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Review Article

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Application of Reflective Coating on the Thermal Performance of a Building's Roof: An Overview

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ABSTRACT

In hot climes, in particular, efficient building cooling solutions are essential for energy efficiency. Applying reflecting coatings to building surfaces is one such technique that can greatly minimize heat absorption and cooling requirements. The endurance and aesthetic appeal of a structure are improved by these coatings, which also offer defense against environmental elements. These coatings include paints, sealants, varnishes, and specialty alternatives including elastomeric and anti-graffiti coatings. The purpose of reflective coatings is to increase surface reflectivity, decrease glare, and minimize heat absorption. Reflective clothes, solar panels, mirrors, and optical equipment are just a few of the many uses for them. The creation of affordable, expandable, and durable radiative cooling materials that can be easily incorporated into architectural design is still lacking in study, nevertheless. More investigation is required to assess these materials' practical performance, long-term durability, and capacity to sustain high cooling efficiency under varied circumstances in order to fully realize their promise. In order to combat climate change and minimize energy consumption, it is imperative that radiative cooling technologies be widely adopted in the construction sector and urban planning.

Keywords: Reflective Coating, Composite Materials, Building Protection, Radiative Cooling, Infrared Reflection

Introduction

The human race depends on solar energy. It covers the globe's entire surface, spreading itself thin. Large structures must be made comfortable for its occupants because they are now necessary for the expanding global population. These radiations aren't always necessary for the occupants' comfort during certain seasons of the year. The cost of cooling is too high if the buildings are exposed to these radiations. The (upper) atmospheric transmittance graph shows how the transmission of light through the atmosphere varies with wavelength and wave number (Figure 1). It highlights an important region of interest known as the prior atmospheric transparency window, which lies between 8 and 13 µm. This window indicates the wavelengths at which the atmosphere is relatively transparent, allowing for easier transmission of light. In the (lower) part of the figure, functional groups that have been previously identified and reported in scientific works are shown. These functional groups represent specific chemical bonds present in molecular structures. The corresponding positions of these groups within the wave number range are also indicated. To aid in visualization, the chemical bonds located before 8 µm are highlighted in red, while those found between 8 and 13 µm are highlighted in blue. This color-coding helps to differentiate between the two regions and provides a clearer understanding of the specific chemical bonds associated with the different sections of the wave number range.

In the summer, heat transfer through building envelopes makes up the majority of the load for indoor cooling. Using high reflectivity materials to coat building outside walls is an efficient technique to lower heat gains from solar radiation and, consequently, use less cooling energy. Thermal insulation, in addition to the appropriate design and selection of the building covering and its components, can reduce the air-conditioning demand. The use of thermal insulation in building walls and roofs is thought to be a major factor in lowering the size required for air conditioning systems as well as the yearly energy expenditure [1]. When a surface of an object (substrate) gets covered with a new layer and acquires new qualities, the process is referred to as coating. Depending on the substrate job, the coating may be functional, aesthetic, or both. The coating itself may be applied and cover the substrate entirely or just a portion of it [2]. Reflective coating refers to a type of coating

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applied to a surface that enhances its reflectivity, making it more reflective to light or heat [3]. Paint reflective typically refers to a type of paint that contains reflective additives or pigments [4]. On other hand, to lower the cooling loads in buildings and ensure thermal comfort in the built environment, high reflective coatings and paints can be applied to the roof and walls. New materials for coating in combination with ancient technologies are an important option to reduce electricity consumption [5]. Coatings can provide a protective barrier against environmental factors such as corrosion, oxidation, UV radiation, and chemical exposure [6]. Although opaque building materials' solar reflectance can range widely—from less than 0.1 (for asphalt) to more than 0.8 (for white paints and coatings)—these materials are typically distinguished by significant solar absorptance. Long-wave thermal exchanges and increased heat flow through the building's envelope are caused by the energy absorbed by the surface materials [7], which also elevates the temperature of the surface [8]. The investigated retro-reflective coating materials can both lower the surface temperature of exterior walls and heat gains from solar radiation during the day [9]. The average interior temperature of the building box covered with retro reflective material in the experiment example (r = 0.59) is around 2.4 ℃ lower than that of the reference box. Developed a coating with a reflectance of over 90%, and the temperature differential in the thermal insulation reached 24℃ [10]. To create an inorganic heat insulation coating with good performance, rutile titanium dioxide and hollow glass beads were chosen as fillers for a polymer film forming material. It was clear that this effect of heat insulation might be used within buildings to save energy. Provided the same function as highly reflecting coatings in terms of thermal loads [11]. The summer saw a 15% reduction in cooling load, which was the largest. Winter saw a 5% increase in heating loads, which was the largest increase. When comparing a building with RRM coating to one without it, the annual cooling load dropped by roughly 157 MJ/(m^2-year) (19%). Present a micro-particle-based radiative cooling device that does not require a metal reflector for operation throughout the day [12]. Conventional cooling systems, such as air conditioners, are being considered for replacement due to their substantial energy consumption and environmental pollution. In response, radiative cooling systems are gaining attention as an eco-friendly alternative that operates without energy consumption or environmental harm. However, most previous radiative cooling devices have utilized metals like silver for solar reflection, posing challenges in terms of practicality, mass production, cost, and light pollution. Inspired by seashells, this study proposes a radiative cooling approach using micro-particles based on calcium carbonate ($CaCO_3$), the primary component of seashells. Leveraging the high-energy band gap of $CaCO_3$, this method achieves high-performance radiative cooling [13]. Unlike previous radiative coolers, this device comprises a single layer of a $CaCO_3$ composite without the need for a metal reflector, making it mass-producible, cost-effective, and environmentally friendly. To demonstrate the cooling effectiveness of the $CaCO_3$-based radiative cooler, the researchers measured its optical properties and temperature reduction capabilities, comparing them to those of commercial white paint. The results indicate that the $CaCO_3$-based radiative cooler has a cooling power of 93.1 W/m^2 and can reduce ambient temperatures by an average of 6.52 ℃ during the daytime and 3.38 ℃ at nighttime. Consequently, it can serve as a practical radiative cooling solution throughout the entire day. Investigated Acrylic elastomeric coating "cool" coating can lower the surface temperature of white concrete tiles by 2 ℃ at night and 4 ℃ during the hottest summer days. It can be just 2 degrees Celsius warmer during the day and 5.9 degrees cooler at night than the surrounding air [3]. That effect in addition to the decrease in cooling loads and building electricity usage. The findings demonstrated that utilizing various coatings reflective coating: acrylic, pigment, ceramic particle, and high reflective coating: ethylene tetrafluoride, pigment, butyl acetate, with thickness 30-40 µm exterior and interior surface temperatures can be decreased by up to 20 ℃ and 4.7℃, respectively, depending on location, season, and orientation. The largest decrease in both the mean radiant temperature and the globe temperature was, respectively, 3.7 and 2.3℃ [14]. The annual decrease in electricity use for the conditioned example was 116 kWh. However, Shanghai, which has scorching summers and frigid winters, may see a negative all-year effect because of the penalty in higher heating demand. The scope of this study is to report the measured data of the surface temperatures of 16 types of commercially available reflective coatings that are used on buildings envelopes All the coatings were applied on concrete tiles.

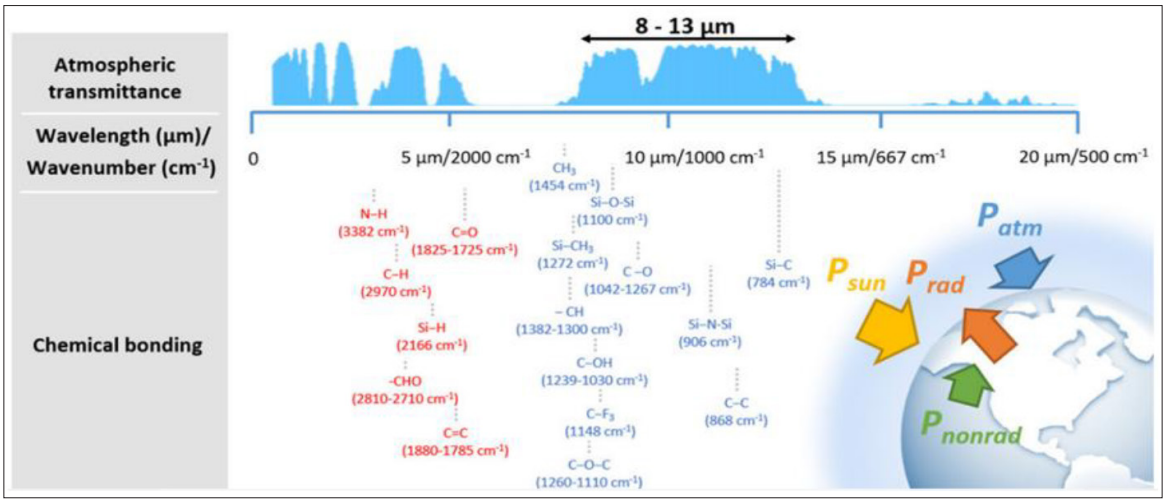

Figure 1: Exploring atmospheric transmittance and functional groups: insights into transparency and chemical bonds.

Properties of Reflective Coating

Material coatings used for building protection can have various properties depending on their intended purpose. Some common properties of material coatings for building protection include:

Weather resistance: Coatings should be capable of withstanding exposure to environmental elements such as sunlight, rain, wind, and temperature fluctuations without deteriorating or losing their protective qualities. Each part of the building envelope has a certain purpose. The cladding offers some degree of insulation and protection for the inner layers of the building envelope as well as defense against wind and water in the form of rain, hail, or snow [7]. The main objective of the air barrier and vapor barrier is to stop air and water vapor from diffusing through the wall, respectively. Heat is not transferred through the wall because of the insulation. Energy efficiency will be most affected by the effectiveness of the insulation, which can also be influenced by the effectiveness of the air and vapor barrier [15]. In the building envelope, polymers in fenestration and gaskets reduce heat loss and seal the window seams. Sealants increase overall air quality [16]. Types of failure in building roof coating

- Exposure to extreme temperature fluctuations, such as rapid heating and cooling cycles, can cause the roof coating to expand and contract. Over time, this can lead to cracks in the coating, allowing moisture to penetrate.
- High temperatures and humidity can cause moisture or air to become trapped beneath the roof coating, resulting in blisters or bubbles on the surface. These blisters can weaken the coating's adhesion and lead to further damage.
- Prolonged exposure to sunlight and UV radiation can cause the roof coating to fade and lose its color. This fading may also be accompanied by chalking, where a powdery residue forms on the coating's surface, indicating degradation of the protective layer.
- Wind, rain, and hail can physically erode the roof coating over time. Water infiltration can lead to delamination, where the coating separates from the underlying substrate, compromising its effectiveness as a waterproof barrier.
- Freeze-thaw cycles in colder climates can cause water trapped within the roof coating to expand when frozen, leading to cracking, blistering, or delamination.
- High levels of moisture and humidity, especially in shaded areas, can create a favorable environment for the growth of algae, moss, or fungi on the roof coating. This growth can deteriorate the coating and compromise its integrity. As shown Figure1, describe the weather effect on building roof coating.

The engineering of roof coating failure is influenced by exposure to various weather conditions, resulting in multiple failure types [17]. Extreme temperature fluctuations can cause roof coatings to expand and contract, leading to cracks that allow moisture infiltration [18]. High temperatures and humidity can trap moisture or air beneath the coating, causing blisters or bubbles that weaken the adhesion. Prolonged sunlight and UV radiation exposure can cause fading and chalking. Wind, rain, and hail can physically erode the coating, potentially leading to delamination and water infiltration. Freeze-thaw cycles in colder climates may result in cracking, blistering, or delamination. Moreover, high moisture and humidity, especially in shaded areas, create conditions conducive to the growth of algae, moss, or fungi, further compromising the coating's integrity. These weather effects collectively contribute to the degradation of building roof coatings, making it essential for engineers and building owners to consider these factors when selecting and maintaining coatings for long-term durability and protection [19].

Figure 2: Roof Coatings Fail

To mitigate these weather-related failures, it is important to select a high-quality roof coating system suitable for the specific climate conditions and ensure proper installation and regular maintenance of the coating. Various coating options are utilized to achieve infrared reflecting capabilities in different applications. Epoxy coatings, known for their durability, protect surfaces like concrete from abrasion, chemicals, and moisture [20]. Polyurethane coatings, prized for their resistance to wear, weathering, and chemicals, serve as protective layers for various surfaces, potentially offering infrared reflecting properties [21].

Durability: Coatings can enhance the durability and lifespan of the underlying material by providing resistance to wear, abrasion, and impact. Some types of coatings that are known for their durability:

- Epoxy Coatings: These extremely resilient coatings can offer superior defense against moisture, chemicals, and abrasion. They are frequently used to industrial surfaces, walls, and floors made of concrete [22].
- Polyurethane Coatings: These coatings provide remarkable resilience against abrasion, environmental factors, and chemical agents. They are frequently applied to concrete, roofing, and metal surfaces as protective coatings [23].
- Silicone coatings: The top choice for coating metal roofs is silicone roof coatings, especially for those exposed to harsh weather conditions. Contractors prefer it for its ease of installation and low maintenance, although its cost is higher due to its physical attributes such as water and weather resistance, UV radiation protection, and heat reflectivity [24].

Heating Resistance: Coatings should be formulated to resist the damaging effects of ultraviolet (UV) radiation from the sun, which can cause discoloration, fading, and degradation of the building materials. Figure 2 shows the operating principle of radiative cooling of $CaCO_3$.

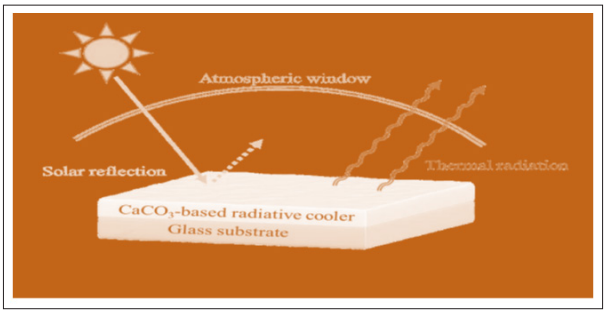

Figure 3: Schematic of radiative cooling principle

Chemical Resistance: Coatings may need to withstand exposure to chemicals, pollutants, or corrosive substances that could otherwise cause damage or corrosion to the building materials. Figure 3 shows concrete corrosion; corrosion has direct effects on reinforced concrete structures. It weakens the structure; reduces the bonding strength of the materials, limits the ductility, and reduces the shear capacity of the buildings.

Figure 4: Stress Corrosion Cracking for concrete

Breathability: Some coatings are designed to allow the building materials to breathe, allowing moisture vapor to escape while still providing protection against water penetration.

Fire resistance: Certain coatings can possess fire-retardant properties, reducing the spread of flames and limiting fire damage.

Adhesion strength: Coatings should adhere well to the building surface to provide effective protection and avoid peeling or delamination.

Aesthetic properties: Coatings can enhance the appearance of buildings, offering various colors, finishes, and textures to suit architectural design preferences.

Waterproofing: Coatings can create a waterproof or water-resistant surface, preventing water penetration and protecting against moisture-related damage.

Thermal properties: Some coatings can provide insulation, thermal conductivity, or resistance to high temperatures, making them suitable for applications involving heat transfer or protection.

Anti-fouling: Certain coatings have anti-fouling properties, preventing the attachment of contaminants, biological growth (e.g., algae, bacteria), or other undesired substances.

Easy maintenance: Coatings can facilitate easier cleaning, maintenance, or removal of stains, making surfaces more manageable and reducing the need for frequent cleaning.

Coating Types

There are various mixture materials and coatings that can be used to reduce heat transfer in buildings. The use of these coatings and materials can significantly impact a building's energy performance, indoor comfort, and overall sustainability. Table 1 lists some commercially available IR reflective coatings, which include various products and their intended applications. These coatings offer solutions for different building surfaces, climates, and energy-efficiency goals, showcasing the versatility of reflective coatings in addressing heat transfer and cooling in buildings. Some commonly employed options include:

- **Reflective Roof Coatings:** These coatings typically have a high solar reflectance and thermal emittance, helping to reduce the absorption of solar heat and minimize heat transfer into the building.
- **Insulating Paints:** Insulating paints contain additives such as ceramic microspheres or hollow glass beads, which create a thermal barrier and reduce heat conduction through the walls or roof.
- **Phase Change Materials (PCMs):** PCMs can absorb and release heat energy as they change from solid to liquid and vice versa. They are frequently used to control temperature and lessen heat transmission in building materials like concrete and gypsum boards.
- **Low-E (Low-Emissivity) Coatings:** These coatings reduce heat transfer by radiation and are applied to windows or glass surfaces. They let visible light through while reflecting a large amount of infrared heat.
- **Thermal Insulation Materials:** To establish a barrier that limits heat movement and lowers thermal conductivity, common insulation materials can be utilized, such as expanded polystyrene (EPS), mineral wool, or fiberglass.

Table 1: Commercially available IR reflective coatings

Brand	Product Name	Main Material Used	Use
GAF	EnergyGuard Acrylic Coating	Acrylic-based	Low-slope roof protection and energy efficiency
Sherwin-Williams	SuperPaint® IR Reflective Technology	Paint with additives	Exterior surfaces, reducing building temperature
Behr Paints	BEHR PREMIUM® Elastomeric Masonry, Stucco & Brick Paint	Elastomeric paint with additives	Masonry, stucco, and brick surfaces, heat reflection
PPG Industries	SolarReflect™ Coatings	Acrylic-based	Exterior applications, reducing surface temperature

Valspar	Valspar® Durabuild® Radiance™ Coating	Acrylic-based	Exterior applications, maintaining lower surface temperature
Nippon Paint	Nippon Paint Cool Coats	Acrylic-based	Exterior surfaces, especially in hot climates
Dulux (AkzoNobel)	Dulux Cool Roof	Acrylic-based	Roof applications, reducing roof temperature
Tnemec	Thermal-Gard® Coatings	Epoxy-based with additives	Industrial applications, thermal protection
Dow	Dow Cool Roof Solutions	Various coatings (elastomeric and silicone)	Roof applications, reducing heat absorption
Tropical Roofing Products	921	Acrylic-based	Roof applications, improving energy efficiency

It's important to keep in mind that requirements, building design, and climate all have an impact on the choice of coatings and materials. Consulting with an architect, engineer, or energy efficiency specialist can provide tailored advice for this specific project. The process of selecting building protection materials and coatings is intricate and impacted by various factors, including project requirements, architectural style, and weather conditions. It is essential to consult experts like architects, engineers, and energy efficiency specialists to ensure recommendations are tailored to the unique requirements of each project. Several common coating materials have a range of protective functions in building applications. High-quality exterior paints offer weather resistance, shielding structures from rain, UV radiation, and temperature fluctuations while simultaneously enhancing the building's aesthetics. Waterproofing coatings, like elastomeric and cementitious membranes, establish a barrier against water infiltration, guarding against issues like leaks and mold growth. Thermal insulation coatings focus on boosting energy efficiency by reducing heat transfer through walls and roofs, resulting in decreased heating and cooling expenses. Anti-corrosion coatings shield metal surfaces, such as steel structures and pipes, from moisture and chemical-induced corrosion, extending their lifespan. Paint: High-quality exterior paints provide protection against weather elements, such as rain, UV radiation, and temperature fluctuations. They also enhance the aesthetics of the building.

- Waterproofing coatings: These coatings create a barrier against water penetration, protecting the building from moisture-related issues like leaks and mold growth. Examples include elastomeric coatings and cementitious waterproofing membranes.
- Thermal insulation coatings: These coatings are designed to improve the building's energy efficiency by reducing heat transfer through walls and roofs. They can help lower heating and cooling costs.
- Anti-corrosion coatings: These coatings are used to protect metal surfaces, such as steel structures or pipes, from corrosion caused by exposure to moisture and chemicals. They help extend the lifespan of the building components.
- Fire-resistant coatings: These coatings provide fire protection by retarding the spread of flames and reducing heat transfer. They are commonly used on structural elements to enhance fire safety.
- Anti-graffiti coatings: These coatings create a protective barrier that prevents graffiti from adhering to the building's surfaces. They make it easier to remove graffiti without damaging the underlying material.

Factors effect on reflective coating

A thin layer of material applied to a surface to improve its ability to reflect heat is called a reflective coating [17]. Its design minimizes heat absorption and transmission, increasing reflectivity and decreasing glare. Mirrors, optical equipment, solar panels, and reflective apparel are just a few examples of the many products that frequently use reflective coatings. The choice of individual pigments, milling and dispersion, particle size, mixing infrared reflective pigments, opacity, and contamination are some variables that may impact the coating's infrared reflectivity [25].

Several factors can affect the coating's infrared reflectivity. Here are some key ones:

- Material Composition: The choice of materials used in the coating can significantly impact its infrared reflectivity. Certain materials, such as metals like aluminum or silver, have high reflectivity in the infrared spectrum and are commonly used for this purpose [26].
- Coating Thickness: The thickness of the coating layer can influence its reflectivity. Generally, thicker coatings tend to have higher reflectivity due to increased opportunities for reflection within the material [27].
- Surface Roughness: The smoothness or roughness of the coating surface affects its reflectivity. A smoother surface tends to provide greater reflectivity by minimizing scattering and promoting more specular reflection [28].
- Wavelength Range: Infrared radiation encompasses a broad range of wavelengths. The coating's reflectivity may vary across different wavelength ranges within the infrared spectrum. It is important to consider the specific range of interest when evaluating reflectivity [29].
- Coating Uniformity: The uniformity of the coating across the entire surface impacts its reflectivity. Any variations or defects in the coating can lead to reduced reflectivity or localized spots with different reflective properties [30].
- Environmental Factors: External environmental conditions, such as temperature, humidity, and exposure to contaminants, can affect the coating's reflectivity over time. Degradation or changes in the coating's structure can occur, leading to altered reflectivity properties [31].
- Contamination: Contamination happens when two infrared reflecting pigments that absorb at various areas are combined. When an infrared reflective pigment is combined with an infrared absorbing pigment, the problem is made worse. Such contaminations have a significant impact on the coatings' overall solar reflectance [31].

- Particle Size: The pigment's particle size is a crucial factor. The particle size should be greater than half the wavelength of the light to be reflected in order to get the greatest reflectivity. In order to reflect infrared light with a wavelength of 700–1100 nanometers, the particle size must be at least 0.35–0.55 microns. Therefore, excessive grinding and dispersion could be detrimental [32].

Coating Tests

Conducting a comprehensive series of coating tests, as outlined in this section, is of paramount importance in ensuring the success of preparing or synthesizing each type of coating, including industrial coatings and paints. These tests serve as critical quality control measures that assess the coating's suitability for its intended purpose and environmental conditions [33]. The adhesion test evaluates the coating's bonding strength to the substrate, which is fundamental for long-lasting performance [34]. Abrasion and impact resistance tests determine the coating's ability to withstand wear, tear, and physical impacts which are essential factors in coatings used in high-traffic areas or industrial settings [35,36]. The chemical resistance test assesses how well the coating can endure exposure to potentially corrosive substances [37]. Weathering tests, including UV radiation exposure, replicate real-world environmental conditions, allowing for predictions of long-term durability [38-40]. The salt spray test evaluates the coating's corrosion resistance, critical in outdoor applications [41]. Thermal cycling and thermal expansion tests check the coating's performance under extreme temperature variations, vital for coatings exposed to weather fluctuations [42]. Lastly, the heat and infrared resistance tests ensure the coating maintains its protective qualities under high-temperature and prolonged sun exposure conditions [43]. Collectively, these tests enable the development of coatings that meet the stringent requirements of various applications, ensuring their effectiveness and longevity in the field [39]. Several common methods can be employed, as shown Figure 4, these tests can be summarized as follows:

- Adhesion Test: This evaluates the bond strength between the coating and the substrate. Different methods, such as pull-off tests or cross-cut tests, can be used to assess the adhesion quality.
- Abrasion Resistance Test: This test measures the coating's ability to withstand wear and tear caused by friction or rubbing. It typically involves subjecting the coating to abrasive materials or rotating brushes and then evaluating any damage or wear.
- Impact Resistance Test: This assesses the coating's ability to withstand impacts or blows. The coating is subjected to controlled impacts using specific equipment, and its resistance to cracking, chipping, or delamination is evaluated.
- Chemical Resistance Test: This examines how well the coating can resist chemical exposure. It involves exposing the coating to various chemicals or solutions and evaluating any changes in appearance, adhesion, or integrity.
- Weathering Test: This evaluates the coating's durability under outdoor conditions, including exposure to UV radiation, temperature variations, moisture, and other environmental factors. Accelerated weathering chambers or outdoor exposure racks can be used to simulate long-term exposure.
- Salt Spray Test: This assesses the coating's corrosion resistance by subjecting it to a saltwater mist or fog. The test measures the coating's ability to resist corrosion, blistering, or rusting.
- Thermal Cycling Test: This evaluates the coating's performance under extreme temperature changes. The coating is subjected to alternating cycles of high and low temperatures, and its ability to withstand thermal stress and maintain adhesion is assessed.
- Thermal expansion test: Evaluate the coating's response to temperature changes. Assess whether it expands or contracts excessively, which could lead to cracking or detachment from the building surface.
- Heat resistance test: Subject the coated material to high temperatures to assess its ability to withstand heat without degradation or discoloration.
- Infrared resistance test: Expose the coating to ultraviolet (FTIR) radiation to evaluate its resistance to fading, degradation, or loss of protective properties under prolonged sun exposure

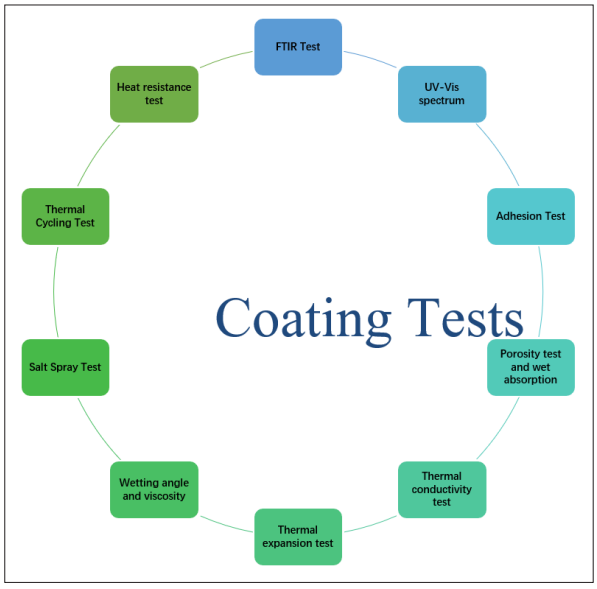

Figure 5: Tests for building roof coating

It's crucial to remember that different test procedures may be needed based on the coating type and intended use. More detailed recommendations for testing materials coating for protection buildings can be obtained by consulting pertinent industry standards and guidelines. The effectiveness of IR-rejecting and solar reflective coatings depends on a number of variables, including the type of coating applied, the application, and the surrounding environment [44,45]. Customized testing procedures are required to accurately assess the performance of the wide range of coatings that are currently available. Essential references are industry standards and guidelines, which offer comprehensive instructions for testing the coatings' capacity to efficiently reject infrared radiation and reflect solar heat [46]. Furthermore, the development of solar reflective coatings is closely related to the need for standardizing performance measurements for irradiative cooling technologies [47]. By reflecting sunlight, these coatings seek to reduce surface temperatures, and the degree of cooling they accomplish depends on a number of variables, including the local climate and thermal environment [48]. Researchers and engineers can

make meaningful comparisons and advancements in passive radiative cooling technology, which has the potential to be a key component in lowering energy consumption and improving thermal comfort in buildings, by establishing standardized performance measurement methods [49].Therefore, adherence to standardized testing procedures and the development of measurement standards are crucial elements in the pursuit of more efficient and effective surface engineering solutions that help beat the heat in buildings [39].

Types of Coating Materials for Building Protective

The selection of the appropriate coating material depends on the specific requirements of the building and the prevailing environmental conditions. The section highlights the versatility of these coatings, offering a wide array of options for building designers and engineers to choose from based on their needs, whether it's to combat excessive heat, enhance energy efficiency, or meet other protective and functional criteria in diverse settings. Reflective coatings utilized on building roof envelopes were all applied to concrete tiles [50], as shown in Table 1. The table summarizes various coating materials used for building protective and reflective coatings applied to concrete tiles. These coatings aim to reflect solar heat, reduce temperature, and enhance energy efficiency [51]. The materials encompass a range of compositions and colors, such as epoxy polyamide coatings in white with 80% reflectance, aluminum pigmented coatings in silver with 70-90% reflectance, and light-blue coatings made of acrylic, pigment, and ceramic particles with 42 % reflectance [52]. Additionally, there are coatings using materials like ethylene tetrafluoride, pigments and butyl acetate, achieving 61% reflectance, and polyurethane with emine agent, epoxy resin, and SiO_2 filler providing a cooling effect of up to 7°C [53,54]. Reflective coatings employing potassium silicate (K_2SiO_3) with aluminum phosphate ($AlPO_4$) and TiO_2 reach 90% reflectance [55]. There are also coatings combining epoxy glue with nano- TiO_2, micro-TiO_2, and nano-ZnO, but their specific temperature effects aren't provided. Chiral Liquid Crystal (Ch-LC) polymers yield highly reflective coatings, reducing temperature by 15°C, while calcium carbonate ($CaCO_3$) combined with different binders achieves 98% reflectance, resulting in a temperature reduction of 6-11°C based on the binder type. Finally, polytetrafluoroethylene (Teflon) coatings reflect 96% of solar radiation, rising to over 99% at shorter wavelengths, leading to a significant temperature decrease of 20-25°C. The choice of coating depends on specific building requirements and environmental conditions.

The significance of NIR reflectance in pigments for various applications. White pigments like Al_2O_3, ZnO, and TiO_2 are known to exhibit high NIR reflectance, which is essential for reducing heat absorption and enhancing energy efficiency in building materials [56]. However, many colored pigments with this property contain heavy metals as chromophore ions, posing risks to human health [25]. To address this issue, recent studies have focused on developing environment-friendly pigments with high NIR reflectance. For instance, Huang et al. synthesized pigments doped with Pr^{4+} and Tb^{4+} that achieved high NIR solar reflectance, offering a color range from light yellow to dark orange [57]. Similarly, Dolić et al. Developed yellow pigments based on $BiVO_4$ with NIR reflectance exceeding 80%. These environment-friendly pigments are valuable for applications that require both color and the ability to reflect NIR radiation, contributing to safer and more energy-efficient materials, particularly in the construction and coatings industry [58]. Another study explores the synthesis and application of polymer-encapsulated pigment to enhance the cooling performance of cool coatings. Additionally, it introduces dirt-repellent fluorinated core-shell particles (FCSP) to improve Total Solar Reflectance (TSR) durability. Waterborne cool coatings utilizing PMMA-encapsulated TiO2 demonstrated approximately 8% higher TSR and 10% greater NIR reflectivity [59].

Environmentally friendly pigments based on various AFeO3 compounds (A = La, Pr, Nd, Sm, Gd, Tb, Y, or Yb) can be synthesized using a coprecipitation method at 1200 °C. These pigments demonstrated high NIR reflectance and offered color stability. In a recent study, these pigments were mixed with siloxane transparent paint and glazes, the mixtures exhibited excellent NIR solar reflectance, with values of up to 50% achieved using $GdFeO_3$, $TbFeO_3$, and $YFeO_3$ pigments [59]. Notably, a roof coating containing $TbFeO_3$ pigment showed a temperature reduction of 3.2 °C compared to a commercial. Additionally, the glazes pigmented with $GdFeO_3$, $TbFeO_3$, and $YFeO_3$ compounds exhibited intense reddish colors. The study also found that the pigments had good thermal and chemical stability. These pigments hold promise for various applications, including cool pigments and pigments for ceramic glazes at high temperatures, contributing to improved energy efficiency and aesthetics in building materials [60]. The studies conducted on fabric coatings with NIR reflective coatings, as in the following study, can be beneficial. The development and characteristics of coated fabrics created using Fe-doped $BaSnO_3$ (BaSn1–xFexO3−δ) powder pigments with varying levels of iron doping [61]. These pigments are found to be pure substitutional solid solutions with no impurities. The pigments exhibit NIR solar reflectance ranging from 64.92% to 79.81%, with changes in NIR reflectance explained by variations in free carrier concentration and electron trap theory. These pigments undergo a color shift from yellow-green to brown, attributed to charge-transfer transitions. The fabrics coated with BaSn1–$xFexO_3$−δ pigments display excellent NIR solar reflectance and thermal insulation properties, with the BaSn0.80Fe0.20O3−δ-coated fabric achieving a NIR solar reflectance of 64.30%. In comparison to uncoated brown fabric and fabric coated with conventional brown pigment (Pigment Yellow 42), the inner surface temperature of the BaSn0.80Fe0.20O3−δ-coated fabric is reduced by 7.6 and 4.2 °C, while heat absorption is decreased by 51.0% and 37.9%, respectively. The coated fabric also demonstrates remarkable durability against washing and chemical stability.

Table 1: Summary

Materials type	Color	Reflectance	Thickness	ΔT	Ref.
Epoxy polyamide coating	White	80% at (700-1100 nm)	Not specified	6 ℃	[3]
Aluminum pigmented coating	Silver	70-90 % at (700-1100 nm)	Not specified	6.3 ℃	[3]
Acrylic, pigment, ceramic particle	Light-blue	42% at (300 –2100 nm)	30-40 µm	6 ℃	[14]
Ethylene tetrafluoride, pigment, butyl acetate	Light blue	61% at (300–2100 nm)	30-40 µm	8.3 ℃	[14]
Acryl-polymeremulsion paint	white	Not specified	Not specified	4.1 ℃	[3]
Polyurethane + emine agent + Epoxy resin + filler SiO_2	Not specified	When the road temperature was 65.7 C, the coating provided a cooling effect of up to 7 ℃	Not specified	7-8 ℃	[62]
$K2SiO_3$ with $AlPO_4$ + TiO_2	Not specified	90%	Not specified	Not specified	[63]
Epoxy glue + Nano-TiO_2, Micro-TiO_2, Nano-ZnO	Not specified	Reflective coating can significantly increase the albedo and decrease the temperature of asphalt mixture. Micro-TiO_2 has better reflectance than Nano-TiO_2 and Nano-ZnO	Not specified	Not specified	[63]
Ch-LC	Not specified	The coating for at least 10 times at 75%	Not specified	15℃	[64]
$CaCO_3$ +binder	White	98% at (200-2500)	500 µm	6-11℃	[12]
Polytetrafluoroethylene	Not specified	96% at (200-2500 nm), and greater than 99% at (350-1800 nm)	Not specified	20-25 ℃	[65]
$GdFeO_3$, $TbFeO_3$, and $YFeO_3$ pigments	Red	50%	70 µm	3.2	[59]
Fe-doped $BaSnO_3$	Brown	64.92%-79.81%	Not specified	7.6 and 4.2 °C	[61]

Calcium carbonate is the most commonly used inorganic filler in polymer materials to improve the mechanical properties and reduce the costs. It's important to note that the specific role and application of calcium carbonate in coatings can vary depending on the formulation, desired properties, and performance requirements. Various functions of $CaCO_3$ in coatings, including its use as an extender pigment to reduce costs, an opacifier to enhance opacity, a matting agent to reduce gloss, a filler to improve rheological properties, and a pH regulator for formulation stability. It also mentions $CaCO_3$'s cost-effectiveness and high reflectance in IR range. In the context of surface engineering and solar reflective coatings, $CaCO_3$ can be employed as an extender and opacifier to enhance the reflective properties of coatings while reducing costs. Its high reflectance into IR heating can contribute to the overall cooling effect, making it relevant in efforts to beat the heat from buildings. Comparing the two passages, the first passage discusses advanced materials like polymer-encapsulated pigments and FCSP that offer specific improvements in solar reflectivity and TSR-durability, whereas the second passage focuses on the versatile applications of CaCO3 as an inorganic filler in coatings, making it an attractive option for cost-effective and reflective coatings with a role in surface engineering and IR rejection. Calcium carbonate, can play several roles in coating applications [66]:

- Extender: Calcium carbonate is often used as an extender pigment in coatings. It can replace a portion of more expensive pigments, such as titanium dioxide, to reduce costs while maintaining opacity and whiteness.
- Opacifier: Calcium carbonate can improve the opacity and hiding power of coatings, especially in interior applications. It helps to cover the underlying surface and provides a more uniform appearance.
- Matting agent: Calcium carbonate can be used as a matting agent to reduce the gloss and create a matte or satin finish in coatings. It absorbs and diffuses light, resulting in a less reflective surface.
- Filler: Calcium carbonate is an effective filler in coatings, helping to improve the rheological properties and reduce the cost. It enhances the viscosity, stability, and coverage of the coating.
- PH regulator: Calcium carbonate can act as a pH regulator in coatings. It can help to adjust and stabilize the pH of the coating formulation, ensuring optimal performance and preventing issues like pigment flocculation or degradation.
- Low cost and high reflectance into IR heating as shown Figure 5.

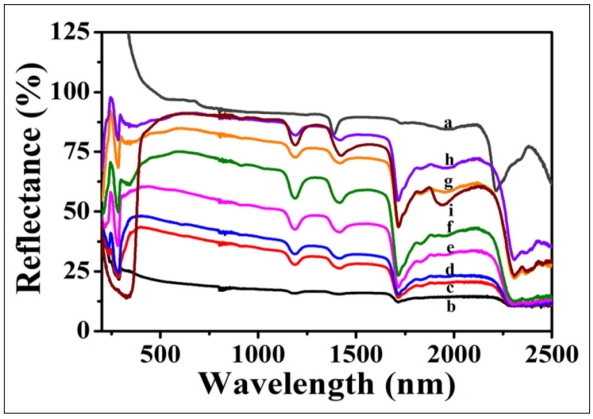

Figure 6: reflectance of composite coating with and without different percent of $CaCO_3$ %w [21]

The mechanical properties of different $CaCO_3$ weight percentages on composite coatings composed of $CaCPO_3$/PVC are displayed in Figures 6 and 7. Important information about the mechanical characteristics of composite coatings composed of $CaCO_3$/PVC (polyvinyl chloride) with varying weight percentages of calcium carbonate can be found in Figures 6 and 7. These numbers are crucial for comprehending how the coating material's performance is impacted by the addition of $CaCO_3$. Tensile strength, elongation at break, Young's modulus, and other metrics that evaluate the coating's resistance to mechanical stress are probably among the mechanical properties shown in Figure 6. These mechanical characteristics are anticipated to change with variations in the weight percentage of $CaCO_3$. For example, a higher weight percentage of $CaCO_3$ may result in improved tensile strength, strengthening the coating's resistance to stretching forces. Nevertheless, it could also lessen elongation at break, which would make the coating less pliable and more brittle. The stiffness-measurement parameter, Young's modulus, can also change as the $CaCO_3$ content changes. This data aids in assessing the composite coating's suitability for particular applications where mechanical durability is a key consideration.

The adhesion characteristics of the $CaCO_3$/PVC composite coating are probably explored in Figure 7. For coatings, adhesive strength is an essential mechanical property, particularly in real-world applications. It gauges the degree to which the coating sticks to the surface it is applied to. Adhesion strength can be influenced by varying weight percentages of $CaCO_3$, whereby certain percentages may lead to a more robust adhesion between the coating and the underlying surface, while other percentages may show a decrease in adhesion. In order to avoid problems like peeling or delamination, it is imperative that this data be used to guarantee that the composite coating stays firmly bonded to the substrate over time. Understanding these mechanical characteristics is crucial for selecting the right $CaCO_3$/PVC composite coating for specific applications. Different applications, such as building protection, automotive coatings, or industrial coatings, require coatings with varying mechanical properties to ensure optimal performance and longevity. Therefore, Figures 6 and 7 provide valuable information for engineers, researchers, and industry professionals looking to make informed decisions about coating materials for their intended use.

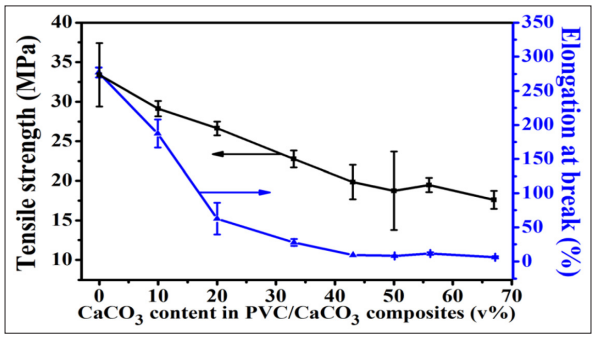

Figure 7: Mechanical Properties of Composite Coating with different weight percent of $CaCO_3$ [21]

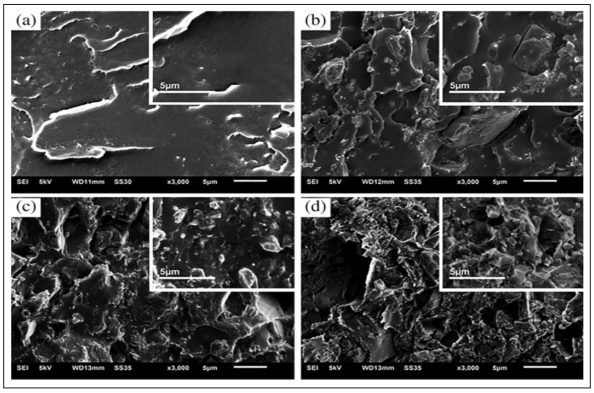

Figure 8: SEM micrographs of cryo-fractured surfaces for PVC film and PVC/$CaCO_3$ composite films [21]

Table 2 represented multi types of $CaCO_3$ composite coating with different in optical properties dependent on Polymer which used [67-69]. The table presents a comparative analysis of optical properties within a wavelength range of 3–2.5 μm for various $CaCO_3$-based coating types used in different applications. These coatings are evaluated based on parameters such as solar absorption, emissivity, particle size diameter, reflectance percentage, and thickness. Notably, the first coating, a blend of $CaCO_3$ and Dipentaerythritol Penta-/Hexa-Acrylate (DPHA), exhibits solar absorption of 4.1%, high emissivity at 89.6%, and a particle size diameter ranging from 20–30 μm. Importantly, its solar absorption behavior is thickness-dependent. The second coating combines $CaCO_3$ nanoparticles with epoxy resin and hardener (M68), demonstrating low solar absorption (2.1%), high emissivity (90%), and a particle size diameter in the range of 40-69 nanometers, but specific thickness data are absent. The third coating, composed of $CaCO_3$ and Poly (Ethylene + Vinyl Acetate), offers 85% reflectance, with a specified thickness of 70 μm, while data regarding solar absorption and emissivity are missing. The fourth coating, incorporating $CaCO_3$ and Poly Vinylchloride, presents 80% reflectance but lacks detailed information regarding solar absorption, emissivity, particle size diameter, and thickness. These coatings exhibit diverse optical characteristics, which are vital considerations for various applications, particularly in managing heat absorption, emissivity, and energy efficiency. These coatings exhibit diverse optical characteristics, underscoring their significance in various applications, particularly in managing heat absorption, emissivity, and enhancing overall energy efficiency. The selection of a specific coating depends on the intended application's requirements and desired optical properties.

The temperature decrease associated with these coatings is intricately linked to their reflectance properties, which can vary significantly based on the choice of polymer binder, as depicted in Figure 8. This figure serves as a valuable illustration of the impact of different polymer types on the overall effectiveness of the coatings. It highlights a direct comparison between two distinct coating types that share the same reflective filler, CaCO3, yet employ contrasting polymer binders. The choice of polymer binder plays a pivotal role in determining the coating's ability to reflect solar heat and, subsequently, its ability to reduce temperature. These in reflectance due to differing polymer types underscore the importance of selecting the most suitable binder variations for specific environmental conditions and performance requirements. This information aids in making

informed decisions when it comes to coating selection for applications aimed at cooling surfaces, improving energy efficiency, and mitigating heat-related issues in various settings [68,69].

Table 2: Optical properties for $CaCO_3$ composite coating

	Optical properties within a wavelength range of 3–2.5 µm for $CaCO_3$				
Coating type	**Solar absorption**	**Emissivity**	**Particle size Diameter**	**Reflectance %**	**Thickness**
$CaCO_3$ + dipentaerythritol penta-/hexa-acrylate (DPHA)	Absorbs 4.1%	89.6%	powder (20–30 µm in diameter		However, the absorption did not increase until the thickness reached 350 µm. Further, at 500 µm, the absorption started increasing, and approximately 8% of the solar incident power was absorbed.
$CaCO_3$ -nano+ Epoxy resin+ Hardener M68 was a salt of organic polycarboxlic acid with a cyclic amidine	Absorbs 2.1%	90%	40-69 nano		50-70 µm acceptable
$CaCO_3$+ Poly (ethylene + vinyl acetate)	Not specified	Not specified	5-10 µ	85%	70µm
$CaCO_3$+ Poly vinylchloride	Not specified	Not specified	Not specified	80%	Not specified

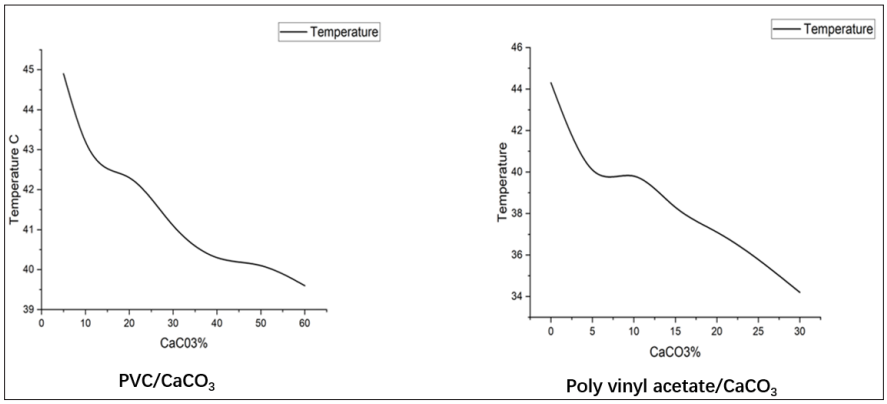

Figure 9: Comparing between two types of CaCO3 composite coating [67].

Conclusion

Acrylic-based coatings, elastomeric paints, and other polymer-based solutions are just a few examples of the materials and formulations that fall under the category of heat-reflective coatings. These coatings provide an adaptable solution for a range of surfaces, including masonry, exterior walls, and low-slope roofs. Their capacity to sustain lower surface temperatures, which keeps buildings cooler and more energy-efficient, is their main benefit. Finally, the thermal performance and other characteristics of sixteen commercially available reflective coatings applied to building envelopes—more especially, concrete tiles—have been examined in this study. The findings highlight how crucial it is to choose the appropriate coating for a given building's needs and climate. These coatings are important for controlling heat absorption, energy efficiency, and weather resistance. The selection of high-quality coatings that are customised for particular applications is essential to guaranteeing durability and long-term effectiveness. Their performance is influenced by a number of variables, including the coating's thickness, response to various infrared wavelengths, and material composition. Making wise decisions requires an understanding of these variables. It is crucial to apply appropriate coating systems and take into account the unique climate conditions in order to reduce failures caused by weather exposure. A variety of coatings, including silicone, epoxy, and polyurethane, have different benefits and can improve energy efficiency and decrease heat absorption. In addition, these coatings offer advantages like strength, adhesion, waterproofing, fire resistance, and thermal characteristics. The study also looks into the application of $CaCO_3$ in coatings. In addition to its many uses as an extender, opacifier, matting agent, filler, and pH regulator, calcium carbonate ($CaCO_3$) is inexpensive and has a high infrared reflectance. $CaCO_3$ composite coatings are a flexible choice for coatings because their optical characteristics change depending on the polymer utilised. Recent advancements in this field have led to the introduction of nanotechnology and microspheres, which enable even more precise tuning of the optical and thermal properties of coatings. More applications and improved performance are the results of these developments. The information provided about patents highlights the continuous

innovation in the building protection coatings field, including advancements in coatings that are infrared emissive and solar-reflective. These developments could have a big impact on environmental sustainability, energy efficiency, and building design.

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