

Research Article

Enhancing Energy Efficiency and Sustainability through Titanium Dioxide Enhanced Cool Roof Paints with Maximum Solar Reflectance

P. Ragupathi^{1,*}
S. Sathesh Kumar²
B. Vijaya Prakash³
J. Justin Maria Hillary⁴
K. R. Sakthivel⁵
M. Krishnan Selvaraj⁶

¹ Department of Mechanical Engineering, Faculty of Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, 641021, India

² Department of Aeronautical Engineering, Nehru Institute of Technology, Coimbatore, Tamil Nadu, 641105, India

³ Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Tamil Nadu, 641105, India

⁴ Department of Mechatronics Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, 641008, India

⁵ Department of Mechanical Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, 641032, India

⁶ Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thudupathi, Perundurai, Tamil Nadu, 63805, India

Received 26 August 2025

Revised 26 November 2025

Accepted 30 November 2025

Abstract:

Cool roofs lower building temperatures by reflecting the sun, reducing cooling energy consumption. Their performance is solar reflectivity (SR) and infrared emissivity (IE) dependent. White ceramic tiles, white cement, and aluminium foil are normally used materials in India, but they lose performance over time. This research offers the addition of titanium dioxide (TiO₂) to paint for roof application to increase and maintain reflectivity. TiO₂, a white pigment, reflects infrared radiation, enhancing SR and prolonging roof longevity. Experimental data indicate indoor temperature decreases of 4.0–5.3°C, substantiating apparent cooling advantages. In contrast to conventional materials, TiO₂-based coatings remedy durability problems, presenting a cost-effective and environmentally friendly method for enhancing energy efficiency in warm regions. This novel method underscores TiO₂'s promise in revolutionizing cool roof technology for long-term use in India.

Keywords: Cool Roof, Pigment, Titanium Dioxide, Indoor Temperature

1. Introduction

Global energy consumption is rising quickly, and using more fossil fuels contributes to global warming, ozone layer thinning, and other issues. Residential buildings are the main consumer of electricity in most of the countries. Based on data from the International Energy Agency (IEA), the residential building sector is responsible for 30% of global

* Corresponding author: P. Ragupathi
E-mail address: ponragupathi@gmail.com



CO₂ emissions and more than 30% of all energy use. Recently, energy efficient buildings have become a major concern.

Phase changing material (PCM) is one among the effective ways to address the concern. It can absorb energy and transition from a solid to a liquid state as the temperature rises, reducing temperature differences. It can also release the absorbed energy and return to a liquid state when the temperature falls, ensuring thermal comfort within the building. Another excellent example for cutting energy use and raising the comfort levels of commercial and residential buildings is green roof tops. White or light-colored coatings have been widely applied to the rear walls or roofs of buildings, because it is well known that white has the best solar reflective performance. This helps to reflect incident sunlight and lowers the amount of energy needed for interior cooling.

Direct and indirect solar radiation (diffuse radiation through the atmosphere) is the main source of heat in the biosphere. The infrared portion of solar energy is prominent within a specific frequency range. The visible spectrum, or what we often refer to as light, is followed immediately by infrared radiation (IR). Infrared is often put into three categories and this portion of the spectrum has the wavelengths from 780 nanometers (nm) to 1.0 millimeters (mm).

- Near infrared: 780 nm to 2.5 micrometers (μm).
- Medium infrared: 2.5μm to 50μm.
- Far infrared: 50μm to 1mm.

The electromagnetic radiation that people are most sensitive to through their skin is infrared. When we are directly exposed to the sun's beams, for instance, we sense near infrared and when an object with a high temperature or a fire is nearby. At terrestrial temperature, which is roughly between -10°C and 100°C, any object emits medium and far infrared radiation. Any object that has a temperature higher than absolute zero (-273°C) can emit far infrared light. Building thermal behavior is significantly influenced by infrared radiation. Part of the sun's energy is reflected by building envelopes, especially roofs and facades, while the remaining portion is let via glazed apertures. Lastly, opaque facings absorb the remaining portion of the radiation. The pain experienced in overheated interiors is partially caused by the heated opaque surfaces, which in turn reemit the radiation in all directions.

A coating is usually applied to the surface of an object which is referred as the substrate. These coatings will be applied to improve the surface properties of the substrate, such as corrosion resistance, wear resistance, heat resistant, etc. When the surface of the substrate is left in an open environment, then there will be a chance for the formation of iron rusts, dents, shrinks and cracks in the surface due to extreme climatic conditions. The people used to apply various coatings on the surface for preventing or minimizing the damage. These coatings add colour, luster and smooth the roughness and irregularities. Paint is composed of various materials like enamels, primers, varnishes, sealers, fillers etc. Painting refers to the spraying of calcium carbonate (CaCO₃), a white pigment which protects the surface to some extent but it rubs off quickly. Therefore, the paint contains another ingredient to bind and hold the pigment particles together. Paint is a mixture of pigment and filmogen in which the filmogen is a binder and the pigment provides colour. These filmogen and pigment combine together to create opacity. The main constituents of paint are resin, pigment, solvent and additives.

Fabrication of cool roofing materials using four types of titanium dioxide, achieving high solar reflectance and heat insulation properties. The hydrophobic rutile nano-TiO₂ enhanced material showed significant temperature reductions and excellent weather resistance [1]. The state of art review on Urban Heat Island (UHI) mitigation, emphasizing cool building envelope materials with high reflectivity and emissivity to reduce cooling energy demands and increase vegetation in urban areas [2]. Some of the passive cooling technologies, particularly radiative cooling using white paints, as sustainable alternatives to air conditioning, aiming to address rising global temperatures and energy consumption in buildings [3]. There are comprehensive reviews on the evolution of research on cool surfaces, emphasizing materials like pigments, phase change materials, and glass for mitigating the urban heat island effect [4]. By incorporating improved paint coatings with pigments in anti-radiant façades and roofs for the Caribbean enhanced the solar reflectance and improved the home comfort [5].

The self-cleaning property of building materials, specifically TiO₂-containing paint applied to self-compacting architectural mortars, demonstrating high photocatalytic efficiency and weathering resistance [6,7]. Near IR reflective materials are evaluated for building cooling, focusing on their impact on surface temperature, solar reflectance, and color durability in External Thermal Insulation Composite Systems (ETICS) [8]. A comprehensive review was

conducted on radiative cooling technology, discussing theoretical fundamentals, material designs, and applications, with a special focus on building-integrated cooling performance [9]. Colored cool materials were fabricated with super hydrophobicity using SiO_2 , TiO_2 , Cr_2O_3 , and Fe_2O_3 , showcasing high solar reflectance, anti-icing properties, and potential outdoor applications [10].

The utilization of TiO_2 in building materials were highlighted for various applications, summarizing advancements in modified TiO_2 materials for practical photo-catalytic building materials [11]. Passive cooling methods, radiative cooling, and cool paint were introduced and discussed their physics, recent developments, and potential impacts on reducing building heat envelope gain and air-conditioning usage [12]. The superhydrophobic surfaces with anti-icing properties were achieved by using SiO_2 and TiO_2 , demonstrating high solar reflectance and cooling performance for potential roofing applications [13]. Nanomaterials as a strategy for energy conservation in building roofs were explored, focusing on their application in administrative buildings in Iraq to improve thermal performance and achieve energy conservation [14]. Ce and Fe-doped gahnites were fabricated with high NIR reflectance to mitigate the heat island effect, showcasing their potential for designing cool roofing materials [15]. The active and passive cool roof systems in industrial buildings are investigated and emphasized the use of solar energy, cavity ventilation, and thermal reflective coating to achieve significant reductions in attic air temperature.

The collective research endeavors aim to combat urban heat and enhance energy efficiency in buildings. Innovations in cool roofing materials, such as hydrophobic rutile nano- TiO_2 , demonstrate remarkable solar reflectance and cooling properties. Strategies like passive cooling technologies, radiative cooling with white paints, and anti-radiant façades offer sustainable alternatives. Reviews on cool surfaces evolution and the utilization of TiO_2 materials underscore their potential in mitigating heat island effects. Superhydrophobic cool materials with SiO_2 and TiO_2 highlight aesthetic appeal and functionality, while nanomaterials present energy conserving solutions for building roofs. The studies collectively contribute diverse perspectives to address challenges in urban environments and building energy consumption. However, there was a lag in data regarding the performance of cool roof paint in Indian climatic conditions. This research aims to address this gap by testing the cool roof samples prepared indigenously and to analyze its output by considering the various factors affecting the solar reflectance. The research aims to investigate the efficacy of heat-resistant paints, specifically cool roof coatings containing TiO_2 , in reducing energy consumption. These coatings are designed to reflect solar radiation, providing protection to roof surfaces. The intended outcomes include decreased interior temperatures, lowered air conditioning costs, and an extended lifespan for the roof. TiO_2 , a naturally occurring oxide of titanium, is a key component due to its inherent reflective properties. This investigation focuses on understanding the technical aspects of TiO_2 infused cool roof coatings and their impact on energy efficiency, thermal performance, and the durability of building materials. This study specifically compares the prepared TiO_2 coatings with normal roof coatings, not with commercial cool roof paints. The objective was to evaluate the effectiveness of locally prepared samples.

2. Materials and Methods

The energy absorption and reflection characteristics of different roofing materials are shown in Fig. 1. The term emissivity refers the amount of energy radiated back after being absorbed. The term reflectance referred as amount of energy reflected back to the sky. The house with black roofing has high emissivity and low reflectance whereas the house with white roof will have high reflectance and high solar emissivity. TiO_2 serves primarily as a pigment, providing opacity, brightness, and whiteness. It is one of the most widely used white pigments in the paint industry due to its excellent light-scattering properties and chemical stability. TiO_2 has excellent light-scattering properties, which means it effectively blocks light from passing through the paint film. This property is crucial for achieving good coverage and hiding under-lying surfaces or colors. TiO_2 contributes to the brightness and whiteness of paints, enhancing their aesthetic appeal. This is particularly important for interior and exterior paints, where a bright, clean appearance is desired. TiO_2 offers some level of ultraviolet protection when used in exterior paints. It helps prevent the degradation of the paint film and protects underlying surfaces from the harmful effects of ultraviolet radiation, thereby prolonging the life of the paint job. TiO_2 is chemically inert and stable under various environmental conditions. This stability ensures that paints retain their color and performance over time, even when exposed to harsh weather conditions or environmental pollutants. TiO_2 can be used in various types of paints, including water-based and solvent-based formulations, as well as in industrial coatings and specialty paints.

2.1 Preparation of samples

Four samples of cool roof paint have been prepared with various compositions of TiO₂. Table 1 shows the composition of the cool roof paint samples. The selected TiO₂ concentrations represent incremental increases commonly used in commercial white coatings to observe performance variations. The purpose was to study the effect of gradual TiO₂ loading on reflectance efficiency. These four levels were chosen to provide a practical comparison without deviating from industry-standard pigment proportions.

Table 1: Composition of cool roof paint samples

Sample	Acrylic binder, %	Titanium dioxide, %	Calcium carbonate, %
A	53	3	35
B	53	5	35
C	53	7	35
D	53	9	35

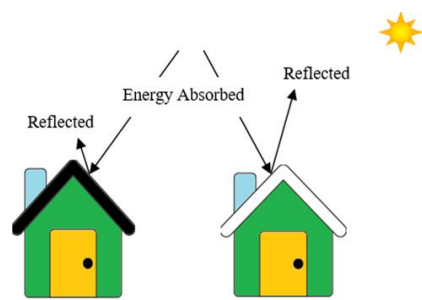


Fig. 1. Energy comparison of different roofing material

A standard roofing sheet, typically used for reflectance evaluation under ASTM E903 guidelines, was used as the substrate. Two coats of the paint samples were applied to ensure uniform coverage and follow common preparatory practices for reflectance measurement. The sample was allowed to dry completely before testing. The test was conducted using a spectrophotometer and integrating sphere setup. The spectrophotometer was calibrated prior to testing to ensure accurate measurements. The painted sample was placed in the integrating sphere setup, covering the entire opening of the sphere. It was illuminated with a stable light source directed onto the painted surface at the specified angle. The spectrophotometer used in this study (Fig. 2) inherently measures reflectance across the standard solar spectrum range (300–2500 nm). The integrating sphere captures diffuse and direct reflectance within this range. Since the study focuses on overall solar reflectance, the full spectral range was utilized without separating individual bands.



Fig. 2. Spectrophotometer

2.2 Preparation of cool roofs

After testing the samples for reflectance, the best sample was selected and coated on the roof and compared its performance with normal coating. The roof was carefully examined for the presence of cracks, dents, wear and debris before applying the coating over the surface. The roof surface was cleaned thoroughly. A pressure washer was used to remove all dirt from the roof surface. Then the surface was allowed to dry completely. After the roof surface was

completely dried, it was once again examined for any visible damages. Now the coating was applied with a help of a roller. Before applying the next coat, previous coating is allowed to dry for five hours. The room temperature was then measured for normal coated and TiO₂ coated roof. The room temperature for the coated surface has been under observation for five summer days at three different timings.

3. Results and Discussions

3.1 Measurement of solar reflectance

Each sample was measured multiple times to ensure consistency. The values presented in Table 2 are the stable readings taken after repeated measurements showed similar results. Fig. 3 shows that the Sample D has a high solar reflectance compared with the rest of the samples. From the Table 2, it is observed that Sample A has the lowest solar reflectance value followed by samples B and C. Sample D has the highest solar reflectance. This is because large particles scatter light more effectively than small particles. Small particle size has the lowest solar reflectance. This is because small particles absorb light more effectively than large particles. Medium particle size has a solar reflectance that is between that of large and small particles. The graph also shows that the solar reflectance of all the four particle sizes decreases as the wavelength of light increases. This reveals that TiO₂ is more effective at reflecting shorter wavelengths of light, such as ultraviolet and blue light, than longer wavelengths of light, such as red and green light.

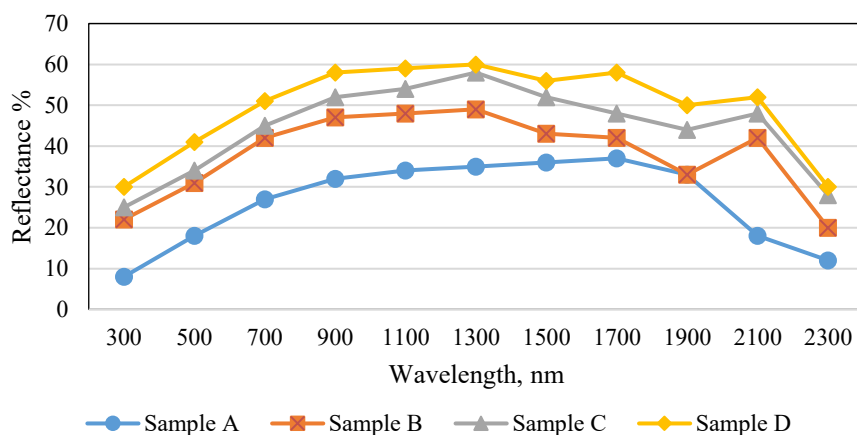


Fig. 3. Solar reflectance measured in Spectrophotometer

Table 2: Solar spectral reflectance of the samples measured in spectrophotometer

Samples	Solar reflectance, %
A	37
B	49
C	58
D	60

3.2 Measurement of indoor room temperature

The results of the actual temperature measurement were listed in Table 3. From the Table 3, it was observed that the roof surface coated with TiO₂ has a temperature drop of 4.0 °C to 5.3 °C inside the building when compared with the normal coating. Fig. 4 to 6 shows the graphical representation of normal coating and TiO₂ coating. The temperature is measured for five consecutive days at different timing in a day i.e. 11 am, 12 pm and 1 pm. These three timings were selected because they represent the peak heat period of the day in summer. The goal was to study how the coating performs during the hottest hours when buildings experience maximum heat load. All five days of measurement fell within the same summer week in a region experiencing consistent climatic conditions. The temperature ranged between 32–36°C during the recording period, with clear sky conditions and similar solar exposure patterns. While exact weather data was not documented, the variation was minimal across the five days.

The TiO₂ coating is much more effective at reducing the indoor room temperature than the normal coating. The maximum indoor room temperature observed in normal coating is 30.4 °C whereas in TiO₂ coating it was 25.6 °C.

The minimum indoor room temperature observed in normal coating is 28.2 °C whereas in TiO₂ coating it was 23.1 °C. It was found that the roof surface coated with TiO₂ has a temperature drop of 4.0 °C to 5.3 °C when compared with the normal coating. This shows that the TiO₂ coating is able to reduce the indoor room temperature more than the normal coating. The temperature drop is consistent across the three measured times with slight natural variations. The reduction falls within 4.0 °C to 5.3 °C across all recordings, showing no extreme deviations at any specific time. The results shown in Table 3 reflect a stable trend of cooling due to the TiO₂ coating throughout peak sunlight hours. Overall, the data in the table suggests that the TiO₂ coating is a much more effective way to reduce temperature than the normal coating. The TiO₂ coating is able to reduce the temperature and the temperature drop is more consistent with the TiO₂ coating.

Table 3: Solar radiation effect at various times by using TiO₂

Day and Time	Room Temperature in °C		Temperature drop
	Normal coating	TiO ₂ coating	
Day 1			
11 am	28.3	23.5	4.8
12 pm	29.6	24.4	5.2
01 pm	29.9	24.8	5.1
Day 2			
11 am	28.4	23.7	4.7
12 pm	29.4	24.6	4.8
01 pm	30.2	25.6	4.6
Day 3			
11 am	28.5	23.4	5.1
12 pm	29.7	24.4	5.3
1 pm	30.4	25.4	5.0
Day 4			
11 am	28.2	23.2	5.0
12 pm	29.2	24.5	4.7
01 pm	30.3	25.5	4.8
Day 5			
11 am	28.3	23.1	5.2
12 pm	29.3	25.3	4.0
01 pm	30.3	25.3	5.0

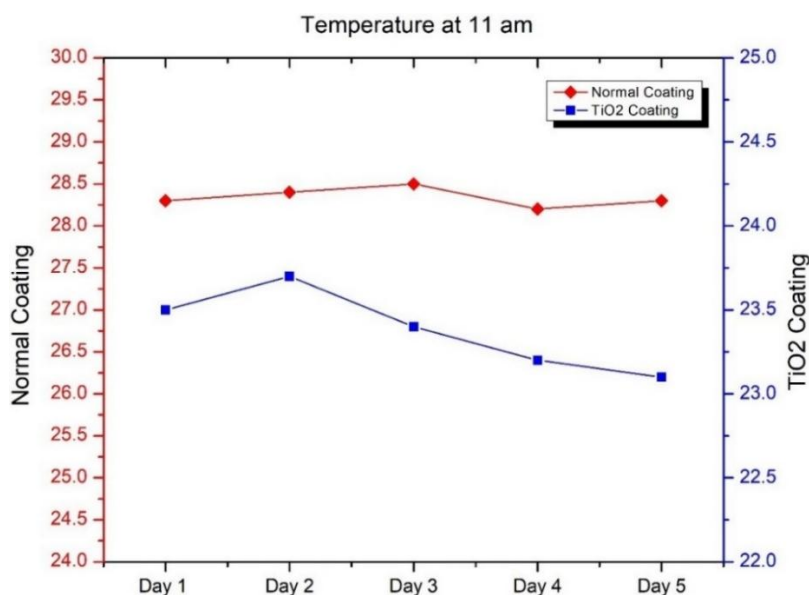


Fig. 4. Temperature comparison of Normal coating vs TiO₂ coating at 11 am

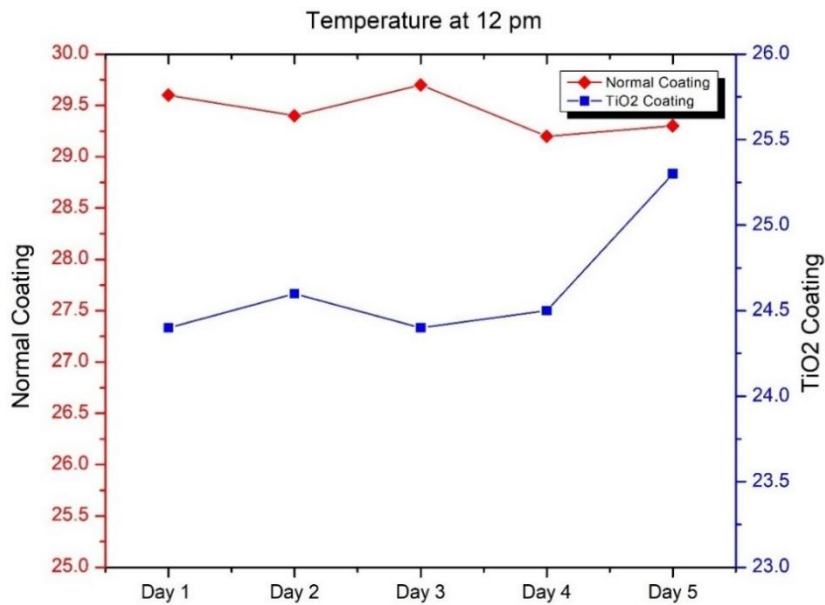


Fig. 5. Temperature comparison of Normal coating vs TiO₂ coating at 12 pm

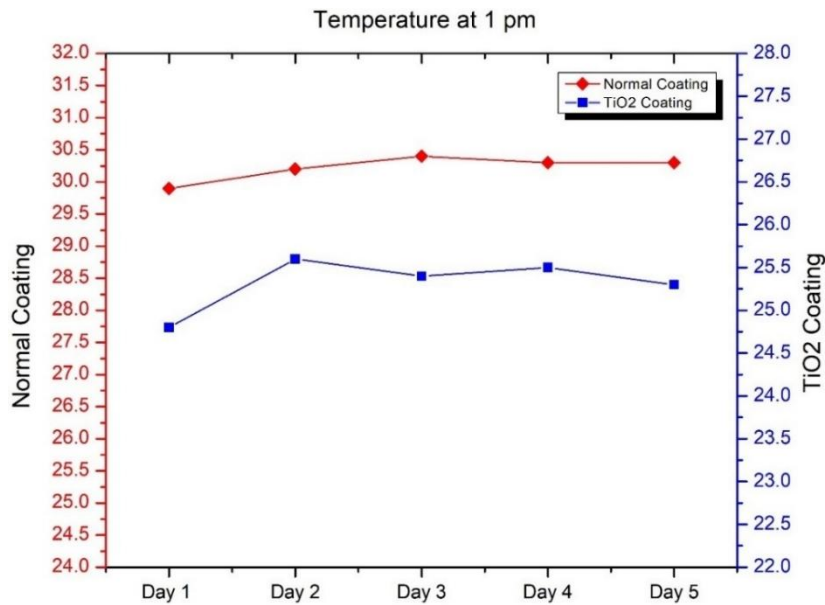


Fig. 6. Temperature comparison of Normal coating vs TiO₂ coating at 1 pm

4. Conclusion

The application of a solar reflective coating on a roof surface plays a pivotal role in influencing indoor temperatures, leading to a substantial enhancement of the cooling effect within a building. The solar reflectance of this coating is directly linked to the content of TiO₂, a crucial component in the paint formulation. Increasing the TiO₂ content in the paint formulation demonstrates a proportional increase in solar reflectance. The results indicate a noteworthy decrease in indoor temperature ranging from 4.0 °C to 5.3 °C. This substantial temperature reduction contributes to a marked decrease in the reliance on air conditioning systems, resulting in significant energy savings. In essence, the utilization of TiO₂ in solar reflective coatings emerges as a highly effective strategy for mitigating indoor heat, enhancing energy efficiency, and fostering sustainable cooling solutions for buildings.

References

- [1] Qi Y, Xiang B, Zhang J. Effect of titanium dioxide (TiO₂) with different crystal forms and surface modifications on cooling property and surface wettability of cool roofing materials. *Solar Energy Materials and Solar Cells*. 2017;172:34-43.
- [2] Ziaemehr B, Jandaghian Z, Ge H, Lacasse M, Moore T. Increasing solar reflectivity of building envelope materials to mitigate urban heat islands: State-of-the-art review. *Buildings*. 2023;13(11):2868.
- [3] Mandal J, Yang Y, Yu N, Raman AP. Paints as a scalable and effective radiative cooling technology for buildings. *Joule*. 2020;4(7):1350-1356.
- [4] Mourou C, Zamorano M, Ruiz DP, Martín-Morales M. Cool surface strategies with an emphasis on the materials dimension: A review. *Applied Sciences*. 2022;12(4):1893.
- [5] Puesan CW, Mestre JL. Technical evaluation of an improved paint coating with NIR pigments designed to reduce thermal discomfort caused by incident solar radiation: Application in the Caribbean area. *Energy Procedia*. 2017;115:463-479.
- [6] Guo MZ, Maury-Ramirez A, Poon CS. Self-cleaning ability of titanium dioxide clear paint coated architectural mortar and its potential in field application. *Journal of Cleaner Production*. 2016;112:3583-3588.
- [7] Orel B, Jerman I, Kunič R. Materials aspects of solar paint coatings for building applications. In: *Advances in the Development of Cool Materials for the Built Environment*. Bentham Science Publishers; 2013. p. 120-173.
- [8] Ramos NM, Maia J, Souza AR, Almeida RM, Silva L. Impact of incorporating NIR reflective pigments in finishing coatings of ETICS. *Infrastructures*. 2021;6(6):79.
- [9] Chen J, Lu L. Development of radiative cooling and its integration with buildings: A comprehensive review. *Solar Energy*. 2020;212:125-151.
- [10] Qi Y, Zhao H, Wu Y, Ren Y. Facile preparation of solar reflective cool colored material with desired superhydrophobicity. *Solar Energy Materials and Solar Cells*. 2022;242:111761.
- [11] Gopalan AI, Lee JC, Saianand G, Lee KP, Sonar P, Dharmarajan R, et al. Recent progress in the abatement of hazardous pollutants using photocatalytic TiO₂-based building materials. *Nanomaterials*. 2020;10(9):1854.
- [12] Lim YF. Novel materials and concepts for regulating infra-red radiation: Radiative cooling and cool paint. In: *Energy Saving Coating Materials*. Elsevier; 2020. p. 113-131.
- [13] Qi Y, Yang Z, Huang W, Zhang J. Robust superhydrophobic surface for anti-icing and cooling performance: Application of fluorine-modified TiO₂ and fumed SiO₂. *Applied Surface Science*. 2021;538:148131.
- [14] Al-Ali D, Kamoona GM. Effectiveness of nanomaterial in the roof of the building to achieve energy conservation for indoor environment of the building. *Journal of Engineering*. 2021;27(2):126-148.
- [15] Elakkiya V, Sumathi S. Ce and Fe doped gahnite: Cost effective solar reflective pigment for cool coating applications. *Journal of Alloys and Compounds*. 2020;820:153174.
- [16] Yew MC, Yew MK, Saw LH, Ng TC, Chen KP, Rajkumar D, et al. Experimental analysis on the active and passive cool roof systems for industrial buildings in Malaysia. *Journal of Building Engineering*. 2018;19:134-141.