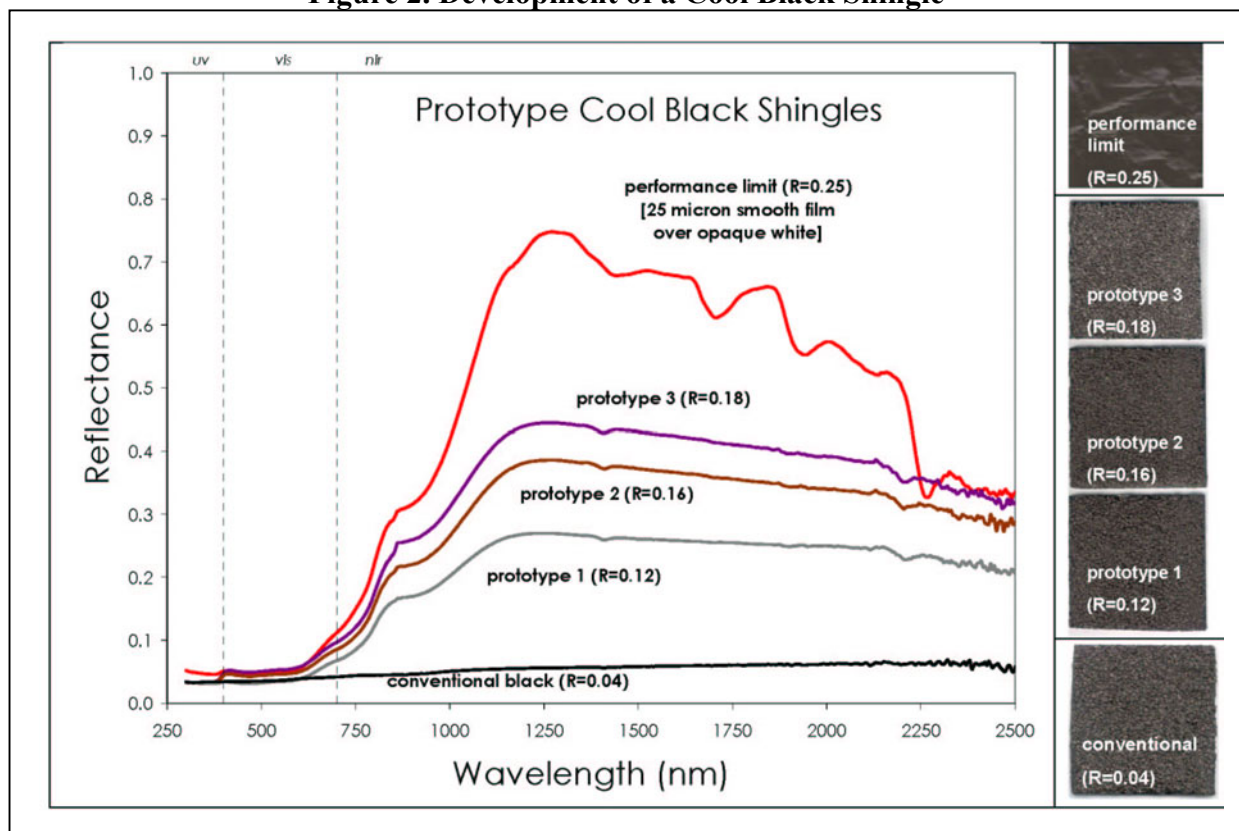


Figure 3 shows the results of similar efforts to develop coatings for concrete tile roofs, which yielded a palette of cool colors each with solar reflectance exceeding 0.4.

Durability of Cool Colored Coatings

Natural, real-time weathering, such as outdoor exposure in Florida or Arizona, and accelerated tests using weatherometers are in progress to gauge the color-stability and integrity (warranty-related properties) of prototype roofing materials. Accelerated testing is essential because the cool pigment combinations must remain fade resistant or the product will not sell.

Pigment stability and discoloration resistance will be judged using a total color difference measure as specified by ASTM D 2244-93 (ASTM 1993).

Figure 3. Solar Reflectance of Several Cool Coatings for Concrete Tile Roofs

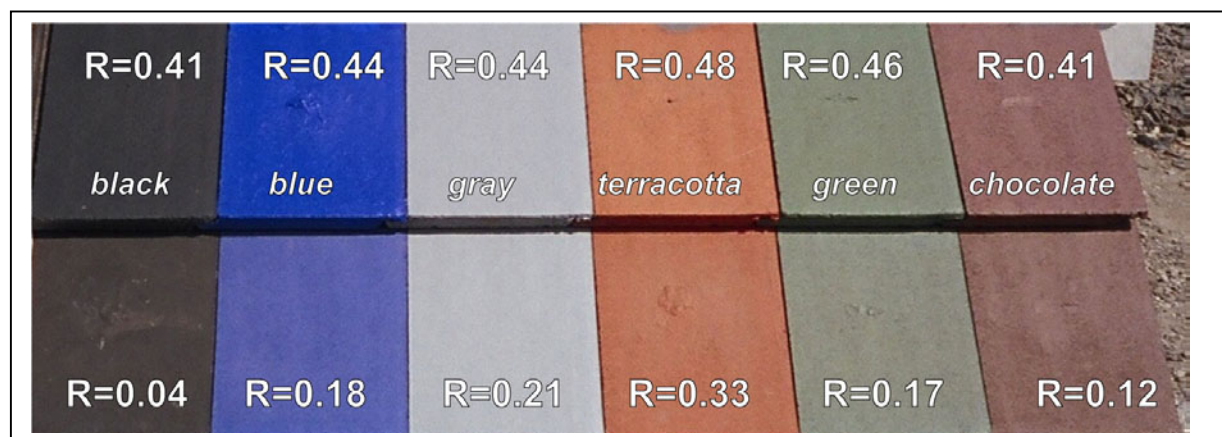


Image courtesy of American Rooftile Coatings (Fullerton, CA)

Natural Weathering

Several different styles and colors of roof samples have been placed in seven of California's 16 climate zones for exposure studies. Reflectance and emittance data are recorded quarterly the first year and twice a year thereafter (weather data are available continuously). In addition, the solar spectral reflectance of each weathered sample is measured annually to gauge soiling and to document color changes too small to perceive.

We will also examine the roof samples for contaminants and determine the elemental composition and biomass on the surface of the roof products. The surface composition studies will identify the drivers affecting the soiling of the roof samples, which in turn will provide valuable information to manufacturers for improving the sustainability of their roof products. The data will be used to formulate an algorithm that correlates changes in reflectance with exposure.

Accelerated Weathering

In collaboration with industrial partners, we are exposing samples to 5,000 hours of xenon-arc light in a weatherometer following ASTM G-155 (ASTM 2000).

Longevity of Cool Colored Roofing Materials

We will soon begin to investigate the effect of reflectance on the useful life of roofing products. There have been claims that cool roofs will last longer, although no specific data have been offered. The research team will work with industry to design and implement a test method for this purpose and use laboratory and outdoor accelerated aging techniques to gather data on the effect.

Roofing materials fail mainly because of three processes: gradual changes to physical and chemical composition induced by the absorption of ultraviolet (UV) light; aging and weathering

(e.g., loss of plasticizers in polymers and low-molecular-weight components in asphalt), which may accelerate as temperature increases; and diurnal thermal cycling, which stresses the material by expansion and contraction. Our goal is to clarify the material degradation effects due to UV absorption and those due to heating. The results will be used to quantify the effect of solar reflectance on the useful life of roofs; provide data to manufacturers to develop better materials; and support development of appropriate ASTM standards.

Demonstration of Energy Savings

Homeowners and utilities considering new rebate programs need proof that an aesthetically pleasing dark roof can be made to reflect like a white roof in the infrared spectrum, and save energy and money. Therefore, demonstrating the potential energy savings is paramount for fostering the market penetration of the cool pigment technology. Field experiments cover a range of conditions necessary to benchmark analytical tools and permit an accurate assessment of energy conservation potential over a range of climates. These experiments include measuring energy savings in pairs of homes at CA field sites, and thermal testing of tile roofs on a steep-slope attic assembly.

Building Energy Use Measurements at California Demonstration Sites

We have set up a residential demonstration site in Fair Oaks, CA (near Sacramento) consisting of two pairs of single-family, detached houses roofed with metal and concrete tile. We are planning for another two pair of houses to demonstrate asphalt shingles and cedar shakes. The monitoring period will last at least through summer of 2005. The demonstration pairs each include one building roofed with a cool-pigmented product and a second building roofed with a conventionally (warmer) pigmented product of nearly the same color.

Solar reflectance and thermal emittance are measured twice a year. Temperatures at the roof surface, on the underside of the roof deck, in the mid-attic air, at the top of the insulation, on the interior ceiling's sheet rock surface, and inside the building are logged continuously by a data acquisition system. Relative humidity in the attic air and the residence are also measured. Heat flux transducers are embedded in the sloped roofs and the attic floor to measure the roof heat flows and the building heat leakage. We have instrumented the building to measure the total house and air-conditioning power demands. A fully instrumented meteorological weather station is set up to collect the ambient dry bulb temperature, the relative humidity, the solar irradiance, and the wind speed and wind direction.

Thermal Testing on Steep-slope Assembly at Oak Ridge National Laboratory

The multiple hazard protection provided by concrete and clay tile from fire, wind and earthquake are making tile the preference of upper income residences in western and some southern states. The typical reflectance of tile is about 0.1; however, applying the cool pigments increases reflectance beyond 0.4 (Fig. 3). The thermal analysis of tile roofing is an interesting challenge because of the air gap formed between the tile and the roof deck. Yet that air gap poses significant energy savings as proved by Beal and Chandra (1999) who demonstrated a 45% daytime reduction in heat flux for a counter-batten tile roof (the reduction over a 24 hour cycle was much less due to differing rates of nocturnal cooling) as compared to a direct nailed shingle

roof. Quantifying the effect of the cool pigments on tile roofs requires testing and analysis to correctly model the heat flow across the air channel.

We are testing several concrete and clay tile on a steep-slope roof to further learn and document the effect of reflectance and emittance weathering on the thermal performance of the cool pigment roof systems. The Roof Tile Institute and its affiliate members are keenly interested in specifying tile roofs as cool roof products and they want to know the individual and combined effects of cool pigments and of venting the underside of concrete and clay roof tile. The data will help better formulate the simulation program, AtticSim, for predicting the thermal performance of the cool colored tile systems.

Market Introduction of Cool Colored Roofing Products

Through close coordination with industry, utilities and code developers, this project is expected to have near-term success facilitating the deployment of cool colored roofing products, particularly in California. In addition to its ongoing close working relationship with coating manufacturers and roofing manufacturers, the team is working closely with California utilities and California codes-and-standards programs.

In April 2004, the research team and several roofing manufacturer representatives introduced emerging cool colored roofing products to the Emerging Technology Coordinating Council (ETCC). Members of the ETCC are responsible for emerging technology programs at each of the investor owned utilities. The emerging technology programs at the utilities are also a critical validation step that can lead to product incentives through the utilities' energy efficiency programs.

Many products developed as a result of this research will be able to meet the residential cool roof credit requirements contained in the 2005 Title 24 California Building Energy Efficiency Standards and the research team will work with the standards program staff to provide input on possible future code enhancements.

Conclusion

The early results from this program indicate significant success in developing cool-colored materials for concrete tile, clay tile, and metal roofs. Since the inception of this program, the solar reflectance of commercially available products has increased to 0.30-0.45 from 0.05-0.25. To be cost effective, shingle manufacturers apply a very thin layer of pigments on the roofing granules. Use of a reflective undercoated (two-layered coating) is expected to soon yield several cost-effective cool-colored shingle products, with solar reflectances in excess of 0.25 (the EPA threshold for EnergyStar roofs). Our ongoing collaboration with granule and shingle manufacturers may yield shingles with solar reflectances exceeding 0.3.

Acknowledgements

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