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THE USE OF TITANIUM DIOXIDE IN CONCRETE MATERIALS TO FILTER SMOG POLLUTION FROM AIR

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Abstract—*With pollution ever-increasing in a rapidly developing world, environmental protection will rely on new innovations to remove pollutants. One such innovation is titanium dioxide-infused concrete and cement, which can remove smog from the air when exposed to ultraviolet light. To clean the air of smog, the nitrogen oxides present must be transformed into different, less harmful substances such as nitrate ions. The nitrate ions formed during the reaction then create nitric acid, which is reacted with grout to create a harmless neutral salt. The salt is then washed out by precipitation. While this reaction can occur naturally, it does so at a slow rate. The process is sped up by the presence of titanium dioxide, which acts as a photocatalyst, meaning it can speed up a reaction when light is also present.*

The technology has already been implemented into various structures and has been subject to performance tests. The titanium oxide-infused concrete has shown to have greater flexural and compressive strength than normal concrete, giving a structural as well as environmental advantage. Furthermore, the titanium oxide concrete proves to effectively remove nitrogen oxides as well as common volatile organic compounds (VOCs) such as benzene, toluene, and ethylbenzene. This material has been integrated into materials ranging from roofing tiles to main structural components of buildings, and proves to be a sustainable solution..

Key Words—Concrete, Nitrogen Oxides, Photocatalyst, Titanium Dioxide, Volatile Organic Compounds, Sustainability

THE POLLUTION PROBLEM IN THE INDUSTRIALIZED WORLD

Ever since the dawn of the Industrial Revolution, the entirety of the planet has battled the byproducts of increased productivity: pollution. Since the mid-1800s, pollution levels have increased at a rapid rate. More recently, pollution has been monitored worldwide more closely by the United Nations. In more recent years, pollution has decreased slightly, but continues to pose massive problems due to high concentrations [1]. To combat this, the World Health Organization (WHO) set maximum acceptable values of common pollutants. Particle matter was limited to between 10 and 20 $\mu g/m^3$, depending on size, nitrogen oxides to 40 $\mu g/m^3$, sulfur dioxide to 20 $\mu g/m^3$, and ozone to 100 $\mu g/m^3$ [2]. These pollutants all contribute to the buildup of smog.

According to the Environmental Protection Agency (EPA), smog, which is mainly produced by the transportation sector, is harmful because it contains both nitrogen oxides (NO_x), and Volatile Organic Compounds (VOCs). VOCs are organic compounds with relatively low boiling points, which also tend to react to other compounds easily. When VOCs react with nitrogen oxides, particularly nitrogen dioxide, NO_2, which is prevalent in smog, ozone (O_3) is created [3] [4].

Currently, the WHO states that 92% of the world's population live in areas where at least one of the air quality standards are not met [2]. As a result, many people inadvertently suffer the consequences of industrialization, particularly poor people due to housing conditions near polluted areas. The WHO estimates 88% of those affected by health problems due to pollution are poverty-stricken, with a majority from southeast Asia [2]. Adverse health effects result from high quantities of pollutants in the air, ranging from minor problems such as chest pain, coughing, reduced resistance to infections, and fatigue, to more serious problems such as acute bronchitis, aggravated asthma, development of chronic respiratory illnesses, irregular heartbeat and premature death [5]. Overall, 3 million deaths occur annually due to pollution, with two thirds of deaths caused by heart disease and stroke [6].

In order to solve the ever-increasing pollution problem in today's world, a sustainable solution is needed. According to the United Nations, sustainability is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," as defined by the document *Our Common Future* [7]. This sustainability includes environmental protectionism, as well as social and economic equity. To achieve a fully sustainable solution, all three of these critical issues must be addressed. The most promising solution to this problem is titanium dioxide-infused concrete. The material has similar structural properties to normal concrete, but because of the titanium dioxide, can remove pollutants from the air by decomposing them into harmless compounds. This solution provides a viable option to urban areas, where pollution levels are generally higher, due to the large potential surface area for the material.

CHEMICAL ANALYSIS OF TITANIUM DIOXIDE

Titanium Dioxide as a Photocatalyst

To understand why titanium dioxide is able to have such a strong effect on nitrogen oxide removal, it is necessary to examine the properties of different titanium dioxide structures. Like many other chemical compounds, titanium dioxide can arrange itself into various shapes and patterns which affect its properties. According to a paper from Czestochowa University of Technology in Poland, there are two particularly important titanium dioxide mineral structures that can be found in nature: rutile and anatase. These two mineral structures are significant because they both have a high refractive index, which means that light travels quite slowly through these minerals. For example, diamond's refractive index is around 2.42 and glass is around 1.5. According to the paper, the refractive index of anatase ranges from 2.5 to 3.0, and that of rutile is around 3.8. This makes titanium dioxide an effective photocatalyst, meaning that it can cause chemical reactions to occur at a heightened rate in the presence of light [8].

When reactions occur in the presence of a photocatalyst such as titanium dioxide, the catalyst has the ability to oxidize and reduce the necessary molecules in order to speed up the reaction. According to the International Research Journal of Engineering and Technology, high energy photons allow electrons to become promoted to the conduction band in the photocatalyst, or the energy level just above the normal valence energy level. This process leaves a positively charged hole in the valence band of the photocatalyst. The necessary energy for this process to occur in titanium dioxide, a semiconductor, is 3.2 electron volts (eV). The promoted electron is used to reduce one molecule in a redox reaction, while the positively charged hole is used to oxidize the other molecule [9]. Thus, when an effective photocatalyst such as titanium dioxide is available, photoreactions such as those that remove air pollution can be significantly optimized.

Reactions with Pollutants

A large source of pollution in the air is nitrogen oxides (NO_x), which are harmful to the environment by themselves and also can react with oxygen in the air to form ozone, the main component in smog. According to the Czestochowa University of Technology paper, titanium dioxide is not consumed when used as a photocatalyst, meaning that it can be used in the process without needing to be constantly replaced. In order to remove nitrogen oxides entirely, a multi-step process is needed. The process, according to the Czestochowa paper, starts with the reaction

$$NO + 2OH^- \rightarrow NO_2 + H_2O.$$

This process alone does not remove nitrogen oxides but rather converts nitrogen monoxide to another harmful compound, nitrogen dioxide, which allows a second reaction to occur:

$$NO_2 + OH^- \rightarrow NO_3^- + H^+.$$

This reaction actually removes the remaining nitrogen dioxide and converts it to nitrate ions, which then form nitric acid, HNO_3, with the ionized hydrogen.

When the reaction takes place on or near concrete, grout (present in some types of concrete) can react with this nitric acid and form a neutral ionic salt. Thus, harmful nitrogen oxides are transformed into harmless molecules. Though this can happen without the presence of titanium dioxide, the photocatalytic properties of the compound are very important for improving the efficiency and effectiveness of this reaction [8].

Efficiency Tests

While the photocatalytic qualities of titanium dioxide provide a useful way filter out air pollutants, this will only have an impact given the correct conditions. As a result, various tests have studied the material in altering conditions to prove the most efficient combinations.

The first of these studies analyzes the effect of the photocatalyst on VOCs. The study was carried out by the California Energy Commission in conjunction with the Lawrence Berkeley National Laboratory. The test used cement infused with 1% titanium dioxide by mass which was then used to make identical concrete tiles. The tiles were exposed to ultraviolet (UV) light over a set interval of time, and the catalytic activity of the material was experimentally calculated for some of the more common VOCs present in air [10]. The titanium dioxide used comes in the form of commercial Degussa P-25 powdered photocatalyst, which contains 70% anatase and 30% rutile [11]. Figure 1 describes the results of the study which analyzed the effectiveness of the titanium dioxide on VOCs.

1% TiO_2 in cement sample	Concentration ppbv	Concentration μmol m^{-3}	Oxidation rate μmol m^{-2} h^{-1}	Catalytic activity m h^{-1}
Benzene	85	3.54	0.16	0.05
Toluene	63	2.60	0.76	0.3
Ethylbenzene	34	1.43	1.24	0.9
o-Xylene	28	1.16	1.29	1.1

FIGURE 1 [10]
Oxidation Rates of 4 VOCs with 1% TiO_2 Concrete

In addition to the concrete tile test, a second test was carried out using the same UV exposure, time, and exposed surface area, but substituting the concrete tile with just the P-25 photocatalyst directly applied to a thin film. Initial concentrations varied slightly, but the catalytic activity was still calculated from these samples. Figure 2 shows the results of this second study.

TiO_2 film of P-25 1 mg cm^{-2}	Concentration ppbv	Concentration µmol m^{-3}	Oxidation rate µmol m^{-2} h^{-1}	Catalytic activity m h^{-1}
Benzene	24	1.01	2.73	2.7
Toluene	13	0.52	2.68	5.1
Ethylbenzene	11	0.47	2.34	5.0
o-Xylene	10	0.42	2.11	5.1

FIGURE 2 [10]
Oxidation Rates of 4 VOCs with P-25 film

Figures 1 and 2 show that benzene has the lowest level of catalytic activity, followed by the three alkylbenzenes, confirming the previous findings of catalytic rates depending on the type of VOCs. Generally, the order, from highest conversion rate to lowest goes as follows: first alcohols and glycol ethers, followed by aldehydes, ketones, and terpene hydrocarbons, then aromatic and alkane hydrocarbons, and finally halogenated aliphatic hydrocarbons. In addition to this, the tests show that just applying the photocatalyst to the surface increases the catalytic activity, due to a greater concentration on the surface exposed to the pollutants [10].

The second major analysis of the material is its efficiency in removing nitrogen oxides from the air. Nitrogen oxides range in concentration between .018 ppm in cleaner parts of cities to up to 2.0 ppm in tunnels and near highways, due to higher vehicle exhaust concentrations [10]. Due to their high concentration in pollution, removing nitrogen oxides is perhaps the most important use for titanium dioxide.

The experiment testing nitrogen oxide removal is similar to the VOCs experiment. Concrete tiles were made from titanium dioxide infused cement and placed into contact with polluted air. The concentration of nitrogen oxides varied from test to test, but the air was held at 80% humidity with a flow rate of 1.5 liters per minute. The test ran for 12 hours and recorded how much of the original concentration of nitrogen oxides was removed. Like before, a separate test took place with the photocatalyst applied directly to a thin film, and their effectiveness was compared to the concrete tiles.

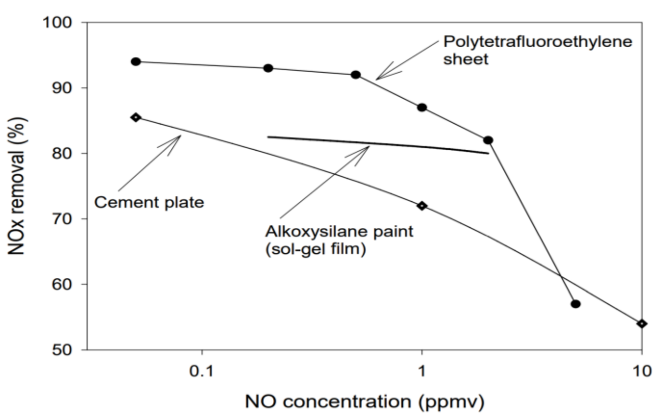

FIGURE 3 [8]
Initial NO concentration vs % NO removed

Once again, it is shown that by applying just a surface coating to the sample, more nitrogen oxides are removed. However, at higher concentrations, the cement-titanium dioxide mix proves to be more effective. In addition, with the data collected, it is calculated that with the average pollution levels of cities, the concrete has an efficiency of 60 mg per meter squared day. The study also notes that at lower humidity levels, the efficiency is not as high, with a slight drop at only 75 % humidity, but only 2/3 efficiency at 25% humidity.

In addition to these tests, another test comparing different coatings and light levels was published in the International Research Journal of Engineering and Technology. In this study, only surface coatings were analyzed. Two coatings of titanium dioxide were tested, one with 25% by mass, and the other 50% by mass. Concrete tiles were coated with a thin layer of the mixture, then set in a container with polluted air. Concentrations of nitrogen oxides were measured with respect to time [8].

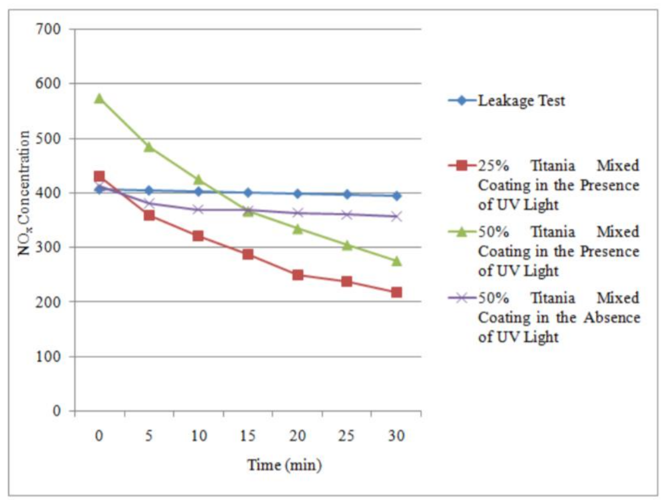

FIGURE 4 [9]
Nitrogen Oxide Concentration vs. Time

Once again, the data shows a significant drop in the concentration of nitrogen oxides over a short period of time. In addition, a higher concentration shows only a slightly higher rate of decomposition between 25% and 50%. This shows that only a small amount of the coating would be required to effectively filter air. Finally, UV light's importance is shown, since without it, the reaction still occurs, but at a significantly decreased rate.

TITANIUM DIOXIDE IN CONCRETE

Structural Analysis

Based on the evidence of the chemical data, titanium dioxide proves to be effective at removing a significant amount of pollutants from air. The problem now arises how to best implement this technology into large scale structures. Since cement is regulated based on quality, certain tests must be performed on the new mixture to ensure it still meets standards.

Portland cement, the standard cement used in most concrete structures, is made up of a mixture of lime, iron, silica, and alumina. The mixture is heated to temperatures of 2500 degrees Fahrenheit then ground to a powder. This is then mixed with other materials in a finishing process, depending on the manufacturer and the cement grade desired [12]. The leading titanium dioxide cement product on the market is currently TioCem, produced by the German manufacturer Heidelberg Cement. The process is the same as standard Portland cement, but the titanium dioxide mix is added to the other materials in the final powder. The TioCem cement is classified as CEM II as opposed to CEM I, meaning that it has greater than 5% by mass of secondary materials other than Portland cement.

Four main tests were performed on the TioCem to test for integrity: flexural strength, compressive strength, frost resistance, and absorbability. The tests were performed on blocks with dimensions 4cm x 4cm x 16cm. The concrete blocks used 450g of either Portland CEM I or TioCem CEM II, 1350g of sand aggregates, and 225g of water. The concrete was then let to cure a set number of days before the tests [9].

Properties		Results		Requirements according to EN 197-1 for 42.5 R grade cement
		TioCem® CEM II/ A-S 42.5 R cement	Portland CEM I 42.5 R cement	
Flexural strength [MPa]	after 2 days	5.4	4.3	-
	after 7 days	6.1	6.9	-
	after 28 days	7.4	7.5	-
Compressive strength [MPa]	after 2 days	32.3	20.5	≥ 20.0 MPa
	after 7 days	43.5	45.0	-
	after 28 days	52.5	50.6	≥ 42.5 MPa ≤ 62.5 MPa

FIGURE 5 [8]
Results of Flexural and Compressive Strength Tests

The flexural strength test is carried out by laying the block across a gap, and applying pressure to the center until the point of failure. The data collected in Figure 5 shows the pressure applied in MPa at the point of failure. Similarly, the compressive strength test placed the concrete block vertically under a hydraulic press, and pressure was applied until the point of failure. For both the flexural and compressive strength tests, the TioCem withheld significantly more pressure after 2 days, with an extra 1.1 MPa in the flexural strength test and 11.8 MPa in the compressive strength test. After a greater period of time, however, the TioCem nearly matched the Portland CEM I in both tests. These tests confirm that the addition of titanium dioxide does not negatively impact the concrete, and it still meets all requirements regarding strength.

A frost resistance test was also conducted in which the concrete sample was rapidly frozen and then thawed a total of 25 times. Following the cyclical freezing, the sample was subjected to a compressive strength test to measure its change in compressive strength. The results of the test, as shown in Figure 6, highlight the significant difference between the two samples. The Portland cement sample lost nearly 40% of its compressive strength after 25 rounds of freezing, as opposed to only 18.6% of compressive strength lost by the TioCem. In addition, the TioCem lost much less of its mass after the test, at only .18% as opposed to .69% lost by the Portland cement sample. Thus, TioCem has a structural advantage over traditional cement in frost resistance. In the absorption test, the sample was placed into a basin with a small amount of water, with only one side surface of the block exposed. Data recorded over a period of a week monitored how much of the water was absorbed by the block. In this test, both the TioCem and Portland cement samples recorded an absorbability of 8.1%.

Property		Mortar based on:	
		TioCem® CEM II/A-S 42.5 R cement	Portland CEM I 42.5 R cement
Frost resistance	average decrease in compressive strength [%]	18.60	39.40
	average decrease in mass [%]	0.18	0.69
Absorbability	[%]	8.10	8.10

FIGURE 6 [8]
Results of Frost Resistance and Absorbability Tests

Self-Cleaning Properties

In addition to the structural benefits of the titanium dioxide concrete, the material also exhibits a self-cleaning property, increasing the lifespan of the structure and lessening the requirements of routine maintenance. This phenomenon is due to two properties of the material: its ability to react with other molecules in the air and its super-hydrophilicity.

As previously stated, the titanium dioxide acts as a photocatalyst. This property allows for the oxidation of various molecules, including the pollutants in the air and on the surface, as well as the formation of hydroxyl and oxygen radicals from water and oxygen in the air. The products of these reactions then form salts. The salts are then washed off of the surface efficiently due to the super-hydrophilicity of titanium dioxide. When water normally encounters a surface, it tends to bead up due to the combination of the surface tension of the water and the difference in polarity between the water and the surface. Since both water and titanium dioxide are polar, they tend to be attracted to each other. This attraction is strong enough to compensate for the water tension, and as a result, water will run as a sheet rather than droplets across the surface, allowing for a more complete wetting of the surface [13].

In addition to removing pollutants, the surface also proves effective at removing bio-film. Because of the reaction to UV light, the titanium dioxide surface can remove biological substances including E. coli, Staphylococcus aureus, staph, SARS, and MS2 coliphage. Tests show that the titanium dioxide concrete can remove nearly 100% of a sample within an hour.

Applications

Since titanium dioxide is such a valuable material both in terms of structural and environmental impact, it can have multiple applications in the field of construction and civil engineering. Two of the most important and effective applications are in roofing tiles and structural concrete, both of which are absolutely essential in construction.

In roofing tiles, titanium dioxide can be used as a coating to significantly increase the rate of oxidation of nitrogen oxides in reaction. In an article by chartered civil engineer (United Kingdom) John Renowden of RCI, Inc., the safety of titanium dioxide is emphasized. Renowden says that titanium dioxide is found in toothpaste, aspirin, and is even used for sterilization in hospitals. The roof tile coating is useful for cleaning the air of smog, but it can also help improve the appearance of a roof, as substances that often accumulate on roofs can be eliminated by the titanium dioxide coating. It is important to note that no structural or health-related aspect of the concrete roofing tile is compromised when the coating is applied, as titanium dioxide is safe to be around and does not affect the structural integrity of the commonly-used traditional concrete roofing tile. Thus, it can serve as an environmentally beneficial method of roofing a structure [14]. Additionally, according to Renowden and researchers from the University of California Riverside, heightened exposure to UV rays speeds up the efficiency of the reaction due to the photocatalytic properties of titanium dioxide.

The UC Riverside study involved coating roofing tiles with titanium dioxide and exposing them to UV light in a closed space containing nitrogen dioxide. The study found that 88-97% of the nitrogen dioxide initially present was removed. The study also found that surface area was the main factor that affected nitrogen dioxide removal, meaning that they only needed to use enough titanium dioxide to form a thin coating on the tile [15]. This is a promising discovery, as it would suggest that the cost of the titanium dioxide can be minimized while still reaping the benefits of its environmental effects.

As important and beneficial as titanium dioxide-coated roofing tiles can be, concrete infused with the compound has the potential to be even more influential. Since structural concrete makes up a large portion of many buildings and is not structurally compromised by the addition of titanium dioxide, it can be used to prevent smog buildup in areas where it is most prevalent. According to a study by Dr. Andrea Folli of the Danish Technological Institute, titanium dioxide can be used on concrete by using it as a coating or inserting it into the outer surface of the concrete mold, thus increasing its effect while minimizing its cost. The study found these methods to be quite useful, as it was tested on a Copenhagen street and was found to significantly reduce the nitrogen oxide levels. Although more testing may be necessary, Dr. Folli also thought it possible that the titanium dioxide paint could be used to treat and clean water as well as air, a development which could be very influential [12]. Other cities around the world are also starting to incorporate this technology into their structures. For example, the Torre de Especialidades hospital in Mexico City implemented a titanium dioxide concrete structure on one of its exterior walls, which it claims can neutralize the impact of approximately 1,000 cars per day and reduce the impact of smog in close proximity to the building [15]. Mexico City is one of many large metropolises worldwide that desperately need some sort of solution to their pollution problem. Its ozone levels are labeled “very unhealthy” by the AirNow website run by the Environmental Protection Agency (EPA) [16].

This hospital is not the only structure to have already implemented titanium dioxide technology. In Rome, architect Richard Meier designed a large church that utilized the compound in its walls. While this was primarily done to achieve a pristine white color on the exterior of the church, the environmental implications of the material were later discovered by the Italian company Italcementi, which provided the construction materials for the structure. The effectiveness of the compound in the church’s exterior has been measured and was found to be primarily effective within very close range of the building [16]. However, even a small effect on pollution in a city as large as Rome or Mexico City could help induce more widespread change worldwide.

While these types of structures have a significant cost and require widespread implementation to have a major impact, titanium dioxide is still an appealing option to removing smog in major cities, as even a small and localized region of cleaner air can make a difference toward the overall health and environmental impact of a large city.

LONG TERM IMPACT

Cost Analysis

Whenever a new technology or product is introduced, the cost of making and implementing such a product is often a barrier. Introducing titanium dioxide into paints and concrete is one of these situations. Unless there is a way for the product to become available at low cost, the chances would be slim that it could be implemented on a large scale. The study from the Danish Technological Institute addresses this issue, as it states that titanium dioxide can drastically increase the cost of concrete, reaching up to a price four times that of normal concrete [12]. For reference, the average price of type I Portland cement costs about $12 per 42kg. The titanium dioxide added to the mix would cost $20.40 per kilogram added [17]. Depending on the concentration added, this addition greatly restricts the availability of the product due to the cost. Although this is not an ideal situation for widespread use, the study also suggests that it can be implemented in a way that minimizes cost.

While still being more costly than traditional concrete, the study states that the titanium dioxide can be incorporated only at the surface level, which does not affect its impact on the environment but does reduce its cost significantly. In order to do this the mold used to lay the concrete would be prepared with a lining of the titanium dioxide photocatalyst and therefore would allow the compound to exist only on the surface [12]. The other option would be to create a spray incorporated with the titanium dioxide and apply the treatment directly to the surface. Based on the method chosen, costs range between $1.08 to $10.70 per meter squared [17]. It is important to note that despite the problems associated with the cost of this technology, there exist methods of decreasing the cost such that the photocatalyst becomes a realistic financial option for large cities and construction companies.

Shortcomings

Even though titanium dioxide possesses qualities that can make it beneficial in civil and environmental engineering, it is important to examine any potential drawbacks before fully endorsing it for widespread use in large cities. Various studies have examined these drawbacks and have raised significant concerns that titanium dioxide is not as perfect as it may sound. In fact, in certain cases and under certain circumstances, researchers have found that titanium dioxide can emit some of the same types of toxic chemicals it has been utilized to remove. In addition, with constant exposure to the elements, the overall efficiency can decrease due to the deterioration of the surface coating.

In a study published in the Water and Environment Journal, researchers investigated the effects of environmental wear on the titanium dioxide coatings. In the experiment, a sample of titanium dioxide coating was applied to a concrete sample. The coating was applied with a thickness of 240 μm. The samples were then subject to rigorous sanding for a given period. Following the sanding, the absorption of the surface was determined for various ultraviolet wavelengths [18].

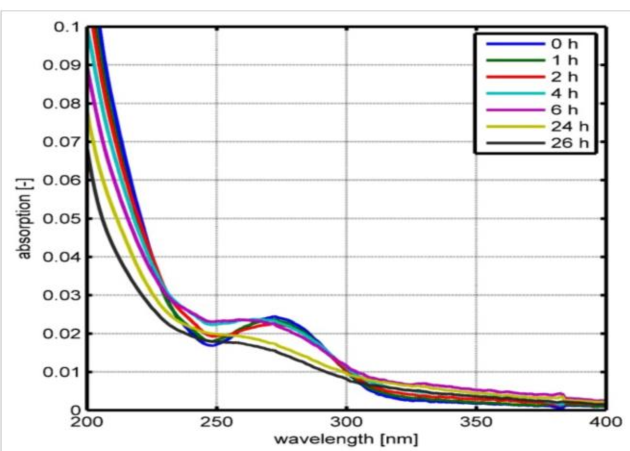

FIGURE 7 [18]
Results of Flexural and Compressive Strength Tests

The results of the data showed a substantial decrease in the absorbability of the titanium dioxide coating, especially for wavelengths of less than 250 nm. After only about 24 hours, the absorption of 200 nm light dropped from over .1 to just under .7, leading to a 30% drop over the 24-hour test. This could potentially lead to long term sustainability issues for the material, since this would require a costly repeated treatment of surfaces to maintain the product integrity. To combat this, new alterations of the titanium dioxide coatings are currently being tested, where the active titanium dioxide particles are coated in inorganic compounds. As a result of this, the titanium dioxide starts in an initial phase where it does not act as a photocatalyst and is generally shielded from exposure to weathering. In the active phase, the titanium dioxide becomes exposed as the inorganic compounds wear off, allowing the titanium dioxide to perform its photocatalytic function. Since various inorganic compounds can be added, each degrading at a different rate, the titanium dioxide in turn becomes exposed at different rates, allowing for an increase in the lifespan of the product, and in turn, creating a more economic and sustainable option [18].

Despite the promising options of titanium dioxide materials, there is still concern as to whether the reverse reaction can be catalyzed, in turn increasing pollution under certain circumstances. A paper by the Royal Society of Chemistry introduces some glaring uncertainties surrounding this issue. The society conducted a study in which they used both micro- and nano-sized titanium dioxide particles to analyze whether they were successful in removing nitrogen oxides and VOCs from the air. Their test produced varying results, as they concluded that the microparticles were generally unable to remove xylene (a type of VOC) from the air, while the nanoparticles were much more successful. However, the more concerning issue in the study was the release of different VOCs by the titanium dioxide paints. The researchers discovered that the paints released four different types of VOCs, including carcinogenic formaldehyde, through their photocatalysis. The study explains that the photocatalytic properties of titanium dioxide are effective, but the photocatalysis takes place on unwanted reactions as well as the desired oxidation-reduction reaction of nitrogen oxides.

An important observation to make when analyzing the results of this study is the chemical makeup of the paint. The researchers say that the organic matrix used in the paint is the nominal cause of the unwanted photocatalytic effects of the titanium dioxide and the subsequent release of titanium dioxide nanoparticles into the environment. Thus, they write, the natural response to such an issue is to modify the chemical makeup of the paint so as to attract the titanium dioxide more strongly to the surface. It is also necessary to use organic compounds that do not react to produce significant levels of VOCs such as formaldehyde [19]. While the formation of these dangerous VOCs is certainly an issue that must be dealt with, the problem is such that a careful attention to detail could potentially minimize the harmful effects while still maximizing the benefits of the compound.

A study from Indiana University made similar conclusions to the previous study. The researchers found that the photocatalytic properties of titanium dioxide could apply to atmospheric ammonia and convert them into the dangerous nitrogen oxides it is meant to reduce. The titanium dioxide catalyzes the reaction of oxygen and ammonia present in air to produce nitrogen oxides, which subsequently contribute to the proliferation of urban smog [20]. This study further reinforces the idea that more analysis and improvement is needed before titanium dioxide can be approved for widespread use. While improvements can be made that will alter the chemical makeup of titanium dioxide paints and make them safe for use, it would be irresponsible to implement the technology on a large scale without further testing and analysis.

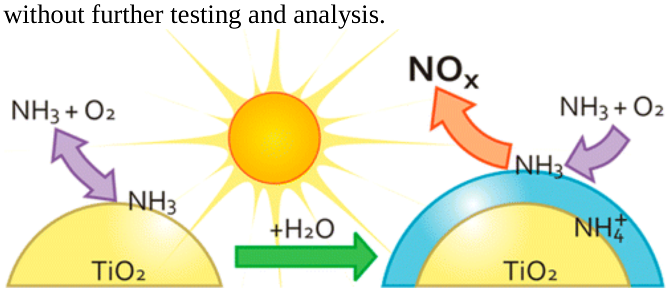

FIGURE 8 [17]
Photocatalysis of nitrogen oxide production

MATERIAL EVALUATION

As many regions of the world continue to industrialize at a rapid rate, solutions will be needed to deal with the adverse side effects of pollution. This continual development will eventually lead to many negative health conditions and lower the quality of life, mostly in impoverished nations. To solve this issue without restricting industrial growth, sustainable solutions to remove pollution from the air are needed. One of the most promising solutions is titanium dioxide concrete, which can remove harmful pollutants like nitrogen oxides and VOCs from surrounding air. The material proves promising, as it can remove up to 60 mg of VOCs in a day per square meter of exposed surface area and has a high potential to remove other pollutants. In addition, the material still adheres to building codes, even with the addition of the titanium dioxide. The material proves to have about the same strength as normal concrete, has greater frost resistance, and contains the added benefit of it self-cleaning.

While titanium dioxide does prove to be effective as a pollution reducer, research is continuing to improve the efficiency of the material, as well as address several of its disadvantages. In order to increase the sustainability of the product, research is under way on extending the lifespan of the material, allowing it to remove more pollutants over time. By adding a covering over the active titanium dioxide, the material is protected, and will be able to withstand greater environmental wear. In addition, studies identifying the environmental conditions that catalyze the reverse reaction are under way, in an attempt to prevent the possibly harmful side effects of titanium dioxide. Furthermore, more cost-efficient materials are still being researched to provide greater accessibility to market. As research on titanium dioxide continues to make its applications broader and to make it more sustainable, options will continue to develop to increase its effectiveness, and in turn, lead to an increasingly cleaner future.

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