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A Review on the Use of Titanium Dioxide in Self-cleaning Technology Applied in Building

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Abstract

Buildings are exposed to various types of organic materials ranging from bird droppings to vehicle emissions where the combustion of fuel continuously makes buildings dirty and also pollute the air we breathe. Buildings are now able to clean themselves and the air around them. The main idea for self-cleaning technology is to make the surface superhydrophilic. On the superhydrophilic surface, the water spreads on it completely forming a very thin layer of water. As the layer of water flows off the surface, it flushes out any contaminants. Photocatalytic self-cleaning coatings are used for building façade. Titanium-dioxide (TiO_2) metal coating is applied on building walls and glass windows, which helps them clean themselves. Because of special properties of Titanium dioxide nano particles, it can be used to realize transparent self-cleaning coatings. There are many researches which are focused on the using of Titanium dioxide as a self-cleaning coating for sustainable buildings. In this paper a review on the use of Titanium dioxide coating technology and the methods of applying it, is presented to throw light on this field and feasibility of using this technology in Saudi Arabia country .

Keywords: Buildings, Coating, Self-cleaning, Titanium dioxide

1. Introduction

There is a growing interest in self-cleaning technology because of their wide range of possible applications in various fields. The self-cleaning theory was discovered from the natural phenomenon which can be observed on leaves of lotus plant. Self-cleaning surfaces are a class of materials that have the ability to readily remove any dirt or bacteria from their surfaces. For example, when raining, the water from the rain will clean the self-cleaning surfaces without a need for any external intervention.

Nano-coatings materials are increasingly used on building surfaces, such as walls, doors, and windows. Titanium dioxide nanoparticles (TiO_2) is widely used in various fields such as building coating. It is a high photocatalytic metal oxide. When it is exposed to sunlight, electrons in the titanium dioxide particles become supercharged and interact with the water molecules in the air forming free radicals (hydroxyl radicals and superoxide anions), Fig.1. These radicals break down organic material on the building facade and pollutants such as nitrogen oxide in the surrounding atmosphere. The superhydrophilicity of titanium dioxide creates a water-loving environment. As such, when it rains, the water doesn't bead on the surface. Instead, it collapses and runs evenly off the building, taking the broken-down organic material and nitrates along with it. It is important to note that even the slightest amount of rain or humidity in the air can create this effect.

2- TiO_2-coated ceramic tiles

The characteristics of additional coatings on glazed ceramics were examined by Määttä et al. [2]. Three glazed tiles coated with ceramic sol–gel derived TiO_2 were tested to investigate the effects of UV-radiation on their cleanability. Oil and organic particle soil residues on the surface were measured using a quantitative radiochemical determination method. The results revealed that the effects of UV-radiation were greatest on rough surfaces (TiO_2-surface) due to increasing the surface area available for photo-induced phenomena. Organic particles was removed more effectively with UV radiation than without.

Ceramic tiles were coated with silver-titanium oxide nanoparticles by Mäkelä and Aromaa [3] to produce a smooth, thin coating with both photocatalytic and antibacterial properties, as shown in Fig. 2. UV light changed the surfaces from being hydrophobic to hydrophilic. Although the obtained photocatalytic reaction rate coefficients were smaller than anticipated, the coatings were photocatalytic. Biofilm removal was also accomplished, but it was still lower than anticipated. The coating's thinness, or the small amount of material on the surface, was the cause of the lower efficiencies. It was suggested that increasing the thickness of the film without losing the transparency requires research and development.

Gürbüz et al. [4] used commercially (TiO_2, 25 nm) and Si-modified TiO_2 nanoparticles to evaluate the photocatalytic activity of the uncoated, unmodified TiO_2 coated and Si-modified TiO_2 coated tiles. Methylene blue was used as organic pollutants for the photocatalytic experiments. The results revealed that, Si-modified TiO_2 coated tiles showed better photocatalytic activities than uncoated and unmodified TiO_2 coated tiles. 100% cleanability degree were observed for Si-modified TiO_2 coated while no completely cleaning was detected for uncoated and unmodified TiO_2 coated tiles.

Shakeri et al. [5] investigated the coating of ceramic with TiO_2. A simple one-step heat treatment method is introduced for coating, (Fig. 3) and different parameters of the heat treatment process are examined. It was found that applying a one-step heat treatment process with the optimum temperature of 200 ^{o}C for 5 h results in successful coating of nanoparticles and rapid degradation of dye in a short time.

Neto et al. [6] coated commercial ceramic tiles with thermally stable core@shell SiO_2@TiO_2 particles. samples are subjected to high-temperature thermal treatment (1000–1140 ^{o}C). The core@shell configuration exhibit excellent self-cleaning activity, much higher than that of control tiles prepared with commercial P25 TiO_2 photocatalyst.

3- TiO_2-coated building surfaces

Cement based Eternit plates modified by TiO_2/SiO_2 surface layers investigated by Yuranova et al. [7]. The transparent TiO2/SiO2 coating indicates that the tiny TiO_2 (rutile) crystals do not significantly scatter light. The concentration and ratio of the components, as well as the length of time and temperature required for the colloid networking to produce the self-cleaning effect, were examined in relation to the compositional parameters of the TiO_2/SiO_2 coating. The TiO_2/SiO_2 coating's consistent performance was demonstrated by the periodic discoloration of natural pigments on the TiO_2/SiO_2/Eternit plates as shown in Fig. 4. The acrylic and cellulose components on the TiO_2/SiO_2/Eternit plates remain stable using FTIR spectroscopy after numerous self-cleaning cycles.

Maggos et al. [8] performed depollution tests in an artificially closed area of the parking, which was polluted by a car exhaust during the testing period. White acrylic TiO_2-containing paint was used to cover the ceiling surface of the car park. Car exhaust gases were supplied to the restricted area. The UV lamps were turned on for 5 hours when the system reached steady state. The results revealed a significant photocatalytic oxidation of NO_x gases. The photocatalytic removal of NO and NO_2 was calculated to 19% and 20%, respectively, while the photocatalytic rate (μgm^{-2} s^{-1}) ranged between 0.05 and 0.13 for NO and between 0.09 and 0.16 for NO_2.

Under simulated atmospheric conditions, Laufs et al. [9] investigated the photocatalytic reactions of nitrogen oxides ($NO_x = NO + NO_2$) on commercial TiO_2 doped facade paints. Fast photocatalytic transformation of NO and NO2 was noticed exclusively for the photocatalytic paints. All of the paints examined produced nitrous acid (HONO) in the dark; however, only the photocatalytic samples effectively decompose it when exposed to radiation, (Fig. 5). Adsorbed nitric acid/nitrate anion (HNO_3/NO_3^-) was observed. Additionally, only in the presence of O_2, traces of H_2O_2 observed in the gas phase. Formation of the greenhouse gas nitrous oxide (N_2O) could be excluded. They concluded that the harmful HNO_3/NO_3^- is formed on the surface of the photoactive paints, whereas it is formed in the gas phase in the atmosphere. Additionally, the application of photocatalytic paints may aid in reducing acid deposition, such as on plants, or nitric acid-related health problems.

Qiu et al. [10] found that grafting nanometer-sized Cu_xO clusters onto TiO_2 produced an excellent indoor risk-reduction material. High-resolution transmission electron microscopy and X-ray absorption near-edge structure analyses with synchrotron radiation revealed that Cu_xO clusters contained Cu^I and Cu^{II} valence states. In the Cu_xO clusters, the Cu^{II} species give TiO_2 the ability to effectively photooxidize volatile organic compounds in visible light, while the Cu^I species give it antimicrobial properties in the dark. In the hybrid Cu_xO/TiO_2 nanocomposites, efficient decomposition and antipathogenic activity were achieved by controlling the balance of Cu^I and Cu^{II} in Cu_xO.

Quagliarini et al. [11] used sol-gel and hydrothermal processes to deposit Titania sol on travertine. Before and after the TiO_2 treatments, water absorption by capillarity, static contact angle, and a specific surface water absorption analysis were evaluated. The characteristics of the treated surface were examined in relation to the amount of titania that was deposited. It was demonstrated that the substrate's reactivity did not change significantly when the substrate was not exposed to ultraviolet (UV) light. Additionally, it appears that hydrophilicity caused by UV light does not result in increased water absorption, which supports the application of TiO_2 coatings in the field of Architectural Heritage. However, additional research is suggested in order to better assess the treatment's durability and sustainability before it is widely used.

Hassan et al. [12] evaluated the benefits of incorporating TiO_2 into asphalt pavements. A water-based TiO_2 spray coating's photocatalytic efficiency and durability were tested on asphalt pavement on Louisiana State University's campus and in the laboratory. According to laboratory testing, TiO_2 was able to remove NO_x and SO_2 pollutants from the air stream with efficiencies ranging from 4 to 20 percent for SO_2 pollutants and 31 to 55 percent for NO_x pollutants. At a rate of 0.05 L/m2, the maximum removal efficiencies of NO_x and SO_2 were achieved. The efficiency of NOx reduction is affected by the flow rate of the pollutant, relative humidity, and ultraviolet (UV) light intensity. To directly measure photocatalytic degradation, NO_x concentrations were monitored in the field for both coated and uncoated sections. To directly measure photocatalytic degradation, NO_x concentrations were monitored in the field for both coated and uncoated sections. In addition, for evidence of photocatalytic NO_x reduction, nitrates were collected from both the coated and uncoated areas. Photocatalytic NO_x reduction is evident in both approaches' outcomes. Further field assessment was suggested to decide the solidness of the surface covering.

In Hengelo, Netherlands, Ballari and Brouwers [13] conducted experiments on a full-scale demonstration of air purifying pavement. Over a length of 150 m, the full width of a street was provided with concrete pavement containing TiO_2. Another part of the street, about 100 m, was paved with normal paving blocks, (Fig. 6). Traffic intensity, NO, NO_2, and ozone concentrations, temperature, relative humidity, wind speed and direction, and visible and UV light irradiance were all measured during the 26-day outdoor monitoring that spanned more than a year. In addition to these measurements taken in the field, the utilized blocks were also tested in the laboratory to determine how well they performed. In comparison to the values that were obtained in the street, the NO_x concentration was, on average, 19% lower throughout the day and 28% lower only during the afternoons. A NO_x concentration decrease of 45 percent was observed under ideal weather conditions (high radiation and low relative humidity).

Munafo et al. [14] used spray-coated titanium dioxide (TiO_2) colloidal suspensions to deposit transparent, self-cleaning coatings on stones in order to preserve the original aesthetic characteristics of historic and monumental structures. The chosen reference substrate was travertine. Indoor laboratory tests were used to evaluate the product's self-cleaning capability and compatibility with travertine. The photo-activity of TiO_2 was measured before and after the stones were artificially aged using a variety of methods. The findings appear to support the use of nano-structured TiO_2 for stone preservation over time.

Graziani et al. [15] studied the photocatalytic properties of TiO_2 that was applied to the surfaces of clay bricks following the deposition and aging processes. Before the durability test, nano-film morphology, wettability, and self-cleaning efficiency were evaluated for TiO_2. During the aging test, the self-cleaning ability was also evaluated in order to assess its variation in long term applications. TiO_2 has a high photocatalytic efficiency when applied to a clay brick substrate, as the results demonstrate that its photocatalytic efficiency remains stable over time. Clay brick specimens treated with TiO_2 have a seven-fold higher photocatalytic efficiency over time than untreated specimens.

The self-cleaning capabilities of titanium dioxide and silicon dioxide-based coatings applied to various cladding materials are demonstrated by Andaloro et al. [16]. All of the samples tested were opaque. Before being used outside, preliminary laboratory tests were done by measuring water contact angle measurements to verify hydrophobic and hydrophilic behavior prior to outdoor application. After that, outdoor tests were carried out to check the product's effectiveness and durability over a 36-month period by observing colour variation. The findings demonstrated that applying a functionalized nanotechnological coating to a facade can, over time, make cleaning operations significantly easier and less frequent.

Guo et al. [17] investigated the method of directly painting self-compacting architectural mortars (SCAM) with a clear paint containing TiO_2. Under both Ultraviolet-A and visible light irradiation, its self-cleaning (in terms of rhodamine b, RhB degradation) and weathering resistance (accelerated façade weathering) were evaluated. SCAM samples that were dip-coated and mixed with 5 percent P25-TiO_2 were also made and tested for comparison. The TiO_2 paint-coated SCAM sample had strong weathering resistance and a high photocatalytic RhB removal capacity, according to the findings. In contrast, the RhB removal efficiency of the 5% P25-TiO_2-mixed samples was only significantly lower. Despite the P25-TiO_2-coated SCAM's satisfactory self-cleaning performance, the façade weathering process resulted in a significant reduction in RhB abatement. The overall findings suggest that the TiO_2-coated SCAM could be used in air-purification and self-cleaning applications as a resource- and energy-efficient product.

Au-TiO_2 photocatalysts was combined with a silica sol-gel synthesis by Luna et al. [18] to create long-lasting coatings on building materials that are self-cleaning and pollutant-free. This simple synthesis can be used on buildings. Soot and NO were used to test the self-cleaning and depolluting properties. The results showed that Au nanoparticles enhance the material's performance. The highest photoactivity is found in the intermedium gold content (0.5 percent w/w Au/TiO_2) and the smallest size of Au nanoparticles (13 nm).

In an urban setting, Lettieri et al. [19] investigated the performance of photocatalytic limestone surfaces coated with water-dispersed TiO_2 nanoparticles. For a year, coated and uncoated samples were exposed to an urban setting. On the sample surface, optical microscopy observations, color measurements, and contact angle measurements were made prior to and periodically after the exposure. Samples were subjected to a capillary water absorption test at the end of the exposure period, and a Rhodamine B photodegradation test was used to assess the self-cleaning efficiency. Ion chromatography and X-ray fluorescence (XRF) were used to measure the amounts of Ti and soluble fraction on the sample surfaces, respectively. Overall, the findings indicated that the TiO_2 coating was better able to maintain the surface's colour properties shortly after exposure. The self-cleaning efficiency was reduced to negligible final rates after eight months due to the loss of this effect. There were no discernible wettability results or capillary behaviors observed. Both partial titania loss and deactivation caused the photocatalytic activity to decline. In the deactivation of the photocatalysts, it was recognized that soluble salt ions, either adsorbed from the environment or produced by the photocatalytic abatement of pollutants, played a role, and their accumulation merits consideration for the potential implications for the risk of stone damage.

Colangiuli et al. [20] investigated TiO_2 NPs/fluoropolymer coatings' ability to simultaneously be hydrophobic and self-cleaning over the medium to long run on limestone. The surface of the nanocomposites-coated samples was monitored after being exposed to urban air for a year. Contact angle measurements and a capillary water absorption test were used to measure hydrophobic properties, and a Rhodamine B photodegradation test was used to measure self-cleaning efficiency. Colour measurements and observations using optical microscopy were also carried out. X-ray fluorescence and ion chromatography were also used to determine the Ti and water-soluble ion contents of the sample surfaces, respectively. The results showed that the polymer's ability to shield the stone surface from water penetration was unaffected by TiO_2 NPs. The surfaces were shielded from dirt by the coatings. However, a polymer modification brought about by aging may have contributed to the gradual decline in photocatalytic efficiency caused by the removal of the photocatalyst from the coating surface. The coupling of the photocatalytic titania with the hydrophobic polymer led to low contents of water-soluble ions adsorbed by the NPs, which may be accumulated on the coated stone surface and may increase the damage risk for the stone. The study provides useful information for the improvement of these nanocomposites and shows that TiO2 NPs embedded in a fluoropolymer host matrix in sufficient quantities may be a suitable option for obtaining stone coatings with barrier effects against water penetration and photocatalytic ability.

4. TiO_2-coated glass surfaces

Mellott et al. [21] used sol–gel to prepare a TiO_2-based photocatalytic film for self-cleaning on glass. The chemical and physical properties of this film are comparable to those of chemical vapor deposition (CVD-based) films that are commercially available. Additionally, the photocatalytic performance of the sol–gel-derived laboratory films deposited on glass is comparable to, or in some cases better than that of the commercially available films on glass.

Piispanen et al. [22] compared commercially available self-cleaning glass to the self-cleaning capabilities of experimental TiO_2 and TiO_2–Ag coatings on float glass. The sol–gel method of applying TiO_2 coating to float glass was used in the experimental surfaces, while TiO_2–Ag coating was applied by the liquid flame spray method, which deposits TiO_2–Ag composite nanoparticles on the surface. Methylene blue and stearic acid degradation tests were used to examine the coatings' photocatalytic activity. Finally, a model soil based on sebum was used to test how well the soil adhered to the surfaces. The sol–gel TiO_2 coating went from being superhydrophilic in a few hours, while the activation time needed for the commercial titania coated glass was several days. The water contact angle of the surface containing the TiO_2–Ag nanoparticles did not significantly change. Compared to uncoated and TiO_2–Ag coated surfaces, commercial titania coated and sol–gel TiO_2 surfaces demonstrated self-cleaning properties and clearly lower soil attachment. It was thought that the thickness of the coatings played a major role in how differently the surfaces interacted with organic contaminants.

Ganesh et al. [23] developed a photocatalytic, superhydrophilic, transparent, porous TiO_2 film with rice-shaped nano/mesostructures deposited on glass substrates by electrospinning. The deposited TiO_2 film's superhydrophilicity, self-cleaning properties (photocatalysis), and optical properties like transmittance and absorbance were investigated. Superhydrophilic transparent coatings can be used in photovoltaic modules and window coatings due to the decreasing water contact angle with increasing TiO_2 thickness. In the photodegradation of Alizarin red dye, the self-cleaning property of the TiO_2 film with its rice-shaped nano/mesostructures was found to be superior to that of commercially available Degussa P-25 as shown in Fig. 7.

The sol-gel process can be used to coat a photoinduced super-hydrophilic nanoporous thin film made of TiO_2 photocatalysts to improve the glass surface's ability to clean itself. Lien et al. [24] developed a method to enhance the photocatalytic activity of TiO_2 thin film, directly coated on the glass by doping SiO_2. The photocatalytic activity of TiO_2 films was examined in relation to post-annealing and the SiO_2 content. Using differential X-ray diffraction and, a field-emission scanning electron microscope they examined the film's microstructure and hydrophilic properties. The SiO_2 doped TiO_2 film, when illuminated by ultraviolet light, is extremely hydrophilic, with a water contact angle of less than one degree. This greatly favors the glass surface's ability to clean itself.

Leong et al. [25] developed a facile immobilisation technique that is based on simple sol–gel process. In this technique, TiO_2 nanoparticles are spray-coated onto a porous glass substrate, (Fig. 8). The uniformity of the TiO_2 coating on the glass surface was studied using a dynamic flowsense charge-coupled device camera. The influence of different TiO_2 nanoparticle concentrations in the ethanol phase was identified through rheological analysis, which showed that nanoparticle concentration is a crucial factor that affects the uniformity of the coating layer. The ability of the obtained material to catalyze formaldehyde photodegradation in presence of artificial UV light was investigated. Results demonstrated that more than 15.0 g/L TiO_2 is required to activate formaldehyde photodegradation and that uniform surface coatings with sufficient surface thickness can be produced. In addition, the uniformly coated photocatalysts for the efficient self-cleaning of indoor air pollutants can be fabricated through a simple technique.

Kartikowati [26] conducted research on the dip-and-spray coating of immobilized TiO_2 powder on glass support. The number of coating processes was varied to studies their effect on photocatalytic efficiency. The annealed process at high temperature was conducted to improve the adhesion of TiO_2 powder to the glass substrates. It was found that the dip-coating method has a better result than the spray coating method. TiO_2 can perfectly cover all glass surfaces, and the photocatalytic activity was unaffected by this procedure. Immobilized TiO_2 was capable of breaking down nearly all of the 4 ppm Rhodamine B.

5- Conclusion

Recently, new materials and new opportunities are being brought to industries by nanotechnology, resulting in an improved living environment and increased comfort. One of these is the construction industry, where nanotechnology can produce products with numerous individual characteristics that can enhance the performance of existing building materials and introduce new applications with enhanced sustainable properties. Building matrices, coatings, and insulating applications all use new nanotechnology-based materials and products. Self-cleaning materials have gained considerable attention for both their unique properties and practical applications in many areas. This paper aims to give an overview on the researches that conducted on TiO_2 nanomaterials coatings on the building applications. The previous research works have revealed the effect of using TiO_2 nanomaterials for a more efficient self-assembly process through implementation of different and multifunctional nanocoating. There are many research opportunities and future possibilities for photocatalytic hydrophilic self-cleaning technologies, e.g. smart windows, building integrated photovoltaics and solar cells in general are areas of application that could benefit greatly from a self-cleaning technology. Furthermore, self-cleaning facades could significantly reduce cleaning costs and maintenance time. Regarding the application of these technologies in buildings in the Kingdom of Saudi Arabia, we see that they will be very useful, as the winds that blow over the country are loaded with dust and sand, as well as the presence of exhausts emitted from cars, which may accumulate on buildings. Also, the presence of rain, which plays a major role in the process of self-cleaning the buildings.

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