Thermochromic energy efficient coatings for buildings and urban structures

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ABSTRACT

In this study, the development and comparative testing of thermochromic coatings to be applied on buildings and urban structures are reported. Eleven thermochromic coatings were developed by using thermochromic pigments into an appropriate binder system. The color-changing temperature was 30°C. The same binder system was used for the production of highly reflective (cool) and common coatings, in order to investigate and compare the thermal and optical characteristics of color-matched thermochromic, cool and common coatings. The results demonstrated that during the experimental period, surface temperatures of thermochromic samples were lower than the temperatures of color-matched cool and common. Mean daily surface temperatures ranged from 23.8°C to 38.4°C for the thermochromic samples, from 28.1°C to 44.6°C for the cool and from 29.8°C to 48.5°C for the common samples. Spectral measurements revealed that all thermochromic coatings are highly reflective in the near infrared. At higher temperatures, being colorless, they reflect solar energy, while at lower temperatures, being colored, they absorb solar energy. The maximum solar reflectance increase from colored to colorless phase was 43%. Solar reflectance values were higher for thermochromic coatings at the colored phase compared to cool and common of the same color.

Introduction

The energy use in the building sector represents about one third of the total energy consumption. Buildings use almost 40% of the world's energy, 16% of the fresh water and 25% of the forest timber, while they are responsible for almost 70% of emitted sulphur oxides and 50% of the CO_2. In Europe, the use of air-conditioners was increased by 100% in 7 years (2000-2007). At the same time many cities around the world suffer from the urban heat island effect with average daytime air temperature 2-5°C higher than the surrounding rural areas (Synnefa et al., 2007(a)).

Various mitigation techniques to fight heat island have been proposed (Santamouris et al., 2004). The selection of appropriate materials to be used in the urban fabric can improve the urban microclimate, decrease the energy loads of the buildings and provide a thermally comfortable indoor environment.

The thermal performance of materials is mainly controlled by their solar reflectance and the infrared emittance. Increased values of reflectance and/or emittance result in lower surface temperatures. Regarding the building's performance, lower surface temperatures decrease the heat penetrating into the building and therefore decrease the cooling loads while creating more comfortable indoor thermal conditions. Regarding the urban environment, it contributes to the decrease of the ambient air temperature, mitigating the heat island effect (Synnefa et al., 2007(b);

Akbari et al., 1992; Berdahl and Bretz, 1997; Bretz et al., 1997). The performance of materials with high solar reflectance and infrared emittance values, known as cool materials, has been extensively studied (Berdahl and Bretz, 1997; Bretz et al., 1997; Rosenfeld et al., 1996; Synnefa et al., 2007(a); Synnefa et al., 2007(c); Bretz and Akbari, 1997; Prado and Ferreira, 2005). An increase in roof albedo of 0.4 resulted in peak cooling demand savings of 20%-40% in residences and 5%-10% in offices at the Los Angeles basin, as proved by building energy simulations (Akbari et al. 1999). In the area of Athens, Greece, the use of a mesoscale model has demonstrated that an increase in building structures albedo of 0.65 can decrease the air temperature by 2.2^{o}C (Synnefa et al., 2007(b)).

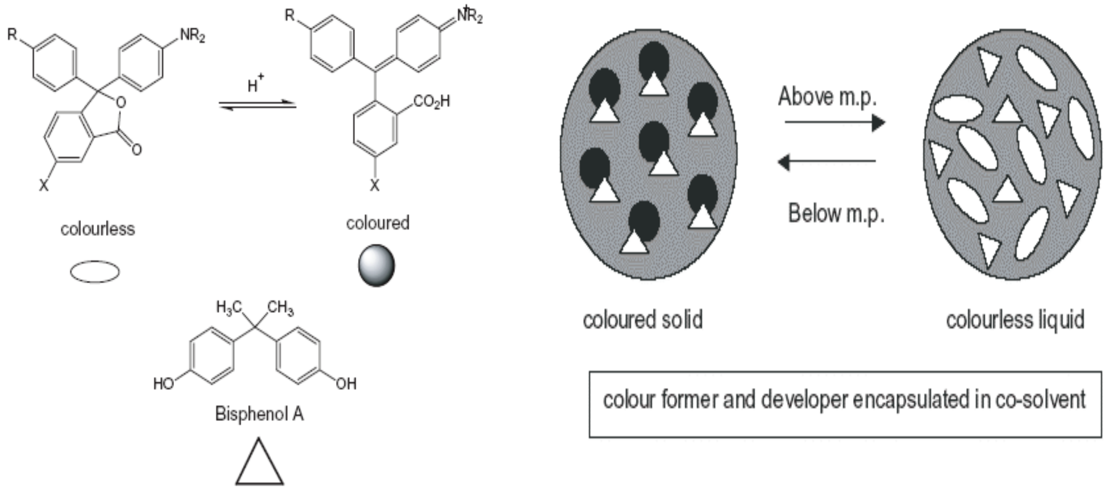
Light colored coatings, when applied on external building surfaces can decrease the cooling load during summer period. During winter period though, in order to reduce energy consumption for heating, the increase of solar gains is required. Thus, there is a need for the development of a technology that can change the optical properties of a material according to the outdoor temperature and solar radiation levels.

Color changing compounds have become increasingly important in recent years in the study and the production of thermochromic coatings, that is coatings which respond thermally to their environment, changing reversibly their color from darker to lighter tones as temperature rises (Azari and Bierman, 2005; Watts et al., 2006; Ma et al., 2001; Ma et al., 2002). The transition is achieved by a thermally reversible transformation of the molecular structure of the pigments that produces a spectral change of visible color (MacNaught and Wilkinson, 1997; Aitken et al., 1996; White and LeBlanc, 1999). A major approach elucidating this alteration is based on organic leuco dye mixtures whose three main components are: the color former, usually a cyclic ester which determines the color of the final product in its colored state, the color developer, usually a weak acid that imparts the reversible color change to the thermochromic material and is responsible for the color intensity of the final product and the solvent, usually an alcohol or an ester, whose melting point controls the transition temperature at which the color change occurs. In order to maintain the thermochromic properties, the mixture is encapsulated in microcapsules of less than 15microns. Microencapsulation serves as a barrier between the thermochromic system and the chemicals around it, such as the paint base, protecting the system from weather conditions, oxidation etc. (Aitken et al., 1996; White and LeBlanc, 1999; Bamfield, 2001; Yoshikawa et al., 1986; Novinson, 1996; Fujita and Senga, 2002; Shibahashi et al., 1984; MacLaren and White, 2003(a); MacLaren and White, 2003(b); White et al., 2000). The thermochromic pigment is colored in the solid form of the material because in this state the color former interacts with the developer, possibly via an ion-pair complex. Melting of the composite interferes with this interaction, leading to a negative thermochromic effect and a loss of color (Fig.1)

This study investigates the thermal and optical characteristics of 11 developed thermochromic coatings to be used in buildings and urban structures. Coatings have been produced using available organic thermochromic pigments incorporated into an appropriate binder system and other stabilizing components to develop a thermochromic paint. The coatings produced have been experimentally compared against common and highly reflective coatings of the same color.

Outdoor measurements of surface temperature were carried out in an hourly basis for two summer months using temperature sensors on concrete tiles coated with thermochromic, cool and common paint. Furthermore, the spectral reflectance was measured and the solar reflectance of the samples was calculated. Aging of the thermochromic coatings is also studied and discussed.

Figure 1. Schematic of a composite organic thermochromic pigment



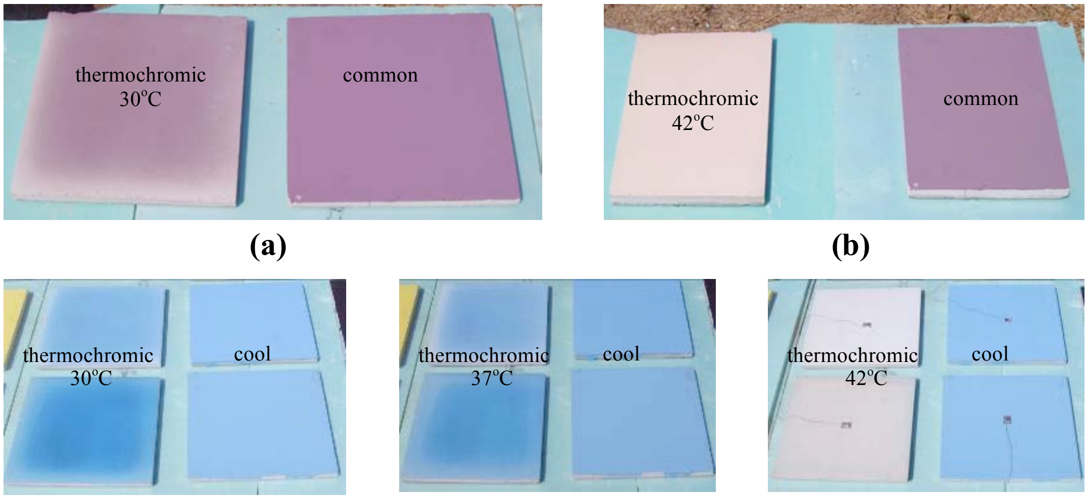
Source: Chromic Phenomena, P. Bamfield , 2001

Production of thermochromic coatings

Organic water based thermochromic pigments were used (Color Change Corporation, Cornelius Group PLC) to develop the thermochromic coatings. All pigments were colored in their cold state and translucent in their warm state having a transition temperature of 30°C. Pigments were microencapsulated with an average particle size of 5 microns. An appropriate binder system that should not itself absorb infrared radiation was produced for the development of the thermochromic coatings. In order to examine the behaviour of thermochromic pigments without the interference of any other type of pigments and simultaneously avoid transparency of the coating at the warm state, two groups of thermochromic coatings were prepared: the first one comprised of the thermochromic pigments and the binder, and the second of the thermochromic pigments, the binder and titanium dioxide (TiO_2). For each of the six colors, two coatings were prepared, one with the addition of TiO_2, and the other without TiO_2. Especially for brown, only the coating with TiO_2 was examined because the color of the thermochromic coating without TiO_2 did not match with any cool brown coating, so 11 thermochromic coatings in total were developed. The coatings were applied on white concrete tiles placed on an unshaded horizontal platform insulated from below. The size of the tiles was 33cm x 33cm.

In Fig.2 (a),(b), on the left, color-changing phase of thermochromic brown coating with TiO_2 is shown. On the right, the tile with the common coating of the same color is shown as well. Fig.2 (a) depicts the color of the tiles 15 min after their exposure to outdoor conditions at a warm day with clear sky and ambient temperature of 35°C. When the surface temperature is increasing above 30°C, the thermochromic coating has started changing color from brown to white due to its temperature increase. The coating has turned almost white 20 min after outdoors exposure, as it is shown in Fig.2 (b), when its surface temperature has become 42^{o}C. Thermochromic blue coatings are presented at the left side of Fig.2 (c), (d), (e), with TiO_2 on top, without TiO_2 on bottom, becoming white and transparent respectively as surface temperature rises above 30^{o}C. Fig.2(c) depicts their color 7min after outdoor exposure where the color has started to change. The color change is becoming more obvious in Fig.2 (d) 10 min after outdoor exposure. The thermochromic coatings are completely decolorized 20 min later as their surface temperature has become 42^{o}C (Fig.2 (e))

Figure 2. Transition phase of thermochromic brown (a), (b), and blue (c), (d), (e) coatings. Thermochromic coatings are on the left side, becoming white as temperature rises above 30^{o}C. On the right side color-matched common and cool coatings are presented.



(a) **(b)**

(c) **(d)** **(e)**

Experimental procedure

For the investigation of the thermal and optical performance of the coatings, the following equipment was used:

i. Temperature sensors, connected to a data logging system, measuring the surface temperature of the samples on a 24 hr basis.
ii. An infrared camera was used for observing the temperature difference between the samples.
iii. UV/VIS/NIR spectrophotometer (Varian Carry 5000), was used for measuring the spectral reflectance of the samples.

Meteorological data recorded from a station near the experimental area, (National Observatory of Athens), including ambient temperature, relative humidity, wind speed, global and diffuse solar radiation on a horizontal surface have been used to characterize outdoor climatic conditions (Table 1). During the experimental period, high temperatures, clear skies and low wind speeds were the dominating meteorological conditions.

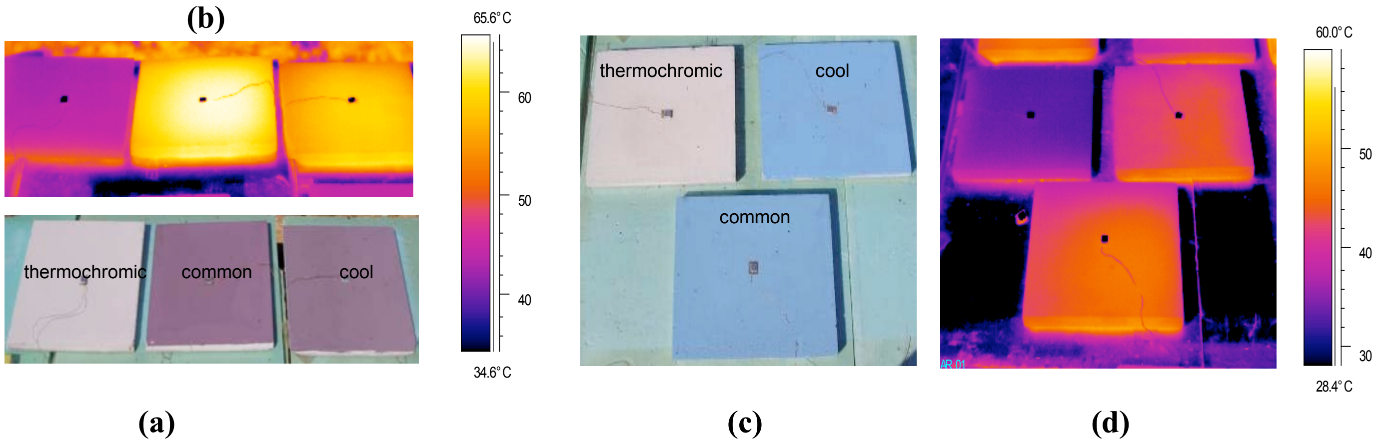
Table 1. Meteorological parameters during the experimental period

Months	T_{amb} (°C)			RH%	Wind Speed (m/sec)	Average daily diffuse radiation (W/m^2)	Average daily global radiation (W/m^2)
	mean	max	min				
AUGUST	29.2	35.1	24.7	44	3.6	1410	6664
SEPTEMBER	23.9	29.9	19.9	54	3.2	1185	5357

Thermal performance of thermochromic coatings

Visible and infrared images were taken at the time of maximum temperature of a representative summer day in order to reveal the temperature differences between thermochromic, cool and common coatings. Fig.3 depicts brown and blue samples with TiO_2 at the visible and the infrared part of the solar radiation. High ambient temperatures result in high surface temperatures of the samples. Thus the thermochromic samples have become white. As shown at the infrared scale thermochromic samples present lower temperatures than cool and common.

Figure 3. Temperature differences of thermochromic, cool and common coatings: visible (a), (c) and infrared (b), (d) images of brown and blue coatings



In order to observe the temperatures that the thermochromic coatings demonstrate and to compare them with the temperatures of the corresponding cool and common coatings, the mean daily and mean maximum daily (6:00-20:00) surfaces temperatures of the samples were calculated from the measured data. The average value of the instantaneous (every 10min.) measured temperatures from 6:00 to 20:00 for each day and for each sample was calculated and used for obtaining the mean daily surface temperature for each month. Mean maximum daily surface temperatures for each month are obtained by the average of the maximum daily temperature values.

The results for each sample are demonstrated in Table 2, for August. For each color and type of coating during the experimental period the samples with TiO_2 (lighter tones) demonstrate lower temperatures than the samples without TiO_2 (darker tones). Light colored common coatings correspond to thermochromic and cool coatings with TiO_2, while dark colored common coatings correspond to thermochromic and cool coatings without TiO_2.

Table 2. Mean daily and mean maximum daily surface temperatures (^{o}C) for thermochromic, cool and common coatings in August

	Mean daily surface temperature (°C) in August					
	Thermochromic		**Cool**		**Common**	
	with TiO_2	**without TiO_2**	**with TiO_2**	**without TiO_2**	**light**	**dark**
GREEN	33.2	36.0	40.9	43.8	44.6	48.5
YELLOW	32.2	32.5	34.4	35.3	36.4	
BROWN	31.0		40.2		42.3	
BLACK	37.6	38.4	44.6	45.2		47.5
BLUE	33.1	37.4	38.7	42.4	39.0	43.9
GREY	34.1	35.5	40.4	44.4	45.1	

	Mean maximum daily surface temperature (°C) in August					
	Thermochromic		**Cool**		**Common**	
	with TiO_2	**without TiO_2**	**with TiO_2**	**without TiO_2**	**light**	**dark**
GREEN	44.2	49.5	57.0	61.1	63.6	69.8
YELLOW	42.5	43.8	44.0	46.7	49.3	
BROWN	40.2		54.9		59.2	
BLACK	50.3	51.5	63.8	64.4		68.0
BLUE	42.7	49.6	52.3	59.2	52.8	62.6
GREY	44.3	46.7	56.1	63.0	64.3	

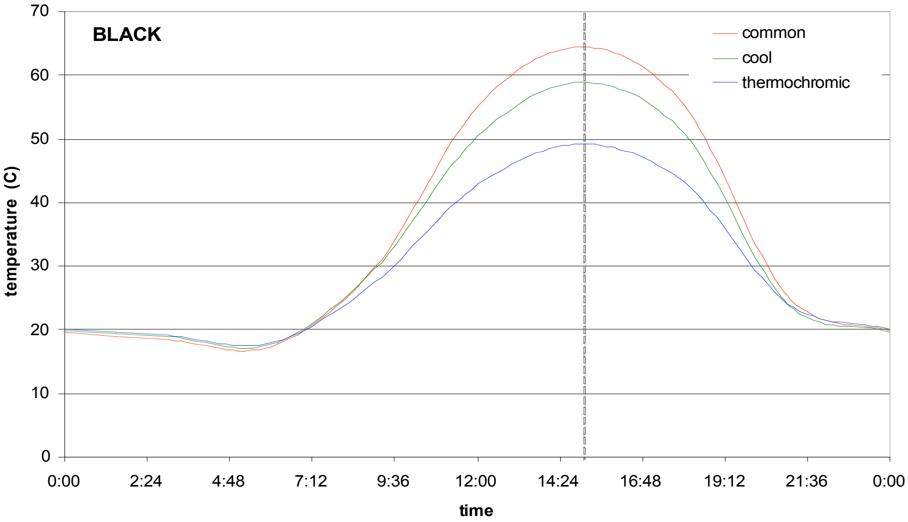
Mean daily surface temperatures range from 31^{o}C to 38.4^{o}C for the thermochromic coatings, from 34.4 ^{o}C to 45.2 ^{o}C for cool coatings and from 36.4^{o}C to 48.5^{o}C for common coatings in August. Comparing the group of thermochromic, cool and common coatings with TiO_2 the following are observed:

- Mean daily surface temperatures of thermochromic coatings are lower than cool and common coatings. During August, temperature difference range from 2.2^{o}C for thermochromic and cool yellow to 9.2^{o}C for thermochromic and cool brown and from 4.2^{o}C for thermochromic and common yellow to 11.4^{o}C for thermochromic and common green. In August, thermochromic coatings demonstrate 10-15^{o}C lower mean max daily temperatures than cool coatings, and 18-20^{o}C lower than common coatings. Comparing the group of thermochromic, cool and common coatings without TiO_2 the following are remarked:
- Thermochromic coatings demonstrate lower mean daily temperatures than cool and common coatings. In August temperature difference range from 2.8 ^{o}C for thermochromic and cool yellow to 8.9 ^{o}C for thermochromic and cool grey and from 3.9 ^{o}C for thermochromic and common yellow to 12.5 ^{o}C for thermochromic and common green.

- In August, mean maximum daily surface temperatures are 10-16°C lower for thermochromic coatings compared to cool coatings except from yellow coating which demonstrates 2.9°C lower temperature. Compared to common coatings, thermochromic coatings exhibit 13-20°C lower temperatures, except from yellow coating whose temperature difference is 5.6 °C.

Fig.4 presents an indicative daily profile of the black common, cool and thermochromic coatings. Maximum temperature difference between common and thermochromic coatings is $\Delta T_{(common\text{-}thermo)} = 15.3^{o}C$ and $\Delta T_{(cool\text{-}thermo)} = 8.3^{o}C$ between cool and thermochromic coatings.

Figure 4. Daily temperature profile of black coatings



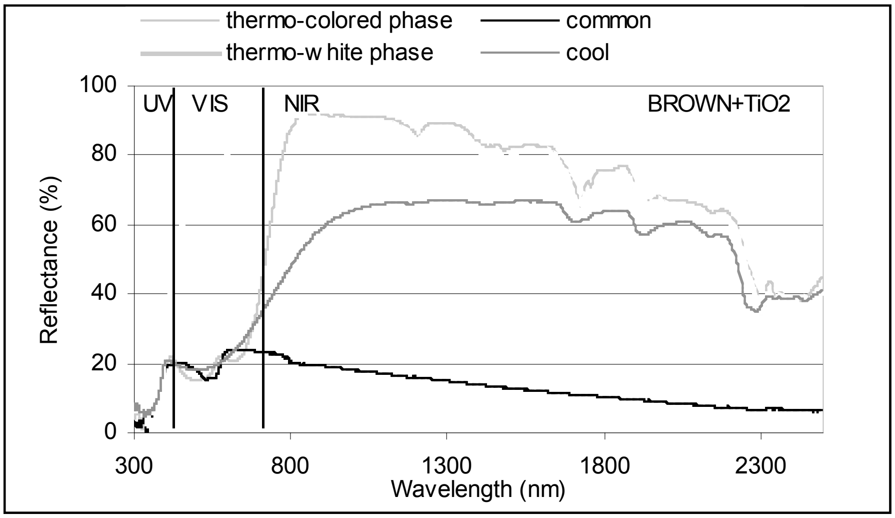
Optical performance of thermochromic coatings

Spectral reflectance of common, cool and thermochromic coatings at their colored and colorless state was measured. The results from the spectrophotometric measurements of the brown samples are presented in Fig.5. In the visible range, the spectral curves of the thermochromic coating in its colored state and the corresponding cool and common coating coincide, meaning that they are of the same color.

All thermochromic coatings are highly reflective in the near infrared (NIR). The reflectance curves of each color in the colored and the colorless state match, as near-infrared properties are mainly influenced by the pigments (Brady and Wake, 1992). The comparison between reflectance curves of thermochromic coatings at their colored phase (below the transition temperature of 30°C) and their colorless phase (above the transition temperature of 30°C) indicate that thermochromic building coatings can absorb solar energy at lower temperatures and reduce the absorption at higher temperatures.

Data of the spectral measurements were used for the calculation of the solar reflectance of each sample. The calculation was performed by the weighted averaging method, using a standard solar spectrum as the weighting function. The spectrum employed is the one provided by ASTM (ASTM E903-96, ASTM G159-98). Table 3 presents the values of solar reflectance (SR) for each sample. Thermochromic coatings at both colored and colorless phase present

Figure 5. Spectral reflectance of brown coatings



higher solar reflectance values than cool and common color-matched coatings, according with the lower temperatures that thermochromic coatings exhibit. Thermochromic samples with TiO_2, being light colored, present higher values of solar reflectance than the samples without TiO_2. The same applies to the colorless phase, where the coatings with TiO_2 become white, while the coatings without TiO_2 become translucent.

Table 3. Solar reflectance (SR) of thermochromic, cool and common coatings

COLOR | TiO_2 content		**Thermochromic SR**		**Cool SR**	**Common SR**
		colored phase	**colorless phase**		
GREEN	**with TiO2**	0.51	0.73	0.41	0.18
	without TiO2	0.33	0.45	0.27	0.04
YELLOW	**with TiO2**	0.78	0.81	0.73	0.64
	without TiO2	0.70	0.73	0.69	0.64
BROWN	**with TiO2**	0.55	0.76	0.41	0.18
BLACK	**with TiO2**	0.40	0.53	0.17	0.03
	without TiO2	0.40	0.47	0.12	0.03
BLUE	**with TiO2**	0.59	0.71	0.53	0.51
	without TiO2	0.41	0.54	0.32	0.21
GREY	**with TiO2**	0.55	0.73	0.44	0.13
	without TiO2	0.34	0.40	0.25	0.13

Conclusions

Eleven thermochromic coatings were developed by using thermochromic pigments into an appropriate binder system. Their thermal and optical characteristics were studied and compared against color-matched common and cool coatings. The color-changing temperature was 30^{o}C. The results demonstrated that during the experimental period, surface temperatures of thermochromic samples were lower than the temperatures of color-matched cool and common. Mean daily surface temperatures ranged from 23.8^{o}C to 38.4 ^{o}C for the thermochromic samples, from 28.1^{o}C to 44.6 ^{o}C for the cool and from 29.8^{o}C to 48.5 ^{o}C for the common samples. Thermochromic coatings with TiO_2 (lighter tones) showed lower temperatures than samples without TiO_2 (darker tones). Spectral measurements revealed that all thermochromic coatings are highly reflective in the near infrared. At higher temperatures, being colorless, they reflect solar energy, while at lower temperatures, being colored, they absorb solar energy. Solar reflectance values were higher for thermochromic coatings at the colored phase compared to cool and common of the same color.

From this study it is concluded that thermochromic systems can function as energy saving systems. For high temperatures, during summertime thermochromic coatings have the ability to reflect solar energy, reducing the surface's temperature, while in wintertime absorb solar energy, increasing the surface's temperature as reversible color change takes place. Applied thus on external building surfaces, they have the potential for the reduction of heating and cooling loads, contributing to the reduction of urban temperatures, fight heat island and reduce air pollution. Further research is being conducted in order to improve the thermochromic coating's performance by preventing photodegradation with the use of innovative technologies.

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