Investigation of Infrared Reflective Pigmentation Technologies for Coatings and Composite Applications

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Abstract

Recent advances in pigmentation technology have allowed formulators to achieve a greater infrared reflectivity versus traditional pigmentation technologies in functional coatings, while maintaining the appropriate light absorption in the visible spectrum to impart color. The ability of functional infrared reflective coating systems to lower heat build-up results in reduced thermal warpage, reduced thermal cycling degradation, lower energy costs related to cooling, and improved comfort and functionality of dark color exterior objects such as park benches, hand railings, and even polymer concrete. This paper will impart knowledge of infrared pigmentation technology to the reader, and explore potential new applications of infrared reflective pigmentation technology in composites.

Introduction

Rising energy costs continue to drive advances in new technologies designed to improve energy efficiency. One such technology is the use of specialty infrared reflective pigments used to impart color to an object, and reflect the invisible heat from the object to minimize heat build-up, when exposed to solar irradiance. Ultimately, the reflection of infrared energy lowers the heat build-up resulting in a reduction on the load of the cooling system, and therefore a cost savings.

In order to understand and maximize the functional mechanisms and effects of infrared reflecting pigmentation technologies, one must understand the sciences regarding solar radiation, black and gray body radiation, emissivity, reflectance, total solar reflectance, light scattering, light absorption, and relevant test methods. The following will explain.

Electromagnetic Radiation

Electromagnetic radiation is a term used for wave energy consisting of magnetic and electric components propagating through space. There are many forms of electromagnetic radiation all around us. The electromagnetic spectrum includes wavelengths of energy (from lowest to highest energy) radio, micro, infrared, visible, ultraviolet, x-ray, and gamma ray radiation (Kotz, Purcell, 4).

Light is a form of electromagnetic radiation. The actual nature of light is quite complex. Light waves produced by a nuclear fusion reaction in our Sun, for example, propagate through space at a very high rate of speed, which is defined as a constant 300,000 kilometers per second in a vacuum. This is the phase velocity (or speed) of light. It takes light waves (also called photons) approximately eight minutes to reach the Earth after they have been generated by the Sun. All living things owe their existence to the Sun's energy bathing the Earth in a broad swath of electromagnetic radiation. Surrounding the Earth is a magnetic field shielding the Earth from much of the higher intensity radiation emitted by the Sun, such as x-rays. In addition, the molecules of gas, water vapor, and particles of dust in our atmosphere absorb a significant amount of electromagnetic radiation. The remaining electromagnetic radiation that reaches the Earth's surface is discussed in the following section.

The frequency of light as it is related to the wavelength of light is shown in Equation 1. This equation applies to light traveling in a vacuum.

$$F=c/\lambda \quad \text{(Eqn. 1)}$$

F = the frequency of light in hertz (cycles per second)
λ = wavelength of light in meters
c = speed of light in meters

When multi-chromatic light penetrates into a medium, a prism for example, the differing wavelength components of the light will travel at slightly different speeds in the medium due to the variation of refractive index with wavelength. This results in a separation of the light into its different color components. A commonly known example of this effect is a rainbow created by sunlight interacting with water droplets.

Sunlight

Terrestrial solar radiation, or sunlight which reaches the ground, consists of three types of radiation; ultraviolet, visible, and near infrared. The ultraviolet portion of sunlight reaching the earth (also known as ionizing radiation) has a wavelength range of 280 nanometers to approximately 400 nanometers. One nanometer is one billionth of a meter. Visible light is typically discussed in wavelengths of nanometers or micrometers. One micrometer is one millionth of a meter. Visible light has a wavelength range of 400 to 700 nanometers (Kotz, Purcell, 4). This energy range is where the human capability of seeing and recognizing color exists (some people may be able to see color in an extended range of 380 – 740 nanometers). Near infrared radiation has a wavelength range of 700 nanometers to approximately 10,000 nanometers (nm), or 10 microns (um). Terrestrial

Total solar reflectance is expressed as a percentage. Typical white coatings exhibit a total solar reflectance of 75% or greater. A white coating with a total solar reflectance of 75% by definition will absorb 25% of the incident energy. A black coating based on carbon black pigmentation may have a total solar reflectance as low as 3.5%, and therefore will absorb 96.5% of the incident solar energy.

Black Body Radiation

Cooling effect optimization of infrared pigmentation technology requires a good understanding of emitted radiation, particularly in the infrared range. All objects emit radiation as a function of temperature. Understanding and maximizing the emissivity of an object allows a greater cooling benefit to be achieved by the formulator.

A black body is defined as an object that absorbs all incident radiation, and that emits specific wavelengths of energy as a function of temperature. Planck developed a mathematical formula yielding a black body's spectral radiant excitance per wavelength as it relates to the temperature of the body. This is known as Planck's law of black body radiation.

The spectral radiant excitance per wavelength per meter squared (M^2) equals M_e (Wyszecki, Stiles, 1):

$M_e = (c/4)\, u_{e\lambda}$ (Watts/(M^2*M)) (Eqn. 3)

h= Planck's constant (6.626176×10^{-34} J*s)

c = velocity of light (2.99792458×10^{8} M*s^{-1})

k = Boltzmann constant (1.380662×10^{-23} J*K^{-1})

where

$u_{e\lambda} = 8\pi hc\lambda^{-5}(e^{hc/kT\lambda} - 1)^{-1}$ (J*m^{-3}) (Eqn. 4)

T= absolute temperature in Kelvins

λ = wavelength in meters

Note: to convert M_e to Watts/(M^2*nM), multiply by 1×10^{-9}

Planck's law explains why an object such as an iron horseshoe has a red glow when placed in a furnace. As the temperature of the iron increases, the color will shift from red to the more energetic (bluer) wavelengths. Figure 5, calculated using Eqn. 3, (Wyszecki, Stiles, 1) shows a plot of the spectral radiant excitance of a blackbody at varying absolute temperatures. Note that as the temperature of a blackbody increases, the maxima of wavelength is shifted towards a higher energy or shorter wavelength.

The total energy radiated from a black body over all wavelengths at a constant absolute temperature measured in Kelvin is expressed in watts per square meter by the Stefan-Boltzmann Law as (Holman, 10):

Energy Emitted = $\sigma(T^4)$ (Eqn. 5)

Where σ = Stefan-Boltzmann Constant
$= 5.670\,400 \times 10^{-8}$ W·m^{-2}·K^{-4}
T = absolute temperature in Kelvins

Figure 6, calculated from Eqn. 5 (Holman, 10) shows a plot of the emitted energy per square meter of a black body radiator at typical temperatures encountered in every day life. Note that a black body radiator at a temperature of 200 degrees Fahrenheit emits a significant amount of thermal energy (just under 1000 watts per square meter).

Gray Body Radiation

A gray body is an object deviating in emittance from a perfect black body radiator by a defined fraction expressed in terms of emissivity ($\varepsilon < 1$). By definition, a gray body's emittance is not wavelength dependent, and is therefore constant. In reality, the emittance of an object is dependent upon wavelength and angle of observation; intensity varies with the measured angle and measured wavelength (Holman, 6).

Emissivity

The greater the emissivity of the surface of a given substrate (closer to that of an ideal black body radiator), the lower the heat build in the object, with all other variables remaining constant. For the formulator, this factor is quite important, as one will want to maximize emissivity when designing infrared reflecting coatings or composites; the greater the emissivity of an object, the greater the object's ability to radiate electromagnetic energy. Table 1 shows several emissivities of common objects (13).

Figure 7 illustrates the relationship between the radiated energy of a gray body at a constant temperature with changing emissivity.

Test Methodologies – Heat Build Testing

Several test methods and procedures are available to aid the formulator using infrared reflective pigmentation technology. ASTM D 4803 is a test method predicting the heat build-up of exterior objects (objects exposed to the Sun) in the laboratory. This test method consists of placing the object to be tested above a thermocouple in an insulated box, and exposing the object to

Coatings formulated with infrared pigmentation are designed for application over substrates to improve among other things, their reflective, emissive, and visual attributes. Frequently these coatings are applied over substrates that are highly absorbing (low total solar reflectance) to yield a coated substrate with a higher total solar reflectance. Reducing the energy transferred into a system will reduce the overall equilibrium temperature of the system when all other variables remain constant. When designing an infrared reflective coating or cool coating, one must maximize total solar reflectance, maximize emissivity, and minimize all contamination by infrared absorbing materials.

IR Reflective Coatings - CASE 1: Infrared Reflecting Gray versus Traditional Gray

The efficacy of infrared pigmentation technology is best demonstrated when comparing a traditional gray coating with an infrared reflective gray coating (Table 2). The gray coatings have a similar light to dark color value (L*) using the CIE LAB system, resulting in a Delta L* of 0.032. This indicates the coatings are achromatically equivalent. The total solar reflectance of the traditional gray coating is measured at 17.5%, and the total solar reflectance of the infrared reflective gray coating is measured at 47.1%. While the visible color difference is negligible, the total solar reflectance indicates a raw 29.6 % difference. The result is a reduced heat build-up as predicted by ASTM D 4803.

IR Reflective Coatings - CASE 2: Traditional Green versus Two Infrared Reflecting Greens

Three green coatings were created to demonstrate the use of color matching with infrared reflective pigmentation. The first green (Green 1) was created using standard colorants. The second Green (Green 2) was created using infrared reflective pigmentation technology, and the third green (Green 3) was created using synergistic infrared reflective technology. All three green color matches are visually equivalent in color.

The total solar reflectance of the traditional green coating (Green 1) is measured at 7.6%, and the total solar reflectance of the infrared reflective green coating (Green 2) is measured at 20.2% (Table 3). The total solar reflectance of the third coating (Green 3) is measured at 36.8%. While the visible color differences were negligible, the total solar reflectance values indicate a significant difference, which has a pronounced impact on heat build-up as predicted by ASTM D 4803 (Table 3).

IR Reflective Technology - Example for Consideration:

Traditional black asphalt shingles are well known for their ability to absorb heat in direct sunlight. Roofers often toil in sweltering conditions when installing or replacing asphalt shingled roofs. Black asphalt shingles have a total solar reflectance of 3.5%, that is, they absorb over 96.5% of the incident solar radiation. This causes the roofs to heat to exceptionally high temperatures. Under the worst conditions, temperatures can well exceed 180 degrees Fahrenheit. This absorbed energy is conducted, convected, and radiated into the building structure via the large temperature gradient. This ultimately results in a hotter building requiring additional air conditioning to cool the rooms and at a greater energy burden. Assuming an average solar irradiance of 900 watts per square meter (an average value derived from the integral of the ASTM solar irradiance spectrum), this translates to energy absorption of 868.6 watts per square meter, or 868.6 joules per second.

Using infrared reflective pigmentation technology, the same black color space can be achieved using specialty infrared reflective pigmentation. By using specialty infrared reflective pigmentation the formulator can develop a coating with a total solar reflectance of approximately 29%. This greater solar reflectance means that although 71% of incident solar energy is absorbed, or around 639 watts per square meter of energy is absorbed, there remains a 26% reduction in energy absorption versus the asphalt shingle roof.

A second approach is to use a specialty synergistic infrared reflective technology. Utilizing this approach allows the formulator to have the visual effect of a dark color while achieving a higher solar reflectance. It is possible to produce a shade of black with a total solar reflectance of 47%, and net energy absorption of 53%, or 477 watts per square meter, and yield a 47% reduction in absorption of energy.

IR Reflective Technology – Contamination Concerns

Contamination is a serious issue when using IR reflective technologies. For example, carbon black is a pigment that has much benefit to the composite and coatings formulators. Carbon black pigments generally produce strong shades, and are used for UV protection and low cost. However, carbon blacks are very strong ultraviolet, visible, and near infrared absorbers. Carbon black, even in low quantities (< 0.01%) can have a deleterious effect on IR reflective formulations. Infrared reflective colorants and IR reflective products developed from these colorants must be manufactured without cross contamination from IR absorbing materials such as carbon black.

IR Reflective Technology – Avoiding Warpage and Thermal Cycling

sus the traditional gray at a total solar reflectance of 42.2% as compared to a total solar reflectance of 20.9% for the traditional gray composite.

The synergistic infrared reflective gray composite shows a total solar reflectance of 56.3% and a predicted vertical heat build of 26.1 Celsius, which is 11.3 degrees lower than the traditional gray composite.

Case 5: Thermoset Composite Infrared Reflective Black %TSR versus Heat Build Evaluation

Figure 10 shows the relationship between total solar reflectance and predicted vertical heat build of an infrared reflective black pigment dispersion in a white ATH filled thermoset composite system.

Figure 11 shows the L* versus predicted vertical heat build of two sets of thermoset composite panels. One set of panels was created with carbon black pigmentation in a titanium dioxide white pigmented, ATH filled system. The other set of panels was created with an infrared reflecting black dispersion in a titanium dioxide white pigmented, ATH filled system.

Cleary, the composite panels created using the infrared reflecting black exhibit a much greater total solar reflectance at a given L* value.

Case 6: Thermoset Composite Infrared Reflective Red %TSR versus Heat Build Evaluation

Figure 12 shows the relationship between total solar reflectance and predicted vertical heat build of an infrared reflective red pigment dispersion in a titanium dioxide white pigmented, ATH filled thermoset composite system.

Figure 13 shows the relationship between L* and total solar reflectance of an infrared reflective red pigment dispersion in a titanium dioxide white pigmented, ATH filled thermoset composite system.

Conclusions

Recent advances in pigmentation technology have allowed the formulator to achieve a greater infrared reflectivity versus traditional pigmentation technologies. These technologies are currently being applied in various coatings applications, and the science behind the technology is applicable to thermoset composites.

A clear understanding of the function and composition of the composite material, along with proper pigmentation selection will yield composites with greater infrared reflectivity, higher total solar reflectance, and lower heat build-up while achieving the target color. This strategy allows the formulator to potentially add value and function to the composite matrix. This value was not previously attainable using traditional pigmentation technology.

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Figure 8: Titanium dioxide white pigmented composite predicted heat build versus %TSR relationship at 10.0%, 5.0%, 2.0%, and 1.0% dispersion loading based on resin and filler.

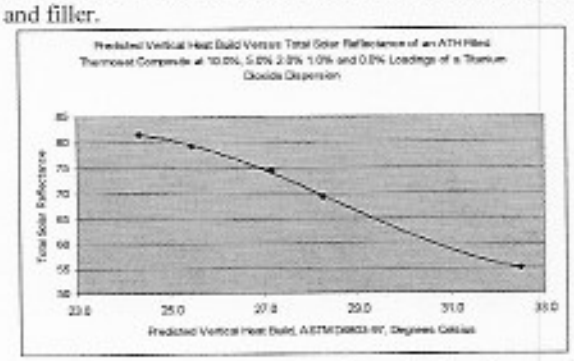


Figure 9: Carbon black and titanium dioxide pigmented composite heat build versus %TSR at 0.0%, 0.25%, 1.0%, 2.0% and 5.0% carbon black dispersion loading based on resin and filler (The white dispersion loading was held constant at 5.0% based on resin and filler).

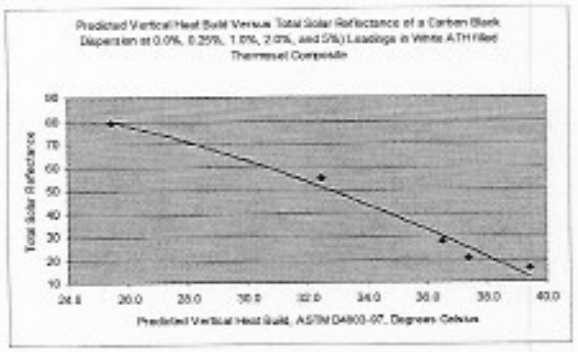


Figure 10: Infrared reflecting black and titanium dioxide pigmented composite heat build versus %TSR at 0.0%, 0.50%, 1.0%, 2.0%, and 5.0% infrared reflecting black dispersion loading based on resin and filler (The white dispersion loading was held constant at 5.0% based on resin and filler).

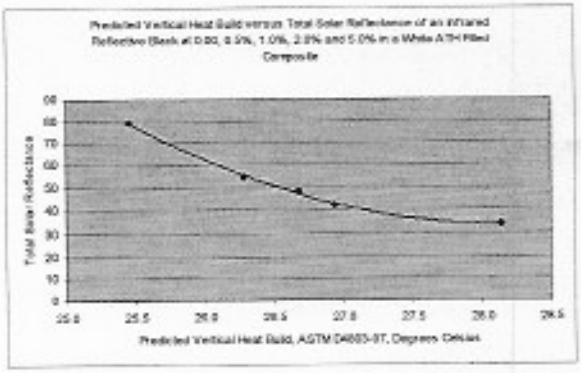


Figure 11: A plot of the relationship of L* and predicted vertical heat build of a white ATH filled composite pigmented with carbon black, and a white ATH filled composite pigmented with an infrared reflecting black.

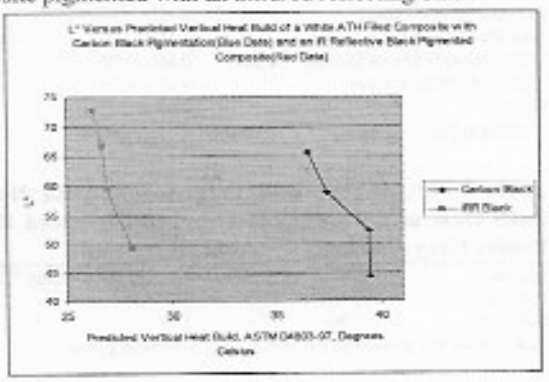


Figure 12: Total solar reflectance versus predicted heat build of an infrared reflective red composite at 0.0%, 0.50%, 1.0%, 2.0%, and 5.0% loadings with a white dispersion at 5%.

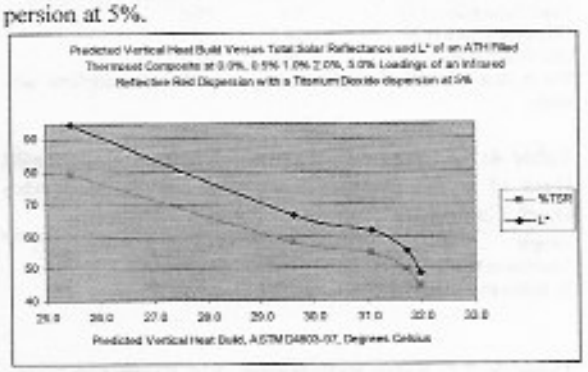


Figure 13: Total solar reflectance versus heat build of an infrared reflective red composite at 5.0%, 2.0%, 1.0%, 0.5%, and 0.0% loadings with a white dispersion at 5.0%.

