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Current Trends in Cool Coating Technology

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ABSTRACT

Global warming can increase urban temperatures by up to 10 °C, with significant health, environmental and energy implications. The materials of the building and urban fabric have an impact on the thermal balance of the city and significantly increase the risk of urban warming. This review describes advances in the design, manufacture and application of ultra-low and low surface temperature coatings for buildings and equipment. It covers the definitions, mechanisms, evaluations, and recent technological advances of natural, light-colored, infrared solar reflective, PCM-doped, thermochromic, quantum dot, and plasmonic cool materials. A comparative analysis of the experimental results on the cooling capacity and thermal performance of the traditional or new materials is provided. It is shown that natural cool coatings can reflect 80-90 % of solar energy and save 18 % of cooling energy, white and colored cool pigments can exhibit 85-95 % solar reflectance, and novel cool materials can reflect more than 93 % of solar thermal energy. In addition, PCM-doped cool coatings can reduce the surface temperature by 2.5 to 19.7 °C. The aim is to present the best method among those proposed in terms of energy and raw material cost for cool coatings. This review also explains how cool coatings with high solar reflectance can absorb less solar energy and increase the lifetime and efficiency of power systems and electronic devices that are typically exposed to sunlight. Prog. Color Colorants Coat. 18 (2025), 219-232© Institute for Color Science and Technology.

1. Introduction

Interior surface coatings such as walls, refrigerators, cabinets, and furniture are coated; exterior surfaces include houses and cars, as well as car interiors, under the hood, and on computer systems and car stereo components. Coatings must meet a wide range of functional and decorative requirements. Coatings are developed, produced and used with the support of a wide range of science and technology. Coatings can be distinguished by appearance (clear, pigmented, metallic, glossy, etc.) and function (corrosion protection, abrasion resistance, slip resistance, decorative, photosensitive, solar reflective or cool coatings, etc.). Despite some overlap, coatings can be classified as organic or inorganic. For example, in many coatings, inorganic pigment particles are dispersed in an organic matrix (the binder). The substance (often a liquid) applied to a substrate, the resulting "dry" film and the application process are all referred to as coatings. The complex

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mixtures of chemicals known as organic coatings fall into four main categories: binders, volatiles, pigments, and additives that can perform specific functions such as passive cooling [1].

As the urbanization process continues, the energy demand of buildings alone accounts for more than 23 % of the world's total energy demand each year. Due to the significant reduction of green spaces in the city and the absorption of solar energy by buildings and roads, the heat island effect leads to an increase of 3-5 °C in the temperature of the city compared to another area. As a building absorbs sunlight, its internal temperature rises, reducing comfort and increasing energy consumption for air conditioning. A very effective way to reduce the heat island effect is to develop cool coatings that help reduce CO_2 emissions, the effect of heat storage in the city center and urban air pollution [2, 3].

Coatings with a high reflectance index are known as cool coatings. The use of this type of coating on the exterior surface of buildings results in a reduction in the absorption of sunlight during the day, which reduces the accumulation of heat on the surface and thus the need for energy to cool the interior of the building. This in turn leads to reduced energy consumption for building maintenance, improved reduction of the urban heat island effect, and increased thermal comfort in the urban environment [4, 5].

In addition, in hot climates, one of the problems with electronic equipment exposed to sunlight is overheating and failure in the summer. Power transformers, traffic cameras and BTS telecommunications equipment are typically housed in outdoor enclosures exposed to direct sunlight. These devices generate heat during operation and can reach critical temperatures when heated from the outside, resulting in high maintenance and repair costs. Cool coatings with high solar reflectance can absorb less solar energy and increase the life and efficiency of this equipment [6-9].

However, a review of the potential cost, energy, and carbon savings of cool coatings could help inform future research on radiative cooling and its application in building and industrial thermal management. An overview of the benefits of using cool coatings is shown in Figure 1.

2. Concepts and environmental impact

A cool coating is generally defined as a material that has both high thermal emittance (TE) and high solar reflectance (SR). According to Gentle et al. SR is the ability of a surface to reflect solar radiation in both direct and diffuse forms across the solar spectrum and hemisphere. In addition, the high infrared emittance of a cool coating allows it to re-radiate absorbed heat, unlike a black body of the same temperature. Typically, a scale of 0 to 1 or 0 to 100 % is used to measure these two characteristics. Therefore, when a cool coating is applied to a building envelope or urban pavement, it can reflect solar radiation, dissipate heat, and reduce its surface temperature under the sun [10-12].

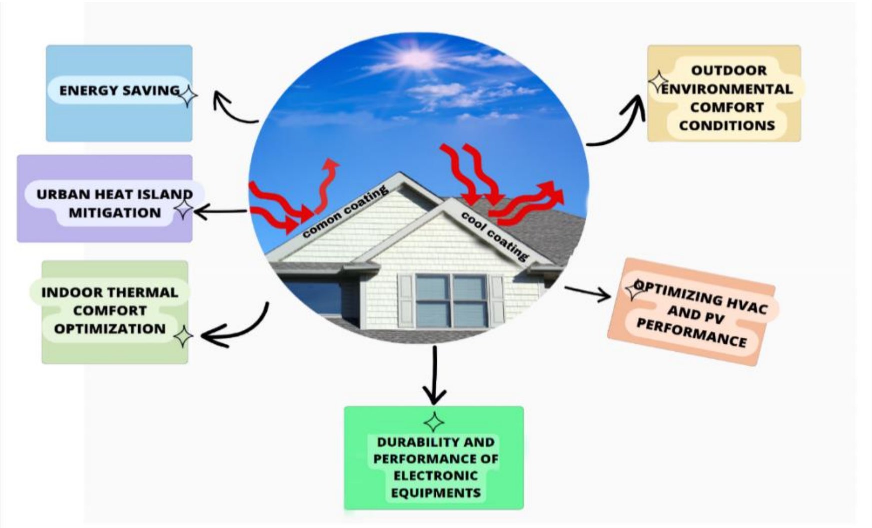

Figure 1: An overall scheme on the benefits of the use of cool coatings [This figure was prepared by the authors].

On an architectural scale, therefore, the application of cool coatings to the building envelope enables

1. Reduce the cooling load of the building.
2. Improve thermal comfort.
3. Extend the life of the roof structure, which is subject to less thermal differential stress.
4. Reduce carbon dioxide emissions from the operation of the building's air conditioning system, especially in the summer.

In addition, in urban areas, cool coatings help to reduce the urban heat island effect by reflecting incoming NIR solar radiation, thereby minimizing the heat absorbed and radiated by the roof and surfaces of the built environment [11, 12].

By applying advanced cool coating properties to well-established building energy models, Nie et al. evaluate the energy, cost, CO_2 emissions, and indoor comfort impacts of solar reflective cool coatings applied to a multi-family building in 32 U.S. climate zones. The model considers both an ideal cool coating and promising cool coating properties based on recent experiments. According to the calculations, the optimal solar reflective cool coating can save up to 6.64 kWh/m^2 of cooling energy per year (Phoenix, AZ), $1.16/$m^2$ of net utility costs per year (Brawley, CA), and 7.7 % of net annual carbon emissions per year (Phoenix, AZ). In addition, they calculate the difference in indoor temperature for structures without cooling and show that, on a cooling degree day basis, cool coatings increase building comfort by 30 to 50 % in the warmest climates of the United States without space cooling [13].

In another study, Zheng et al. show that composites containing transparent thin films with nanosized additives, known as transparent nanomaterial-based solar reflective cool coatings or nSCCs, are designed to reduce solar heat gain and passive cooling in buildings.

They studied transparent nSCCs from a nano-materials perspective, including morphologies, enhanced properties, prototype applications in buildings, and different types of nanosized additives. This paper compiles more than 80 references on transparent nanostructured solar cells (nSCCs), including 19 nano-materials that fall into three general categories: metal-based, metal oxide, and metalloid nSCCs. It is well known that solar heat gain through the building is the primary cause of up to 60 % of the cooling loads in buildings, resulting in significantly high building energy consumption. Therefore, there is great interest in studying nSCCs as a passive cooling and solar heat reduction technique for energy efficient buildings [12-14]. Figure 2 illustrates the main issues addressed by Zheng et al.

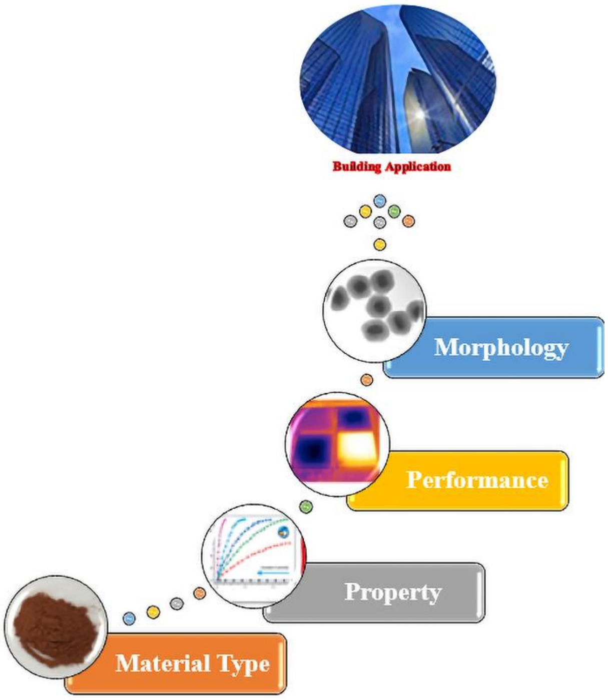

Figure 2: Main point to be covered in the Zheng study [This figure was prepared by the authors].

3. Measurement methods and evaluation

Both the solar reflectance index and the thermal performance of a cool coating are characterized to evaluate the passive cooling effect. Research indicates that material degradation and surface accumulation are likely to cause a decrease in solar reflectance. However, microbial growth and degradation can cause a permanent change in the chemical composition of the material, which would change the solar reflectance. In addition, the solar reflectance of a surface depends on its morphology, its glassy nature, and its texture [15].

3.1. Solar reflectance measurement

The standard test methods for evaluating the solar reflectance index of a surface from the solar spectrum, including the calculation process from laboratory experimental data obtained using a spectrophotometer instrument with an integrating sphere, are [15]:

1. ASTM E903-2012: This test method refers to the

calculation of the solar reflectance index from laboratory data obtained from a spectrophotometer with an integrating sphere [16].

2. ASTM C1549-02: This method refers to the measurement of solar reflectance using a portable reflectometer in a field method [17].

3. ASTM E1918-06: This method refers to the measurement of solar reflectance on horizontal or slightly inclined surfaces using pyrometers in the field when the angle of the sun to the surface normal is less than 45° [18].

For infrared emissivity, the standard methods are:

1. ASTM C1371-2015: This method refers to the measurement of thermal emissivity using a portable emissivity meter [19].

2. ASTM G173-03-08: This method provides values for wide-angle and direct solar irradiance introduced by the sun at various tilt angles, including variables such as angle of incidence, air mass, and others [20].

Compared to standard black coatings (e.g., bitumen-based, etc.) that reflect less than 10 % of NIR solar radiation, the best performing cool coatings typically exhibit SR of 80 % and higher. They are also rated by thermal emittance between 0.80 and 0.90.

Compared to standard black coatings (e.g., bitumen-based, etc.) that reflect less than 10 % of solar radiation, the best performing cool coatings typically have SRs around 80 % or higher. They are also characterized by thermal emittance values between 0.80 and 0.90. For surface applications, these two essential characteristics are referred to as "coatings" because they are both sensitive to the outermost layer of the surface exposed to solar radiation. As a result, under steady-state conditions, they have a significant influence on the thermal balance of a horizontal surface exposed to solar radiation, such as a roof or urban pavement, which is described by equation 1 [11, 18-20]:

$$(1\text{-SR})\text{I}=\text{t}=\text{TE}\sigma\,(T_S^4-T_{sky}^4)+h_c(T_s-T_a)\text{-}\lambda\frac{dT}{dx} \qquad (1)$$

SR: refers to solar reflectance of the surface, which ranges from 0 to 1.

I: represent solar irradiation factor [W/m^2].

TE denotes thermal emittance, which also ranges from 0 to 1.

σ is the Stefan-Boltzmann constant 5.6708 times 10^{-8} [W/m^2 K^4].

T_s is the temperature of the given surface [K].

T_{sky} is the temperature of the sky [K].

h_c is convective heat transfer coefficient [W/m^2 K].

T_a is the air temperature [K]

λ is the thermal conductivity from a similar surface [W/mK]

$\frac{dT}{dx}$ is the gradient of temperature (change in temperature in the x direction)

As shown in equation 1, the thermal behavior of a thermally insulated roof exposed to solar radiation is primarily influenced by SR and TE when a cool coating is applied over it; the λ component is comparatively less important. More specifically, SR is the primary parameter that, if optimized, can reduce the surface temperature Ts during the day, when solar forcing is the primary constraint on the surface temperature of the coating. On the other hand, during the night, infrared emittance has a significant impact on performance by influencing the ability of the surface to reflect heat upward [11, 18-20].

3.2. Thermal performance evaluation and characterization

The thermal performance of cold coatings can be characterized in a laboratory thermal setup. For this purpose, Gao et al. designed an apparatus similar to those previously built by other researchers. A sealed box of polystyrene foam board was constructed with dimensions of 200 mm by 200 mm by 200 mm. Cool-coated aluminum plates were placed over the box under a 250 W infrared lamp (Philips) with a wavelength of 0.76 to 5 µm. The internal temperature was recorded over time [21-23]. Figure 3 shows the thermal test apparatus and a sample thermogram.

The surface temperatures of the samples were measured with type T thermocouples connected to a data logger model DT800. The collected data was displayed on a computer every 60 s. The sensors were placed in the center of the outer and inner surfaces of the samples and in the center of the fixture designed for the test. The temperatures of coated and uncoated panels exposed to the same incident IR energy were measured simultaneously to compare the effect of the cool coating. The temperature of the air inside the apparatus was kept constant to avoid heat accumulation and to ensure that the heat absorbed by the panels was due exclusively to irradiation and not to convection [21, 22].

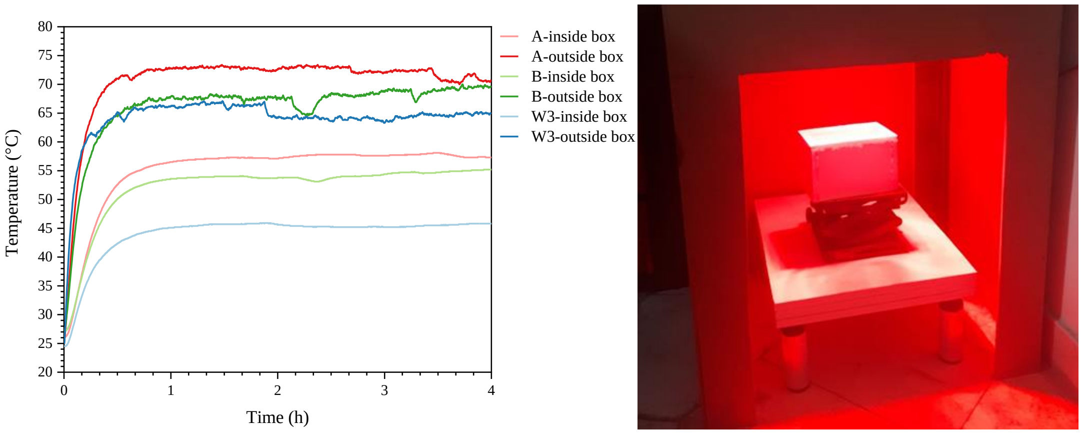

Figure 3: Schematic of the apparatus developed for exposure to NIR radiation and a sample thermogram [This figure was prepared by the authors].

4. Trends and history

Berg and Quinn reported that in late summer, colored roads with a solar reflectance close to 0.55 had temperatures close to the surrounding environment, while uncolored roads with a reflectance factor close to 0.15 were about 11 °C warmer than the air. A study by Asaeda and colleagues tested the effect of different pavement materials commonly used in urban environments during the summer season. Their results showed that asphalt had significantly higher surface temperatures, heat storage, and subsequent heat release to the atmosphere compared to concrete and bare soil. According to Santamouris , asphalt temperatures could reach as high as 63 °C, while white coatings reached temperatures close to 45 °C. A study conducted at the University of Athens investigated the compatibility of materials used in urban open spaces. Infrared thermography methods were used to evaluate the thermal performance of 93 common flooring materials. These materials were classified as "cool" and "warm" based on their thermal behavior and physical characteristics. Tiles made of marble, mosaic and stone were found to have cooler temperatures than those made of concrete and asphalt. In addition, light-colored tiles with smooth surfaces were cooler than darker versions with rough surfaces [23-27].

Through their studies, Bretz and his colleagues found that the use of high solar reflective materials is considered a cost-effective solution for reducing cooling energy consumption and improving air quality in urban environments. They focused on SR materials that control surface temperatures in sunlight and thus have direct and indirect effects on reducing cooling energy consumption [28, 29].

In another study, a single building with a cool coating on the roof would require 15 % less energy for air conditioning each year, according to a model previously developed by the U.S. Department of Energy. A significantly larger reduction in cooling load was calculated by Lamba et al. using modeling for a passive radiative cool coating with a cooling capacity of 100 W/m^2 compared to a cool roof coating. According to the model, a passive radiative cool coating covering 50 % of the roof surface would eliminate the peak cooling load of a single building in Chicago, Illinois in July. However, it would miraculously reduce the cooling load of a building in Miami, Florida by 95 % (in July) and 90 % (in August) [28, 30]. An overview of the current state of cool coating technology is shown in Figure 4.

According to a report by Grand View Research, reflective cool roof coatings have the largest market among passive cool coatings, with a global market size estimated at $3.59 billion in 2019. Thick elastomeric coatings account for more than 64 % of the revenue in this market. Some of the important factors for consideration in the selection of cool coatings are [11, 30]:

1. High solar reflection coefficient (SR): This is the most important material selection criterion.

2. Intended use: The suitability of materials for various applications, such as architectural coatings for roofing, road construction, sidewalks, or industrial coatings for covering electrical and electronic equipment enclosures.

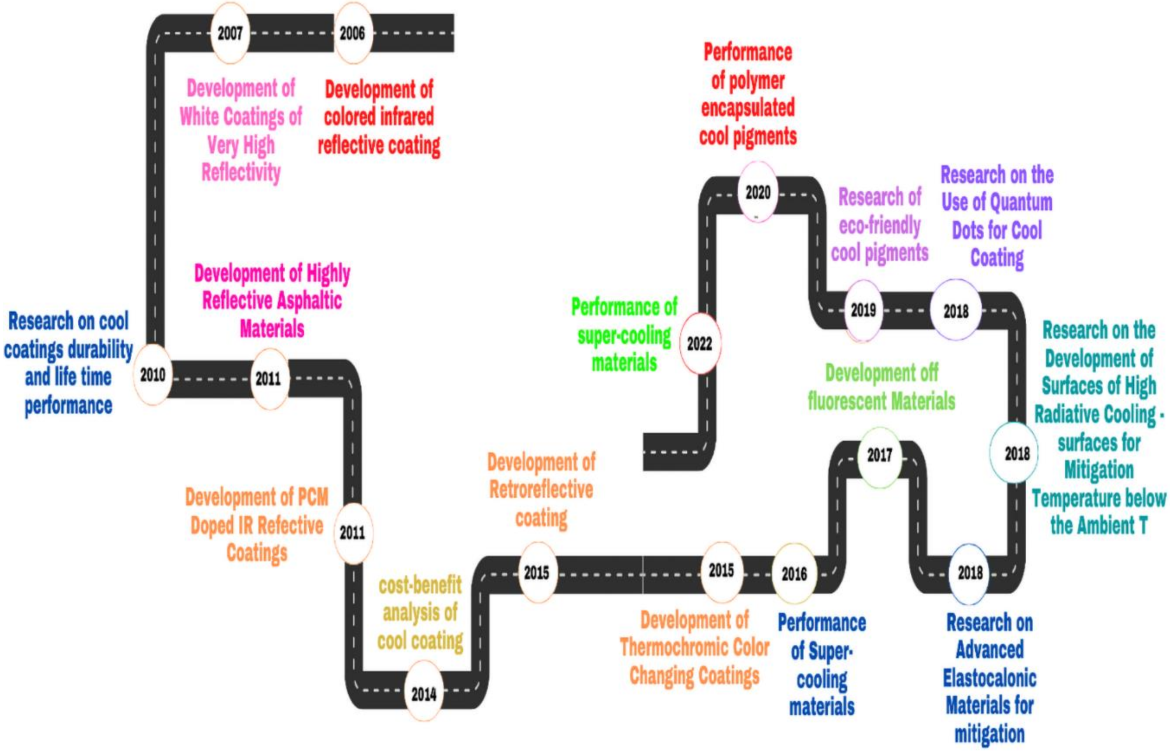

Figure 4: Review of the latest trends in cool coating technology [This figure was prepared by the authors].

3. Ease of application: Materials should be easy to apply and use without operational problems in urban or industrial environments.

4. Weather Resistance: Materials should be able to withstand weather elements such as rain, snow, temperature changes, UV radiation, etc.

5. Durability: Materials that have a longer lifespan and undergo less degradation and wear over time are a better choice.

6. Energy efficiency: Solar reflective materials should be able to reduce cooling energy consumption.

7. Aesthetic impact: The integration of materials with an attractive appearance.

8. Cost and Economy: The cost of production, application and maintenance of materials should be economical in the implementation phases.

9. Environmental Impact: The impact of materials on the environment and sustainability of the region.

10. Laws and regulations: The compliance of materials with local and national laws and regulations.

5. Materials for cool coatings

Embedding micro/nano-sized materials such as nanoparticles and pigments in a lossless material such as a polymer can help reflect the desired spectrum. The polymers used for cool coatings depend on the final applications. Solventborne and waterborne acrylic resins, styrene acrylate, PVA and PVC resins, PVDF and polyurethane elastomers are formal resins that can be used for coating preparation. Reflective Cool pigments promote reflection of NIR wavelengths due to their unique structure. In addition to a specific crystallographic structure, the particle size of the pigment is an important factor. The particle size must be greater than half the wavelength of the light to be reflected to achieve effective NIR reflectivity. Consequently, IR radiation should be reflected in the heat-generating region, i.e., the 700-1100 nm wavelength range. Particles should have a minimum size of 0.35-0.55 μm. While the reflectivity and absorptivity of the pigment are independent, cool pigments can be any color. The reflection is in the infrared and part of the visible light. Compared to conventional pigments with the same color appearance, NIR reflective pigments show increased reflectance in the non-visible NIR range. In addition, the ideal IR emissivity of a cooling pigment should be high to promote radiative passive cooling of the material in which it is embedded [30-33].

The following categories of cooling materials and pigments are the main components of cooling coatings.

5.1. Natural cool materials

To achieve satisfactory thermal performance with less environmental impact, it is possible to combine intrinsically cool properties with low cost and low production energy by using naturally cool materials. One of the most popular "natural" cool materials for horizontal application is gravel, especially in the Mediterranean region, where it can be easily applied over the bituminous surfaces that typically already exist on existing roofs. Due to the stones' natural light color and the material's local availability, it is highly sustainable, both environmentally and economically. Pisello et al. evaluated the passive cooling capacity of different gravel types characterized by different grain sizes. It was found that as the grain size decreases, the albedo increases.

Due to its naturally ideal cooling properties, light-colored marble was also identified as a cool natural material in the same situation (Rosso et al., 2014). Experimental data on the cooling potential of the material showed solar reflectance values as high as 79 %, and dynamic simulations showed energy savings of up to 18 % compared to a conventional non-cooling concrete envelope for summer cooling [34-36].

5.2. White cool pigments

5.2.1. Titanium dioxide (TiO_2)

One of the best cool coatings is white acrylic paint. White acrylic paint is an example that is produced on the basis of titanium dioxide pigment (rutile) in a polymer resin. The strong ultraviolet absorption of titanium dioxide pigment is considered a positive feature because UV absorption can protect the polymer and substrate from atmospheric degradation. Pigment manufacturers optimize the particle size to achieve the highest possible reflectance in the visible wavelength (centered in the green region with a wavelength of 550 nanometers or 0.55 micrometers). The optimum size in this case is a particle diameter of about 200 nanometers. In this case, the visible reflectance is over 90 %. However, the solar reflectance is only 83 %. Near ultraviolet reflectance can be increased by using larger particles, e.g. 260 nanometers. There are also some absorption features in the near ultraviolet due to the vibrations of hydrogen atoms in the coatings [37, 38].

Sharma studied the effect of adding nanostructured titanium dioxide on the properties of cold coatings. Titanium dioxide was used as an additive in these coatings and its effect on the performance of these coatings was evaluated. The effect of titanium on the properties of cool coatings can be described as solar reflectance, thermal stability, environmental resistance, and improvement of optical properties [9].

5.2.2. Zinc oxide (ZnO)

One of the most important metal oxide powders with near infrared (NIR) reflectance is zinc oxide (ZnO). ZnO nanoparticles modified with zinc aluminate have higher reflectance performance than unmodified pigments. Currently, a ZnO-based pigment additive and calcium potassium silicate (SR: 80-90 %) are used in thermal control coating systems for space assets to maintain the ability to reflect sunlight over time. In addition, to completely eliminate the phenomenon known as "white spotting," the best approach is to introduce pigments that provide color by absorbing visible wavelengths and can also provide a cooling effect by reflecting near infrared light [39, 40].

5.3. Colored cool pigments

5.3.1. Terbium-doped

Athira and colleagues used pigments based on terbium-doped materials. In this research, $Y2Ce_2$-xTbxO7 (x = 0, 0.2, 0.4, 0.6, 0.8, and 1.0) was used as the main pigment to produce a ceramic yellow color with high solar reflectance properties. These pigments improved the mechanical and optical properties of the coatings and increased the NIR reflectance of the coatings to 93 %.

Multi-purpose coatings were then prepared from the prepared yellow pigment and various properties, including surface properties, NIR reflectance (80 %), and their cooling performance, were investigated. The results indicate that these coatings are capable of providing environmental cooling below ambient temperature on hot days, as well as possessing suitable mechanical properties and high water resistance [41].

5.3.2. $Li_3InB_2O_6$

Divya and colleagues have synthesized red slag-based pigments using the solid state reaction method based on $Li_3InB_2O_6$. To achieve the red color in these environmentally friendly pigments, Mn^{3+} ions were substituted for indium ions in the $Li_3InB_2O_6$ structure. The optical properties of these pigments are attributed to the presence of Mn^{3+} ions in their structure. As a result, the pigments prepared in this study have very good color attractiveness and appearance and good NIR reflectance (85-87 %). The measurement of the internal temperature of the coated and uncoated sheets shows a temperature difference of 1.9 °C. These properties make these pigments suitable options for roof coatings using cooling technology. In addition, these pigments have been shown to effectively reduce surface temperatures compared to uncoated surfaces, indicating that they can serve as effective candidates for cooling coatings [42].

5.3.3. $Fe_{0.7}Cr_{1.3}O_3$

In another research, $Fe_{0.7}Cr_{1.3}O_3$ brown cool nano pigments were synthesized by the hydrothermal method. The effect of TEOS as a silica source on the synthesis process was also investigated. The SR (52 %) was observed in the DS9 sample synthesized with 1.875 wt. % TEOS and 2.63 wt. % succinic acid due to the flaky morphology of the particles and the difference between the reflectance index of the silica layer and the $Fe_{0.7}Cr_{1.3}O_3$ particles. In addition, silica provided a significant increase in the IR reflectance of the base pigment and caused a decrease in particle accumulation [43].

5.3.4. Blue pigments

Nowadays, several types of mineral blue pigments such as cobalt blue ($CoAl_2O_4$), ultramarine ($Na_7Al_6Si_6O_{24}S_3$), Prussian blue ($Fe_4[Fe(CN)_6]_3$) and azurite $[Cu_3(CO_3)_2(OH)_2]$ are used as cool pigments. However, these pigments have environmental drawbacks such as high toxicity, instability at high temperatures and acidic conditions, and release of harmful substances. Researchers have made significant efforts to improve traditional cobalt aluminate blue pigments, including the incorporation of rare earth metal ions, which has led to an increase in NIR reflectance. Replacing cobalt and chromium ions with rare earth ions in the blue matrix has reduced the amount of cobalt and chromium while maintaining the optical properties. In addition, replacing Mn^{3+} in the hexagonal $YInO_3$ structure has resulted in blue pigments with pure color and high infrared light reflectance. Other innovations include pigments such as $YMnO_3$, produced by various methods, that exhibit blue-green colors with high near-infrared and solar reflectance 67-70 %). These pigments have provided environmentally friendly alternatives and can be used as cool pigments [39, 44-46].

5.3.5. Green pigments

In the 18th century, a cool green pigment was made from cobalt and zinc oxide, but it had low tinting strength. In the 1960s, cadmium and zinc sulfide greens were used as cool green pigments, but green pigments based on Cr_2O_3 attracted the attention of the scientific community due to their cost-effectiveness, strong chromophoric properties and thermal stability. Complex Cr_2O_3 green pigments are used as cool green coatings due to their near-infrared reflecting properties (50-57 %). Doping Cr_2O_3 with Ti^{4+} instead of Cr^{3+} increases the brightness of the green color and increases the NIR reflectance from 84.04 to 91.25 %. Recently, a green pigment with $BaCr_2(P_2O_7)_2$ pyrophosphate with high NIR reflectance (90 %) has been reported. However, these pigments contain the toxic chromium ion, which necessitates the development of non-toxic mineral green pigments with high NIR reflectance properties [39, 47-49].

Green pigments have been used as camouflage pigments, and the reflectance spectrum of the camouflage pigment in the green region closely resembles chlorophyll, the green pigment found in plants. Iron Complexes has developed a green pigment that matches the light reflectance of green plants. Ferrous Complexes have developed a green pigment that matches the light reflectance of green plants. Green pigments that reflect infrared light have been used as camouflage pigments. The reflectance spectrum of the camouflage pigment in the green region is only similar to chlorophyll, the green pigment found in plants [39, 47-49].

5.3.6. Perylene black pigments

Over the past decade, perylene bisimide (PBI) derivatives have inspired the design of functional materials with a wide range of applications. These applications include the creation of organic solar cells, organic light-emitting diodes, and field-effect transistors, as well as their use as dyes in luminescent solar concentrators, smart polymer materials, and cool coatings. In addition, PBIs have been widely used in the development of high-performance industrial pigments due to their exceptional tinting strength, insolubility, chemical stability and weather resistance, as well as the ability to create a wide range of colors and optical qualities by adjusting the substituents at the periphery of the PBI core. The chemical structure of PBI pigments is shown in Figure 5.

Recently, there has been considerable interest in the reflectivity and transparency properties of PBIs in the near infrared (NIR) region of the electromagnetic spectrum, making them promising candidates as "cool" organic pigments [50].

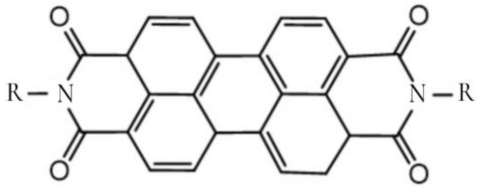

Figure 5: Chemical structure of perylene black pigments.

5.3.7. Dioxazine purple colorants

The black coatings colored with NIR-transmitting perylene black and dioxazine purple colorants are cool black coatings, although they have a green and purple hue, respectively, according to the latest research in the work of Qin et al. The black coatings reduce the surface temperature by 11.2 and 12.0 °C over bare aluminum alloy substrates, and by 12.4 and 13.8 °C over cool white basecoats. For coatings pigmented with chromite iron-nickel black colorant, the estimated energy savings resulting from the application of black coatings in Beijing range from 1.21 $kWhm^{-2}yr^{-1}$ to 5.52 $kWhm^{-2}yr^{-1}$ for coatings pigmented with dioxazine violet colorant [51].

5.4. Phase change materials

Phase changing materials (PCMs) are used to effectively increase the apparent heat capacity of buildings and reduce their surface temperature at specific points. These materials have the ability to store and release latent heat and are used as a component in asphalt and concrete coatings. Studies indicate that the use of PCMs in asphalt can prevent cracking and deterioration of the asphalt coating and improve the viscoelastic properties of asphalt binders. In addition, these materials can improve the resistance of concrete coatings to cracking, torsional stress, hydration and thermal shrinkage. Research shows that by adding PCMs to coatings, it's possible to moderate their surface temperature and release stored thermal energy with a certain delay. The effect of this temperature reduction depends on the amount of PCM in the total mix, the transition temperature of the PCM, the method used to add PCM to the coating, and the local weather conditions. According to available experimental results, the surface temperature of coatings containing PCM varies and depends on various parameters such as the volume of PCM, the melting temperature, the method of adding PCM to the coating, and the local climatic conditions. Experiments have shown that the reduction in surface temperature of coatings with PCM can range from 2.5 to 19.7 °C [52-55].

6. Current technology and challenges

Zheng et al. published research (2022) on the surface modification of hollow glass microbeads (HGMs) and thermal hydrolysis of $TiCl_4$ to produce needle-shaped rutile shell-coated HGMs. A potential mechanism for shell formation was also proposed. The NIR reflectance of the coated HGMs was 93.3 %; however, after heat treatment to enhance the crystallinity of the rutile shell, this value could be increased to 97.3 %. In addition, the thermal insulation performance of the HGM/styrene-acrylic composite reflective coating applied to the gypsum board surface was measured using a self-developed experimental thermal setup. The results show that the coating of HGM coated with a rutile shell has superior NIR reflectance and thermal insulation performance compared to the pure organic coating and uncoated HGM. In addition, it exhibits improved surface hydrophobicity, which supports stable and long-term IR reflectance performance [56, 57].

Passive daytime radiative cool coating (PDRC) uses highly reflective solar radiation to increase the amount of energy used for heating in winter. In another research, Dong et al. combine temperature-adaptive solar absorption and PDRC technology to achieve "warm in winter and cool in summer," inspired by the skin color of the chameleon. The color-changing temperature-adaptive radiative cool coating (TARCC) was designed and fabricated to regulate 41 % of visible light. Extensive seasonal outdoor testing validates TARCC's reliability: In summer, TARCC exhibits high SR (approximately 93 %) and atmospheric transmittance window emittance (approximately 94 %), resulting in a subambient temperature of 6.5 K. In winter, TARCC's dark hue effectively absorbs solar radiation, raising the temperature by 4.3 K. In mid-latitude regions, TARCC can increase suitable human comfort by 55 % and save up to 20 % of energy consumption compared to PDRC coatings. TARCC has the potential to create environmentally friendly and comfortable interiors due to its low cost and simple construction process. Figure 6. describes the schematic diagram of the TARCC [58].

Materials that change color due to thermochromic temperature can exhibit a reversible color shift, changing from white and reflective in summer to dark and absorptive in winter. There are many different types of thermochromic materials, including thermochromic blends, that change color by different mechanisms. The most well-known mechanisms include refractive index modulation in photonic crystals [59], phase transition in liquid crystals [60], surface plasmon absorption, luminance changes in sol-gel films, aggregation and disaggregation mechanisms between dyes and dye polymers, and pH variation with temperature [61]. Leuco dyes are the most studied color changing material, although there are other materials that change color with temperature. According to recent research reports, materials with remarkable and attractive thermochromic properties are based on plasmonics, quantum dots, photonic crystals, conjugated polymers, Schiff bases, and liquid crystals. In particular, the unique optical properties of quantum dots, which are organic materials with a nanoscale size of 2-10 nm, allow them to emit radiation at completely different wavelengths while simultaneously absorbing light at a specific wavelength. Their optical properties can be tailored by adjusting the surface chemistry and dot size. Because quantum dots lose some of their photoluminescence as the temperature rises, they are not a viable option for heat dissipation. This phenomenon is called thermal quenching. According to recent research, quantum dots can exhibit anti-quenching effects and increase their photoluminescence with temperature when combined with polymers. This property makes them useful for mitigation purposes [62-64].

In studies of reflective coatings and various surface products, resistance to "dirt pickup" is one of the most important criteria. This is the ability of a coating to prevent the absorption and accumulation of dirt and dust on its surface. Coatings with the ability to resist dirt pickup typically retain their properties for a longer period of time and prevent the negative effects of surface contamination. This property is important because it can improve the performance and efficiency of the reflective coating over time. Therefore, when selecting reflective coatings for use in urban and building environments, consideration should be given to those with adequate dirt pick-up resistance to ensure they positively impact thermal performance and appearance over the long term. The effectiveness and durability of cool coatings can be evaluated through natural and accelerated weathering.

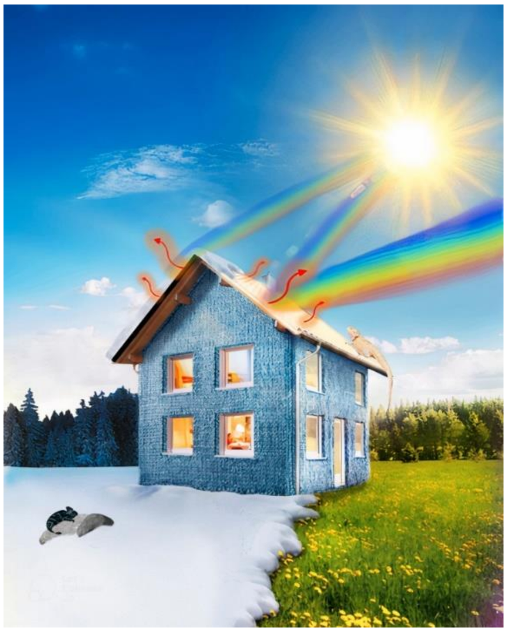

Figure 6: Schematic diagram of the TARCC.

White reflective coatings in urban environments typically face problems such as erosion and optical degradation. After approximately 60 days of outdoor exposure, the daily temperature difference between these coatings and the environment increases significantly, indicating problems such as the accumulation of salts, soils, soot particles, and organic particulate matter as the primary reasons for their reduced reflectivity. Bacterial growth on these coatings has also been reported. Washing the surfaces helps to restore some of their optical properties, but their reflectivity is expected to decrease by at least 20 % in the first three to five years. Research indicates that white reflective coatings experience a decrease in reflectivity over time, and after a few years, the decrease in reflectivity can be as high as 0.2. It has also been reported that white solar reflective coatings lose 0.05 to 0.10 of their reflectivity as early as 50 days after exposure.

There is a lot of research going on to improve the durability of white reflective coatings. Optical performance and the potential for improved optical durability depend on several factors, including the composition and processing of the coatings, as well as environmental conditions. Research is underway to reduce the effects associated with aging of coatings, increase the self-cleaning capabilities of surfaces, and reduce degradation caused by various environmental factors. It has been observed that enhancing the optical effects of coatings by incorporating titanium dioxide (TiO_2) nanoparticles helps to improve the self-cleaning performance of surfaces and their optical enhancement. It has been found that doping titanium dioxide with Al, Li or K significantly increases the photostability of coatings, but not their solar reflectance.

The application of photocatalytic technologies enhances the optical performance and self-cleaning capabilities of the coatings. When TiO_2 nanoparticles are incorporated, the organic materials deposited on the coating surface are decomposed into sulfate, water, nitrate and CO_2, which can then be removed by washing with water or rain. In addition, there is a significant reduction in bacterial adhesion to the coating surface [65-68].

7. Conclusion

One of the major environmental, energy and human health concerns is urban overheating. Novel low surface temperature materials and coatings have been developed to offset the extra heat released in the urban atmosphere. Traditional light-colored natural and man-made materials are widely used in cooler climates, but new creative cool materials have recently been used in many major urban projects. While there is a noticeable reduction in temperature and a significant reduction in heat released into the urban atmosphere on highly reflective surfaces, significant weathering and aging issues remain to be addressed. While there is a noticeable reduction in temperature and a significant reduction in heat released into the urban atmosphere on highly reflective surfaces, significant weathering and aging issues remain to be addressed.

This review provides a thorough analysis of the scientific research on the development of cool coatings and their practical applications. Many new alternative materials with significantly higher mitigation potential have been discovered as a result of intensive research in both pure and applied materials science. For natural cool coatings, research has shown that coatings can reflect 80-90 % of solar energy and save 18 % of cooling energy. For white and colored cool pigments, research has shown that coatings can have 85-95 % solar reflectance, and novel cool materials can reflect more than 93 % of solar thermal energy. In addition, PCM-doped cool coatings can reduce the surface temperature by 2.5 to 19.7 °C. This review aims to classify the cool materials based on their thermal efficiency, preparation, optical properties, and end-use applications. Technologies based on plasmonic and photonic structures, nanofluorescent materials, thermo-chromic materials, and quantum dots have attracted the most research interest. However, much research remains to be done to translate the latest scientific discoveries into engineered products. Further research could focus on issues such as improving the thermal efficiency of materials, optical aging, material scalability and cost reduction, thermal modeling, industrial applications, and the overall impact of cool coatings on the buildings and urban structures.

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