PHOTOCATALYTIC CONCRETE

Dathi Sathya A[1], Gnanavarshini R[1], Mughileeshwar N K[1], Rajalakshmi S[2]
[1] *UG Students, Department of Civil Engineering*
[2]*Assistant Professor, Department of Civil Engineering*
Kumaraguru College of technology. Coimbatore, India

***Abstract*— Concrete is one of the most widely used materials in construction, offering durability and strength. However, urbanization has contributed to rising levels of air pollution, particularly due to nitrogen oxides (NOx) emitted by vehicles and industrial activities. In response to this environmental challenge, photocatalytic concrete with titanium dioxide (TiO_2) has emerged as a promising solution due to its ability to break down air pollutants through photocatalysis. While TiO_2 has been proven effective in degrading harmful pollutants, its efficiency varies under different lighting conditions, limiting its large-scale application in urban environments.**

This study aims to bridge the gap between laboratory efficiency and real-world applicability by evaluating the performance of M25 grade concrete with TiO_2 at 1%, 3%, and 5% dosages. The research focuses on assessing the mechanical properties (compressive strength, split tensile strength, and flexural strength) of the modified concrete, along with its pollutant degradation efficiency under controlled lighting conditions.

Experimental findings indicate that 3% TiO_2 provides an optimal balance, improving both structural strength and NOx reduction capacity. The NOx degradation tests demonstrate that TiO_2 -modified concrete can significantly reduce airborne pollutants, making it a viable solution for sustainable urban development. This research contributes to the advancement of environmentally friendly construction materials and offers insights for future innovations in smart city infrastructure.

***Keywords*— Photocatalysis, Nitrogen oxides (NOx), Photocatalytic concrete, Mechanical properties, Pollutant degradation, Smart city infrastructure, Titanium dioxide (TiO_2), Dosage levels.**

I. INTRODUCTION

Concrete construction relies on the use of durable and strong materials. The degree of strength and durability offered by concrete can be damaging to the environment in enduring urban heat islands and pollution. The photocatalyst technologies can be useful in dealing with this concern because of the ability of titanium dioxide (TiO_2) polymers to decompose airborne pollution constituents like NOx and SO positively. Air purifying capabilities make titanium dioxide (TiO_2) useful because of its photocatalytic property to break down pollutants. Its efficacy, however, is reliant on exposure to light and distribution of material. Since TiO_2 is responsive to UV light, the effectiveness of this material is diminutive in low UV regions. Moreover, while optimal concentration improves performance in a well dispersed manner, excessive concentration leads to the dispersion diminishing structural integrity. This research assesses the impact of varying proportions of TiO_2 (1%, 3%, and 5%) on mechanical strength and air purification effectiveness under different conditions to establish the optimal for better performance of the material in real world sphere. Cities are now facing a daunting challenge of air pollution due to speedy globalization and industrial growth. Nitrogen oxides (Nox) and Volatile organic compounds (VOCs) are primary agents contributing to the degradation of air quality, elevation of breathing and pathological and environmental concerns.

PROBLEM STATEMENT

While TiO_2 has been shown to facilitate photocatalytic oxidation, its effectiveness is limited by light availability and material distribution. This study investigates how various TiO_2 concentrations (1%, 3%, and 5%) impact both mechanical properties and air purification efficiency under different environmental conditions.

RESEARCH OBJECTIVES

1. Investigate the effects of TiO_2 integration into M25 concrete.
2. Evaluate compressive, split tensile, and flexural strength variations.
3. Measure NOx degradation efficiency under controlled lighting environments.

4. Identify optimal TiO_2 dosage for maximizing both structural strength and environmental benefits.

II. LITERATURE REVIEW

The capacity of titanium dioxide (TiO_2) to degrade pollutants via photocatalytic oxidation has drawn a lot of interest. TiO_2 is helpful for purifying air and water because it produces reactive oxygen species (ROS) when exposed to ultraviolet (UV) light, which breaks down organic pollutants. TiO_2 has been extensively investigated for environmental remediation, antimicrobial coatings, and self-cleaning surfaces since its initial photocatalytic application was shown by Fujishima and Honda (1972). But even with its efficacy, TiO_2 's practical performance is frequently constrained by elements like material distribution and light dependency.

TiO_2 's dependence on UV light, which accounts for only 3–5% of natural sunlight, is one of its main disadvantages. This limits its effectiveness in settings with little UV exposure. Through a variety of tactics, researchers have tried to overcome this constraint. To increase TiO_2 's light absorption into the visible spectrum, one method is to dope it with metal (such as Fe, Ag, and Cu) or non-metal (such as N, C, and S) elements. These changes increase visible-light activity, but they can also cause stability problems like charge recombination. To improve charge separation and expand light absorption, TiO_2 can also be coupled with semiconductors such as ZnO or g-C_3N_4 . Optimizing the concentration of TiO_2 in a material is still crucial for attaining high performance, even though these methods have shown promise.

The incorporation of photocatalytic materials into concrete has received considerable interest because of the urgency of environmental issues related to urban air pollution. Titanium Dioxide (TiO_2), a widely recognized semiconductor with photocatalytic activity, has yielded encouraging findings in decomposing pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs) upon exposure to UV light.

Zhang et al. (2021) carried out an experimental investigation on nano-TiO_2 -coated concrete surfaces and noted a dramatic decrease in NOx concentrations in actual traffic conditions. Their research pointed out that the efficiency of photocatalytic reactions is heavily dependent on environmental parameters such as humidity and exposure to sunlight.
Kim and Lee (2020) investigated the long-term performance of TiO_2 -modified concrete in wet environments and found that, although initial performance was impressive, durability of the photocatalytic surface was subject to maintenance and cycles of exposure. They advised periodic cleaning or reapplication to maintain its effectiveness.
Gupta et al. (2022) conducted a comparative analysis of normal concrete and TiO_2 -treated concrete under comparable environmental loads. Their findings showed that compressive strength and surface durability improved with the incorporation of TiO_2 , especially at 3% by weight of cement. But percentages above that had lower performance because of agglomeration.

Poon and Cheung (2007) showed that the addition of TiO_2 in paving blocks improved the self-cleaning capacity of the concrete and gave it aesthetic advantages as a result of its whiter appearance. This property is particularly advantageous in architectural uses where visual cleanliness is important.

Chen and Poon (2009) examined the impact of TiO_2 on mechanical and photocatalytic properties of concrete and summarized that though strength is increased very slightly by TiO_2 , its major contribution is towards decomposing pollutants. They further underlined the utilization of waste-generated materials with or without TiO_2 to produce more sustainable concrete.

Demeestere et al. (2008) studied NOx and VOC degradation with TiO_2 -infused cementitious materials. In their work, they highlighted the need for UV exposure to trigger photocatalytic processes and suggested optimal surface exposure in engineering.
Beeldens (2007) critiqued field research of TiO_2 use in road pavements and urban surfaces and affirmed its capability to lower NOx levels significantly. She reported that the performance of TiO_2 relies heavily on porosity of the concrete, roughness of the surface, and weather.
Together, these studies indicate that the incorporation of TiO_2 into concrete increases both mechanical toughness and environmental functionality, especially towards NOx degradation. Yet optimal dosage, dispersion methods, and long-term response in different environments still need more in-depth investigation.

III. MATERIALS

Ordinary Portland Cement (OPC) was the cement used in this investigation. Because of its great strength, longevity, and compatibility with TiO_2 integration, it was chosen. OPC is appropriate for photocatalytic concrete applications due to its good workability and hydration qualities. The fine aggregate was well-graded river sand that complied with IS 383-1970. With a fineness modulus of roughly 2.75 and no organic impurities, the sand guaranteed reduced porosity and good particle distribution. For increased load-bearing capacity and structural integrity, 20 mm crushed angular coarse aggregate was utilized. Before mixing, the aggregates were cleaned and sieved to get rid of dust and other impurities. To meet IS 456-2000 requirements for construction water, potable water was utilized for both mixing and curing. Water-to-cement ratio (w/c = 0.45) was maintained to achieve the required workability and strength characteristics. TiO_2 nanoparticles were incorporated into the mix at 1%, 3%, and 5% by weight of cement.

MATERIALS COMPOSITION

Concrete grade:M25
Mix ratio: 1: 1.64: 3.104: 0.45
Cement used:7.5kg
Fine aggregate:12.3kg
Coarse aggregate:23.28kg
Water:3.75 litres
Titanium dioxide:1%, 3%, 5% of cement weight

IV. METHODOLOGY

This study involves designing concrete mix ratios incorporating different TiO_2 variants (0%, 1%, 3%, and 5%) to evaluate their impact on mechanical properties and pollutant degradation efficiency. The process begins with the homogeneous dry mixing of cement and TiO_2 , followed by the incorporation of aggregates and water to ensure uniform distribution. The prepared mixtures are then cast into standard cube, cylinder, and rectangular mould to create concrete samples for testing. These samples undergo water curing for 7, 14, and 28 days to facilitate proper hydration and strength development. The pollutant degradation efficiency of the TiO_2 -enhanced concrete is then assessed under UV and visible light exposure. Finally, the mechanical properties of the concrete samples are tested to determine the effects of TiO_2 concentration on structural performance and durability.

Concrete samples with varying TiO_2 concentrations (0%, 1%, 3%, and 5%) undergo standard strength tests after 7, 14, and 28 days of curing. Compressive strength is measured using a universal testing machine (UTM), where cube samples are subjected to axial loads until failure to determine their load-bearing capacity. Similarly, cylindrical samples are tested for split tensile strength to assess their resistance to cracking under tension. Flexural strength tests are conducted on rectangular specimens to evaluate their ability to withstand bending forces. The results help determine how different TiO_2 concentrations impact the structural integrity of the concrete, providing insights into its suitability for various applications.

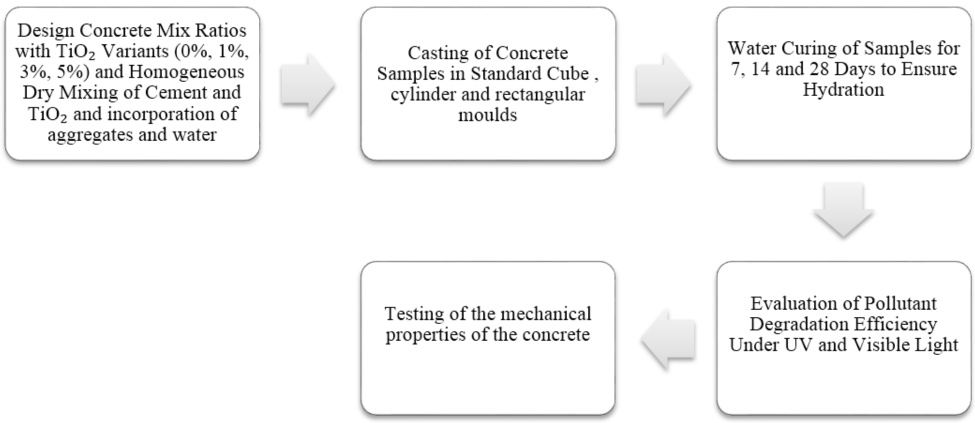

Figure 1: Methodology

V. STRENGTH TESTING

Compressive Strength Test conducted using a Compression Testing Machine (CTM). Concrete cubes of size typically 150mm x 150mm x 150mm are used. Failure is due to the concrete reaching its ultimate compressive stress. Good-quality concrete generally shows cone or pyramidal failure, demonstrating proper compaction and material uniformity. The specimen shows cone and split type failure. Split tensile strength test conducted using a compression Testing Machine (UTM). Cylindrical concrete specimen is typically 150 mm diameter and 300 mm height. Concrete fails under tensile stresses induced indirectly by compressive forces applied diametrically. Failure provides an indication of concrete's tensile capacity, critical for crack control in structures. The specimen shows vertical split failure. The flexural strength test conducted using Flexural Testing Machine, typically with centre-point or three-point loading. Standard beam size commonly used is 500 mm x 100 mm x 100 mm. The specimen is kept under centre point loading. Flexural strength indicates concrete's ability to resist bending stresses. Understanding failure patterns helps in evaluating the suitability of concrete for pavements and slab construction. The specimen shows flexural tension failure.

Total three samples were casted for each dosage of TiO_2 in all the three types of mould namely cube, cylinder and beam. The values of compressive strength, split tensile strength and flexural strength are noted at 7, 14 and 28 days of curing. The average value is tabulated from all the three values of sample. (1 Control Mix+3 Experimental Mixes) ×3 samples each=12 samples for each set of casting.

Figure: 2 Strength testing

VI. PHOTOCATALYTIC ACTIVITY TESTING

The methylene blue test (MBT) is done in the laboratory to determine pollution degradation efficiency and the photocatalytic activity of the TiO_2 -infused concrete. Photocatalytic activity of TiO_2 -infused concrete is done by measuring the degradation of MB dye under light exposure. Initially 10mg of methylene blue is stirred in 1 litre of distilled water. A TiO_2 -infused cube and a control cube sample of size 75mm are immersed in the solution, and it is kept under the sunlight for 5 hours. The control sample shows no change in colour, whereas the solution with TiO_2 -immersed concrete shows discoloration; dark blue turns lighter, which indicates the photocatalytic activity.

Figure: 3 Sunlight exposure

VII. RESULT AND DISCUSSION:

COMPRESSIVE STRENGTH TESTING

Compressive strength testing measures the ability of concrete to withstand axial loads.

Specimens were placed in the Compressive Testing Machine (CTM). Failure load was recorded, and compressive strength was calculated using the formula:

Compressive Strength= Failure Load (N) / Area of Cube (mm^2)

TYPE OF TEST (COMPRESSIVE STRENGTH TEST)	CONTROL SAMPLE (MPa)	1% TiO_2 (MPa)	3% TiO_2 (MPa)	5% TiO_2 (MPa)
7 days	16.25	20.92	21.78	19.25
14 days	22.25	27.36	28.47	25.18
28 days	28.20	32.19	34.58	30.8

Table: 1 Compressive strength result

The results of the compressive strength tests show that the addition of titanium dioxide (TiO_2) in concrete enhances its strength to a point, after which strength starts to decrease as dose percent increases. At 1% TiO_2, there is a significant increase in compressive strength relative to the control sample, which shows a 29% increase at 7 days and 14% increase at 28 days. This suggests that having small amounts of TiO_2 aids the hydration process and densifies the concrete matrix. The combination with 3% TiO_2 gives the overall highest strength, reaching a compressive strength of 34.58 MPa at 28 days, which was a 22% increase relative to the control group and thus a favorable level of TiO_2 to achieve the highest compressive strength. However, there is a decrease in compressive strength for 5% TiO_2, suggesting too much TiO_2 is possible to disrupt cement hydration or create micro-voids and thin out the matrix.

SPLIT TENSILE STRENGTH TESTING

Split tensile strength measures the ability of concrete to resist tension.

The cylinder was placed horizontally in the UTM. The maximum failure load was recorded. The split tensile strength was calculated using the formula:

$ft = 2P/\pi DL$

TYPE OF TEST (SPLIT TENSILE STRENGTH TEST)	CONTROL SAMPLE (MPa)	1% TiO_2 (MPa)	3% TiO_2 (MPa)	5% TiO_2 (MPa)
7 days	2.93	4.03	4.23	3.84
14 days	3.80	5.27	6.82	5.02
28 days	5.82	6.20	9.44	5.90

Table: 2 Split tensile strength result

According to the results from the split tensile strength test, adding titanium dioxide (TiO_2) increases the tensile strength of concrete up to a certain percentage, after which greater percentages tend to decrease the strength. For the test sample with 1% TiO_2, the tensile strength increased compared to the control sample, with a higher increase of 37% at 7 days and a slightly lower increase of 6.5% at 28 days observed, indicating a partitioning effect with bonding in the concrete matrix that could improve cohesion and stability. The tensile strength ultimately increased when testing a sample with 3% TiO_2, which resulted in the highest tensile strength value of 9.44 MPa at 28 days - an increase of 62% compared to the control sample. This study suggests that the optimal percentage content of TiO_2 when considering the tensile properties is 3%. When testing a sample with 5% TiO_2, tensile strength decreased noticeably; by the end of the experiment, the 28-day value decreased to only 5.90 MPa. This shows that excessive TiO_2 may reduce the internal cohesion of the mixture and thus create microstructural defects. Overall, these findings suggest that TiO_2 provides a consistently positive effect regarding tensile strength.

FLEXURAL STRENGTH TESTING

Flexural Strength Test evaluates the bending resistance of concrete. The beam was placed on two supporting rollers with a span of 400mm.Load was applied gradually until failure. The flexural strength can be determined using the formula.

$f_b = 3pa/bd^2$ (a<13.3cm)

$f_b = pl/bd^2$ (a>13.3cm)

TYPE OF TEST (FLEXURAL STRENGTH TEST)	CONTROL SAMPLE (MPa)	1% TiO_2 (MPa)	3% TiO_2 (MPa)	5% TiO_2 (MPa)
7 days	2.27	3.12	3.31	2.99
14 days	2.98	4.08	4.33	3.91
28 days	3.5	4.8	5.1	4.6

Table: 3 Flexural strength result

The addition of 1% TiO_2 increases the flexural strength compared to the control from 3.7 MPa to 4.9 MPa at 7 days (37% increase) and 3.5 MPa to 4.8 MPa at 28 days (37% increase), suggesting that TiO_2 may promote improved bonding and densification of the concrete matrix. The 3% TiO_2 mix exhibits the most beneficial impact on flexural strength, achieving a maximum value of 5.1 MPa at 28 days (46% higher than control). Therefore, for this study, the effective dosage for maximum flexural performance is at 3% TiO_2 . However, with a dosage of 5% TiO_2 , the bending strength starts to decline, with the 28-day strength dropping to 4.6 MPa. This indicates that too much TiO_2 may disrupt the hydration rate and introduce weaknesses into the microstructure. The results illumine that while TiO_2 is beneficial for improving flexural strength, 3% is the most beneficial dosage and excessive doses may diminish the structural benefit of adding TiO_2 to cement.

The reduction in strength seen at 5% TiO_2 in concrete is attributed to a series of interdependent factors that impact hydration, microstructure, and particle distribution. At higher percentages, TiO_2 has been shown to impede cement hydration by adsorbing water and delaying the development of essential hydration products, such as calcium silicate hydrate (C-S-H), which can contribute to the potency of strength gain. This all culminates in a less-than-complete hydration and yield a weaker bond in the hydrated cement matrix. Furthermore, an excess of TiO_2 promotes porosity and removes workability, as compacted values were observed to be difficult to achieve, which allowed for voids and micro-cracks to compromise the structure. Additionally, particle agglomeration is a significant issue, and TiO_2 nanoparticles would not properly distribute but clump together, therefore are unable to perform optimally in terms of filling pores and weakening the bond at points of contact with concrete. Ultimately, those agglomerates would be seen as points of stress concentration to the concrete, disrupting compressive and flexural strength. An overabundance of TiO_2 can also alter the rheologies of the mix, with improved segregation and improper distribution of cementitious components in the mix. Thus, lower amounts (> 1-3% TiO_2) ultimately exhibit stronger attributes in the concrete, with prompter microstructure and photocatalytic effects, whereas a percentage like 5% disrupts these effects where it would injure the mechanical properties of the concrete. An optimal amount of TiO_2 must be specifically designed, which is often around 3% to enhance and obtain strength while decreasing structural integrity of the specimen.

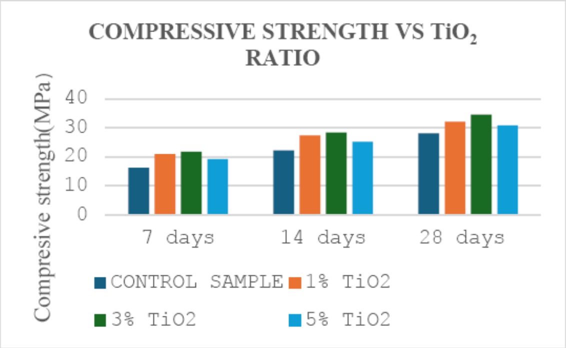

Figure :4a

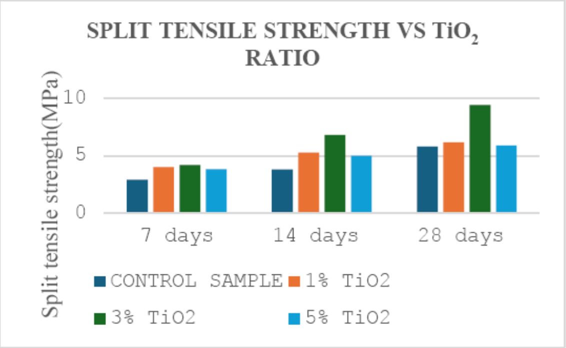

Figure :4b

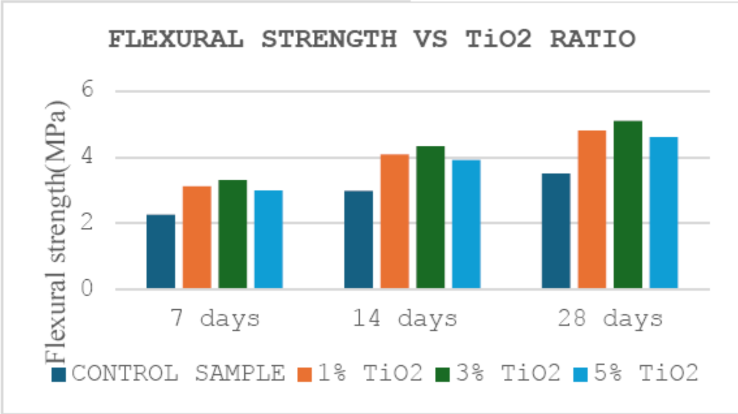

Figure :4c

Figure: 4 Graphical representation of strength Vs TiO_2

The figure 4a shows how adding Titanium Dioxide (TiO_2) affects the compressive strength of a material over 7, 14, and 28 days. Initially, the control sample (without TiO_2) has the lowest strength, while adding TiO_2 improves it. At 7 days, the 3% TiO_2 mix performs best, reaching 21.78 MPa, but at 14 and 28 days, its advantage becomes even clearer, achieving the highest strength of 34.58 MPa by the end of the test. Interestingly, while 1% and 3% TiO_2 consistently boost strength, the 5% TiO_2 sample does not perform as well as expected, showing lower values compared to the 3% mix. This suggests that beyond a certain point, too much TiO_2 may negatively impact the material's structural integrity, possibly due to issues like particle dispersion or weak bonding. Overall, the findings indicate that 3% TiO_2 is the optimal amount for maximizing compressive strength, making it a promising choice for applications requiring stronger, more durable materials.

The figure 4b illustrates how adding Titanium Dioxide (TiO_2) influences the split tensile strength of a material over 7, 14, and 28 days. Initially, the control sample (without TiO_2) has the lowest tensile strength, starting at 2.93 MPa at 7 days, while the TiO_2 -enhanced samples show better performance. Among them, 3% TiO_2 achieves the highest strength across all curing periods, reaching 4.03 MPa at 7 days, 6.82 MPa at 14 days, and an impressive 9.44 MPa at 28 days. While 1% and 5% TiO_2 also improve tensile strength compared to the control, their performance is noticeably lower than the 3% mix, suggesting that an excessive TiO_2 ratio may lead to diminishing returns. The 5% TiO_2 sample does not perform as well as 3% TiO_2 , reinforcing the idea that too much TiO_2 may impact material properties negatively. Overall, 3% TiO_2 emerges as the optimal ratio, significantly enhancing tensile strength, making it a promising option for applications where improved tensile performance is essential.

The figure 4c presents the effect of Titanium Dioxide (TiO_2) on the flexural strength of a material over 7, 14, and 28 days. Initially, the control sample (without TiO_2) has the lowest strength, measuring 2.27 MPa at 7 days. The addition of TiO_2 enhances flexural strength, with 3% TiO_2 consistently showing the best performance across all curing periods, reaching 3.31 MPa at 7 days, 4.33 MPa at 14 days, and 5.1 MPa at 28 days. The 1% and 5% TiO_2 samples also exhibit improvements compared to the control, but they do not match the strength achieved by the 3% mix. The 5% TiO_2 sample performs better than the control but slightly lower than 3% TiO_2 , indicating that excessive TiO_2 might not be beneficial for flexural strength. Overall, 3% TiO_2 emerges as the optimal ratio for maximizing flexural strength, making it a suitable choice for applications requiring enhanced bending resistance and durability.

VIII. CONCLUSION

From strength testing, The TiO_2 ratio of 3% has shown maximum compressive strength, split tensile strength and flexural strength. Whereas the TiO_2 ratio of 5% had a slight decrease in strength and resistance due to particle agglomeration, affecting concrete microstructure.

Addition of titanium dioxide to the concrete has proved that if 1% and 3% TiO_2 is added, we see improved compressive strength at 28 days. Split tensile strength testing has shown that TiO_2

improves tensile properties up to a certain limit. 3% TiO_2 maximized flexural strength without affecting workability. 3% TiO_2 provides the best balance of mechanical strength and environmental benefits. From photocatalytic activity testing, the methylene blue test has proven the photocatalytic nature of the TiO_2 infused concrete. Hence, Photocatalytic concrete is effective in air pollution control, making it a sustainable material for urban infrastructure. Several projects have effectively used photocatalytic concrete, they were able to demonstrate reductions in NOx emissions, even achieving reductions in targeted air pollution of 25–45% in certain cases.

Photocatalytic concrete that is doped with titanium dioxide (TiO_2) has previously shown the ability to reduce air pollution and increase structural durability. Future study and large-scale field application, however, can improve both performance and economy. As our society shifts toward sustainable construction and smart building principles, the use of innovative materials or applications in photocatalytic concrete could change the landscape of infrastructure. The future could include the dopation of hybrid nanomaterials like graphene or carbon nanotubes and thus enhancing the photocatalytic activity. Also, the use of smart technologies, characterized by IoT-based pollution monitoring and AI-based optimization models, enable new tracking and monitoring of photocatalytic concrete performance with real-time alterations based on environmental conditions. Large-scale scanning of TiO_2 doped concrete in highway, tunnel, and urban settings could have significant impact on the reduction of Nox emissions and improvement of air quality in dense cities.

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