Cool Color Roofs with Complex Inorganic Color Pigments

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ABSTRACT

Temperature measurements taken on a highly reflective roof show the surface as only about 5°F (3°C) warmer than the ambient air temperature, while a dark absorptive roof exceeds the ambient air temperature by more than 75°F (40°C). Lowering the exterior roof temperature reduces the heat leakage into the building, which in turn, reduces the air conditioning load. In the residential market, however, the issues of aesthetics and durability are more important to the homeowner than are the potentials for reduced air-conditioning loads and reduced utility bills. Dark roofs simply look better than highly reflective "white" roofs. Yet the aesthetically pleasing dark roof can be made to reflect light like a "white" roof in the infrared portion of the solar energy spectrum. Researchers have formulated new complex inorganic color pigments (CICPs) that exhibit high reflectance in the near-infrared portion of the electromagnetic spectrum and boost the total hemispherical reflectance by a factor of 5 over that of conventional dark roofing.

Introduction

A building's required comfort cooling and heating energy, termed *load*, is directly related to several factors: the solar insolation absorbed by the building; the level of roof, wall, and foundation insulation; the amount of fenestration; and the building's tightness against unwanted air and moisture infiltration. The solar reflectance and long-wave infrared (IR) emittance and the airside convective currents strongly affect the envelope's exterior roof temperature, which in turn drives the load.

In the summer, the higher the roof temperature, the greater the potential for heat leakage into the building, and the greater the burden on the comfort cooling system. In winter, the lower the temperature, the greater the potential for heat leakage from the building, and the greater the energy consumed for comfort heating. In moderate to predominantly hot climates, an exterior roof surface with a high reflectance and high IR emittance will reduce the exterior temperature and produce savings in comfort cooling (Miller and Kriner 2001). For climates predominated by heating loads, surfaces with moderate reflectance and low IR emittance will save in comfort heating.

Field measurements of ten homes by Parker and Barkaszi (1997) showed that reflective white roofing reduced space-cooling energy use an average of 19% as compared to

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dark asphalt shingles. Measurements made during the summer by Parker and Sherwin (1998) showed that white tile roofing caused a 76% reduction in the ceiling heat flux into the house relative to a black shingle roof; the second-best performer in this study, a white-painted metal surface, showed a 61% reduction. Field studies conducted by Parker et al. (1998) on several homes in Fort Myers, Florida, showed that the roof, attic, and air-conditioning ductwork accounted for about 25% of the total cooling load in residences. Highly reflective roofs yielded cooling energy savings upwards of 23% of the annual load.

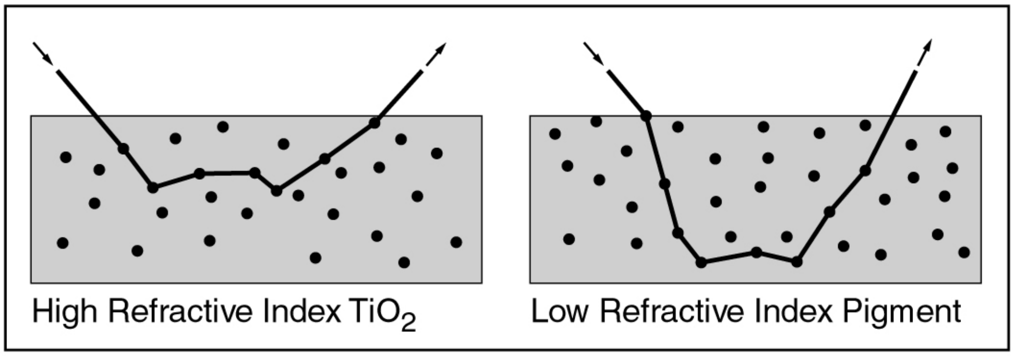
Each field study documented energy savings by simply raising the reflectance of the roof from a value of about 5% to about 60%. The opportunity therefore exists for a significant impact on energy use in commercial buildings and residential housing, both in new construction and reroofing work. The total sales volume for roofing and reroofing is booming and nearly doubled between 1997 and 2000, from \$20 billion to \$36 billion (Good 2001). Of the sales volume in 2000, low-slope roofing accounted for 64% (\$21.7 billion), while steep-slope roofing comprised about 35.6% (\$12 billion) (Good 2001).

High-reflectance single-ply membranes, painted and unpainted metal, and spray-on roof coatings are reducing energy use in the commercial market as building contractors substitute these high-reflectance roofs for bitumen-based built-up roofing (BUR) and ethylene propylene diene monomer (EPDM). Since a high-reflectance low-slope roof cannot be seen from the ground, the roof's functionality is far more important than its looks. However, in steep-slope roofing the issues of appearance, cost, and then durability typically drive the selection of the roofing material because the homeowner wants the roof to complement the décor of the house while protecting the underlying residential structure for a long period of time at an affordable cost. To homeowners, dark roofs simply look better than a highly reflective "white" roof. With the new CICPs, however, an aesthetically pleasing dark roof can be made to reflect like a "white" roof in the infrared portion of the solar spectrum and save energy for both homeowners and utilities.

Surface Properties Affecting Reflectance

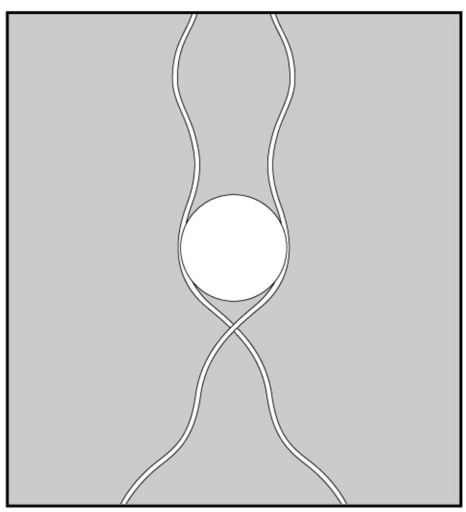
Titanium dioxide (TiO_2) is currently the most important white pigment used in the manufacture of paints and plastics. TiO_2 is chemically inert, insoluble, and very heat-resistant. It has been commercially processed from rutile since as early as 1941 (Du Pont Ti-Pure 1999). Rutile TiO_2 increases surface reflectance through refraction and diffraction of the light. As a light ray passes through a TiO_2 particle, the ray bends, or refracts, because light travels more slowly through the pigments than it does through the resin or binder. This occurs because TiO_2 has a much larger refractive index than the resin. This phenomenon is depicted in Figure 1 for two pigmented films. The film containing the pigment with higher refractive index bends the light more than does the film containing the lower refractive index pigment. The light travels a shorter path and does not penetrate as deeply into the film; therefore, less heat is absorbed. The reflectance of the surface increases because the surface opacity increases through refraction induced by the TiO_2 particles. In general, the greater the difference between the refractive index of the pigment and that of the resin or filler in which it is dispersed, the greater will be the light scattering and therefore the increase in surface reflectance.

Figure 1. Path of Light as It Penetrates Two Different Coatings, One Having Pigments with a Higher Refractive Index Than the Other



Diffraction is another physical factor affecting a pigment's ability to scatter light. As a light ray passes by a TiO_2 particle, the ray bends, or diffracts, around the pigment (Fig. 2). Maximum diffraction occurs when the diameter of the pigment is slightly less than one-half the wavelength of the light to be scattered. Physical modifications of the size, the distribution, and the shape of pigment particles will therefore affect the light scattering. If particles are too large or too closely spaced, little diffraction occurs. Conversely, if the pigment particles are too small, the light will not "see" the particles. Commercially processed rutile TiO_2 has particle diameters ranging from about 200 to 300 nm and is highly reflective in the visible spectrum (yellow-green light at about 550 nm; see Fig. 3). However, as the wavelength of light increases, the reflectance of TiO_2 drops in the infrared spectrum, especially for wavelengths exceeding 1250 nm (Fig. 3).

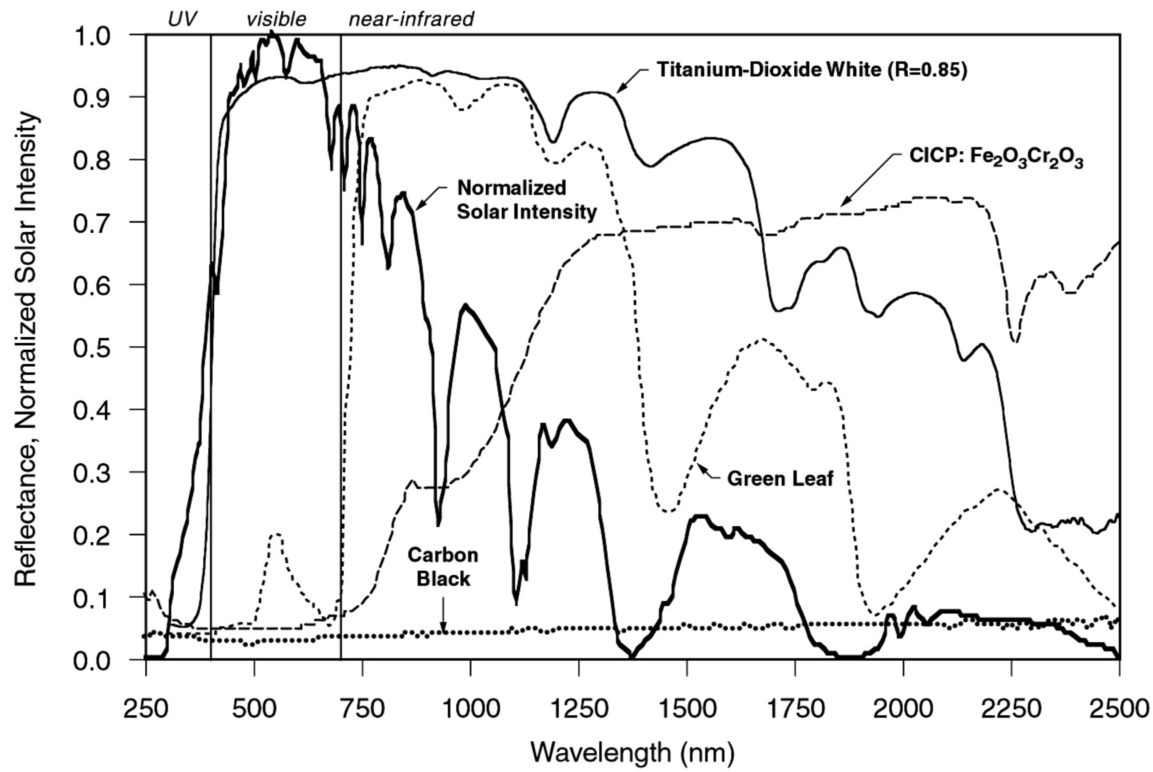
Figure 2. Light Diffraction as a Light Ray Travels near a Pigment Particle



Complex Inorganic Color Pigments (CICPs)

Aesthetically pleasing dark roofing can be formulated to reflect like a highly reflective "white" roof in the IR portion of the solar spectrum. For years the vinyl siding industry has formulated different colors in the same polyvinyl chloride base by altering the content of TiO_2 and black IR-reflective (IRR) paint pigments to produce "dark" siding that is "cool" in temperature (Ravinovitch and Summers 1984). Researchers discovered that a dark color is not necessarily dark in the infrared. Brady and Wake (1992) found that 1-µm particles of TiO_2 when combined with red iron, or ferric, oxide effectively scattered IR radiation at a wavelength of 2300 nm. Researchers working with the Department of Defense developed new complex inorganic color pigments (CICPs) that exhibit dark color in the visible spectrum and high reflectance in the near-IR portion of the electromagnetic spectrum (Sliwinski, Pipoly & Blonski 2001). The new CICPs are used in paints for military camouflage to match the reflectance of background foliage in the visible and IR spectrum. At 750 nm the chlorophyll in foliage naturally boosts the reflectance of a plant leaf from 0.1 to about 0.9 (Fig. 3), which explains why a dark green leaf remains cool on a hot summer day.[2]

Figure 3. Spectral Solar Reflectance of TiO_2, a Green Leaf, Standard Carbon Black and a Complex Inorganic Color Pigment Containing Infrared Reflective $(Fe,Cr)_2O_3$ Pigment (Normalized Solar Irradiance Shown for Reference)



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[2] Chlorophyll, the photosynthetic coloring material in plants, naturally reflects near-IR radiation.

CICPs, having been tailored for high IR reflectance similar to that of chlorophyll, are very suitable for roof applications where increased IR reflectance is desirable. A CICP consisting of a mixture of black IRR pigments, chromic oxide (Cr_2O_3) and ferric oxide (Fe_2O_3) boosts the total hemispherical reflectance of carbon black from 0.05 to 0.26 (see CICP:$Fe_2O_3 \cdot Cr_2O_3$ in Fig. 3). Typically, a black asphalt shingle or a black Kynar®[3] metal roof has a reflectance of only about 0.05. The CICP therefore boosts the reflectance by a factor of 5, and in the infrared spectrum CICPs boost the reflectance to almost 0.70 (Fig. 3).

CICPs are formed by calcinating blends of metal oxides or oxide precursors at temperatures over 1600°F (870°C). The calcination causes the metal and oxygen ions in the solids to rearrange in a new structure that is very heat-stable. The inherent heat stability of CICPs makes them ideal for high-temperature coatings in roofing applications. Because of their small particle size and high index of refraction, CICPs will effectively backscatter a significant amount of ultraviolet (UV) and IR light away from a surface. Martin and Pezzuto (1998) observed that pigments that are transparent in the required spectral range and that have a refractive index substantially different from that of the binder work well as IRR pigments.

Thermal Performance of CICPs

CICPs offer excellent opportunities for improving the thermal performance of roofs. About 44% of the sun's total energy is visible to the eye (Fig. 3). Absorbing this 44% is what makes a black appear black. Sunlight emits another 51% of its energy in the invisible IR spectrum. Adding CICPs to roof material can make a black roof reflect near IR energy and therefore maintain a lower roof surface temperature. Using a heat buildup test procedure described by Hardcastle (1979), Ravinovitch and Summers (1984) measured a 23.4°F (13°C) lowering of temperature when a mixture of Cr_2O_3 and Fe_2O_3 was used in place of carbon black.

Light-Color CICPs

The authors tested several IRR pigments against standard pigments using the ASTM D4803 test procedure (ASTM 1997a). This procedure has long been used by the vinyl siding industry to quantify the heat buildup properties of vinyl siding, even though it overstates the sample's properties in the near IR at the expense of visible portion of the spectrum (Ravinovitch and Summers 1984). Table 1 shows the temperatures for both CICPs and standard light-gray, mid-tone bronze, and dark-tone bronze colors when exposed to a flux of 484 Btu/(hr·ft^2) [550 J/(hr·cm^2)] emitted from an infrared heat lamp. These colors are very popular for low-slope roofing in commercial and academic applications where bronze Kynar metal roofing is commonly used.

The colors containing CICPs show a significant drop in temperature as compared to the temperatures of standard light-gray, mid-tone bronze, and dark bronze colors. The temperature is 55°F (30.5°C) cooler for the light gray color if CICPs are contained in the pigment mixture. Similarly, a mid-tone bronze showed a 63°F (35°C) reduction in surface

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[3] Kynar, the registered trademark for polyvinylidene fluoride (PVDF) paint finish, has excellent corrosion and abrasion resistance.

temperature. Even the dark-tone bronze had a measured 54°F (30°C) drop in temperature because the IRR pigments absorb less electromagnetic energy near the cutoff between the visible and infrared wavelengths. They have a more selective absorption band and reflect much of the infrared.

Table 1. CICP Color Matches vs. Standard Pigmentation Exposed to ASTM D4803 Heat Lamp Protocol [a]

Pigment	Pigment Constituents		Maximum Temperature	Temperature Difference (ΔT)
Light gray				
Standard	Carbon black TiO_2 Fe_2O_3	1.5% 96.8% 1.7%	202°F (94.4°C)	
CICP	IRR black TiO_2	10% 90%	147°F (63.9°C)	55°F (30.5°C)
Mid-tone bronze				
Standard	Carbon black TiO_2 Fe_2O_3	11.8% 75.0% 13.2%	225°F (107.2°C)	
CICP	IRR black TiO_2	50% 50%	162°F (72.2°C)	63°F (35°C)
Dark-tone bronze				
Standard	Carbon black TiO_2 Fe_2O_3	33% 29% 38%	220°F (104.4°C)	
CICP	IRR black TiO_2	90% 10%	166°F (74.4°C)	54°F (30°C)

[a] A flux of 484 Btu/(hr·ft^2) [550 J/(hr·cm^2)] emitted from an infrared heat lamp.

Dark-Color CICPs

We also exposed dark colors containing the IRR pigments to the infrared heat lamp. Again, the increased reflectance in the near-IR spectrum (Fig. 4) significantly reduced the surface temperature as compared to carbon black. An IRR green was a measured 54°F (30°C) cooler than carbon black, an IRR dark brown was ~48.6°F (27°C) cooler, and an IRR black was a measured 46.8°F (26°C) cooler.

For our test site at Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, the maximum irradiance from the sun, at solar noon, is about 308 Btu/(hr·ft^2) [350 J/(hr·cm^2)]. ASTM procedure D4803 (ASTM 1997a) relates the intensity of solar irradiance to the intensity derived from the infrared lamp via a ratio of the temperature rises above the ambient air temperature (i.e., the ΔT for IRR black to the ΔT for standard carbon black, see the right side of Eq. 1) to predict the specimen's solar temperature rise by:

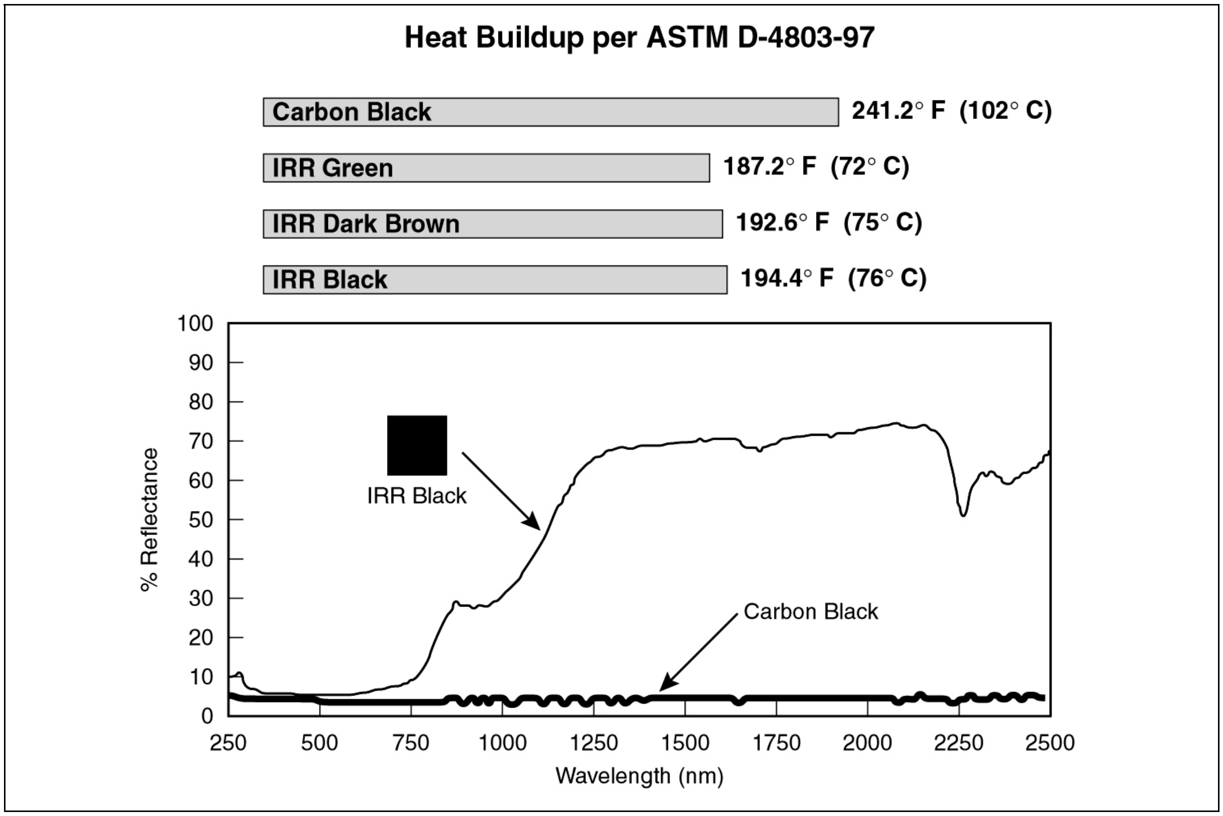
$$\left[\frac{\Delta T_{\text{IRR Black}}}{\Delta T_{\text{black Kynar}}}\right]_{\text{solar}} = \left[\frac{\Delta T_{\text{IRR Black}}}{\Delta T_{\text{carbon black}}}\right]_{\text{ASTM D4803}} \quad (1)$$

where

$\Delta T_{IRR\ Black}$ = "predicted" temperature rise above ambient air temperature for IRR black when exposed to solar irradiance

$\Delta T_{black\ Kynar}$ = "experimentally measured" temperature rise above ambient temperature for a black Kynar roof (~40°C above ambient as field-tested at ORNL)

Figure 4. Heat Buildup of High-IRR Pigments vs. Standard Carbon Black and Reflectance of IRR Black vs. Standard Carbon Black



Based on Equation (1) and summertime field data for a black Kynar metal roof tested at ORNL, the IRR black sample would be about 25°F (14°C) cooler at solar noon than a conventional dark roof.

Durability and Weathering of CICPs

Testing protocols to determine the resistance to weathering of paints and coating systems designed for outdoor use include both natural, real-time weathering, such as outdoor exposure in Florida or Arizona, and accelerated tests using a weatherometer equipped with carbon-arc, fluorescent UV, and xenon-arc light sources. To evaluate color changes in roof samples with CICPs as compared to samples with standard colors, we used a one-year exposure test to natural sunlight in Florida and also a 5000-hour xenon-arc accelerated exposure test, following ASTM G-155 (ASTM 2000). Test data showed excellent light fastness for all the CICPs. Pigment stability and discoloration resistance were judged using a total color difference measure (ΔE) as specified by ASTM D 2244-93 (ASTM 1993). The ΔE value for all the colors tested was a color change of approximately 1.0 or less (Figs. 5 and 6).

The total color difference value, ΔE, is a method adopted by the paint industry to numerically identify variability in color over periods of time. This value shows the difference in color between a standard and a batch and includes the three following values computed in the formula:

- lightness (*L*), where a +*L* value is lighter and a –*L* value is darker;
- redness/greenness (*a*), where a +*a* value is redder and a –*a* value is greener; and
- yellowness/blueness (*b*) where a +*b* value is yellower and a –*b* value is bluer.

$$\Delta E = \left[(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\right]^{1/2}, \qquad (2)$$

where

$\Delta L = L_{batch} - L_{standard}$
$\Delta a = a_{batch} - a_{standard}$
$\Delta b = b_{batch} - b_{standard}$

Typically, coil-coated metal roofing panels are warranted for 20 years or more and specify ΔE of 5 units or less for that period. ΔE color changes of 1 unit or less are almost indistinguishable from the original color, and depending on the hue of color, ΔE of 5 or less is considered very good.

The xenon-arc accelerated weathering initially saw most of the colors rise in ΔE up to about 1500 hours of exposure and then level off; at the end of 5000 hours all are clustered together at less than 1.5 ΔE, which is considered a very good result (Fig. 5). Control products with known performance characteristics were included in the testing to compare results with the new products. The Florida exposure data in Figure 6 is just as promising, indicating that over the one-year test period the CICPs do not fade in the presence of ozone, acid rain, SO_x, NO_x, or other airborne pollutants. Tests have shown that CICPs remain colorfast in the presence of strong acids, bases, and oxidizing or reducing agents. They are non-migratory and showed no dissolving or bleeding in contact with airborne solvents.

Conclusions

Accelerated weather testing using natural sunlight and xenon-arc weatherometer exposure proved that CICPs retain their color. After one year of natural sunlight exposure in south Florida the CICPs show excellent fade-resistance and remain colorfast. CICPs are very stable pigments and have excellent discoloration resistance, as proven by the 5000 hours of xenon-arc exposure; their measure of total color difference was a ΔE value less than 1.5. Therefore, color changes in the CICPs were indistinguishable from their original color.

CICPs have a selective light absorption band in the infrared spectrum. They reflect much of the near-IR heat and therefore reduce the surface temperature upwards of 50°F (28°C) as compared to carbon black pigments when exposed to irradiance from an infrared lamp. For a steep-slope roof in the field, an IRR black would be about 25°F (14°C) cooler at solar noon than would a conventional dark roof. The lower exterior temperature leads to energy savings and provides an ancillary benefit in older existing houses with little or no attic

Figure 5. Total Color Difference (ΔE) Values for Color Samples in Xenon-Arc Accelerated Weathering Test

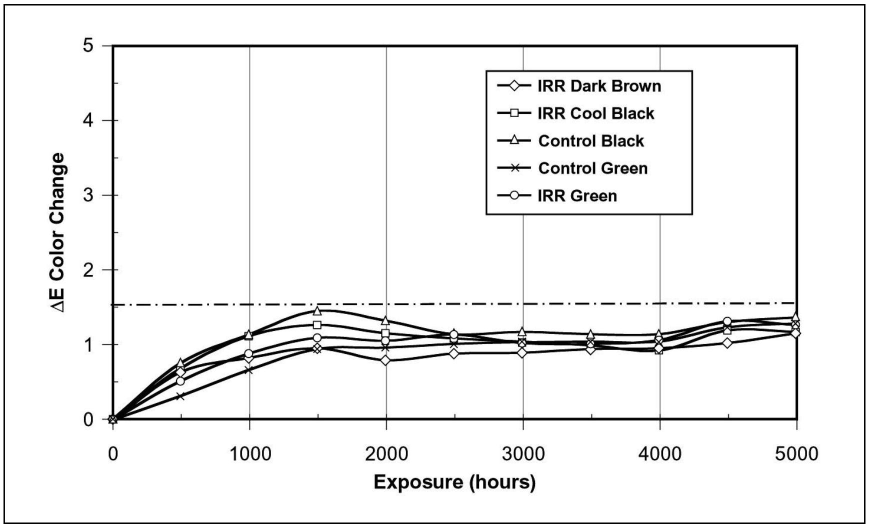
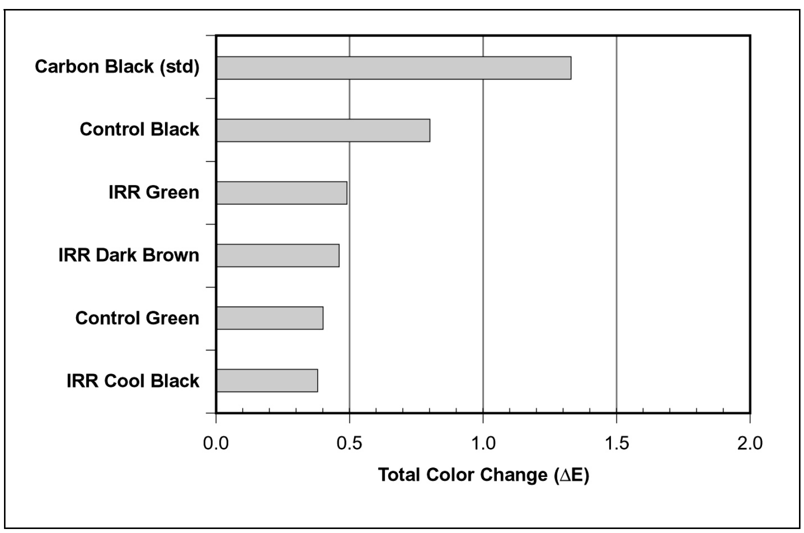


Figure 6. Total Color Difference (ΔE) Values for Color Samples in One-Year Florida Weathering Test



insulation and poorly insulated ducts in the attic because the cooler attic temperature in turn leads to reduced heat gains to the air-conditioning ductwork.

Recommendations

The United States has about 102 million residential homes, with more than 1 million new homes being added each year (Kelso and Kinzey 2000). The space conditioning of these homes accounts for 5.78 quadrillion BTUs (quads) of site energy use per year (EIA 1995); of this amount of energy use, heat leakage through roofs contributes about 14% (Huang, Hanford & Yang 1999). The net national residential cooling load is about 1 quad, and electrically driven air-conditioning is used in about 66 million U.S. residences (Census Bureau 1987).

Improving energy savings in residential housing for both new housing and existing homes can reduce utility loading significantly. The adoption of CICPs in roof manufacturers' products has the potential to save the nation about 0.1 quad per year. This decrease in electric demand would translate to a decrease of approximately 30.4 million tons in CO_2 emissions per year from utilities powered by coal. Hence, both air quality and quality of life would be improved if measures were enacted to implement the use of CICPs in tile, metal, wood shake, and asphalt shingle roofing products.

Therefore, Lawrence Berkeley National Laboratory (LBNL) and ORNL have initiated a collaborative research and development project in conjunction with pigment (colorant) manufacturers. LBNL and ORNL will work with roofing materials manufacturers to reduce the sunlit temperatures of asphalt shingles, roofing tiles, metal roofing, wood shakes, roofing membranes, and roof coatings.

The addition of CICPs to roofing products will reduce the exterior roof temperature and produce energy savings in space cooling. Moreover, in the case of asphalt shingles, durability and life expectancy should improve, helping to reduce the replacement and disposal costs of solid asphalt shingle roofing (asphalt shingles are typically replaced every 15 years).

The cost to the homeowner to achieve this efficiency improvement when replacing an asphalt roof is estimated to be an incremental cost of about 10¢ per square foot for the CICP reflective roof (Akbari, Berdahl & Levinson 2002). However, only prototypes have been developed in asphalt roofing. In coil-applied metal roofing, which is already painted, the cost could be anywhere from no additional cost to approximately 2¢ per square foot.

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