PERFORMANCE ANALYSIS OF SUSTAINABLE PHOTOCATALYTIC CONCRETE: EVALUATING TITANIUM DIOXIDE AND ZINC OXIDE.

Dr B V Mathew[1], Krishnapriya S, Chithranjali CJ, Rohith R[4], [5], Roshan KK[6]

[1] Head of the Dept, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.
[2]Assistant Professor, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.
[3]UG Scholar, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.
[4]UG Scholar, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.
[5]UG Scholar, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.
[6]UG Scholar, Dept. of Civil Engineering, Ahalia School of Engineering and Technology, Kerala, India.

---***---

Abstract

Sustainable construction materials play a crucial role in mitigating environmental challenges. This study evaluates the photocatalytic efficiency and mechanical performance of Titanium Dioxide (TiO_2) and Zinc Oxide (ZnO) in cementitious composites. A total of 72 concrete cubes with 0%, 1%, 2%, and 3% TiO_2 and ZnO were prepared and subjected to compression tests, photocatalytic efficiency analysis, and air purification assessments. The results indicate that TiO_2 has superior photocatalytic properties, whereas ZnO contributes to enhanced mechanical strength. This study highlights the potential application of these materials in sustainable construction for air purification and self-cleaning functionalities. By integrating these photocatalytic materials into cementitious composites, the built environment can actively contribute to pollutant degradation and improve urban air quality. Future work should focus on optimizing material composition to maximize efficiency and cost-effectiveness for commercial construction. Further investigation is necessary to assess the economic implications of large-scale application and to analyze the long-term sustainability of these materials under different environmental conditions.

***Key Words*: Photocatalytic concrete, titanium dioxide (TiO_2), zinc oxide (ZnO), sustainable construction materials, self-cleaning properties, nano-engineered concrete, UV-activated materials, green infrastructure, environmental remediation, smart concrete technology, advanced cementitious composites, eco-friendly construction**.

1. INTRODUCTION

As the global population continues to urbanize, cities face increasingly complex environmental challenges, particularly with regards to air pollution, energy consumption, and the urban heat island effect. Concrete, as one of the most widely used construction materials in urban infrastructure, has a significant environmental footprint due to its production process, which releases large amounts of carbon dioxide (CO_2) into the atmosphere. However, recent advancements in sustainable construction materials, such as photocatalytic concrete, have the potential to revolutionize the way we approach urban development, making it more eco-friendly and efficient. By assessing the effects of two widely used photocatalytic agents—zinc oxide (ZnO) and titanium dioxide (TiO_2)—on the concrete's capacity to break down pollutants, enhance air quality, and preserve its mechanical qualities over time, this study focuses on the performance analysis of sustainable photocatalytic concrete.

Using light energy to speed up a chemical reaction that converts poisonous compounds into non-toxic ones is known as photocatalysis. Particularly TiO_2 is well known for having potent photocatalytic qualities that are triggered by ultraviolet (UV) light. Reactive oxygen species (ROS), which are produced as a result of this activation, have the ability to break down a variety of dangerous contaminants such as volatile organic compounds (VOCs), sulfur oxides (SOx), and nitrogen oxides (NOx). Similar environmental advantages can be obtained by including zinc oxide (ZnO), another strong photocatalytic material, into concrete. ZnO also exhibits promise in the degradation of contaminants. By decreasing air pollution, the addition of these components to concrete improves the structural qualities of the material while also improving the environmental quality of urban areas.The hunt for novel materials that can solve these issues has been fueled by the growing worries about air quality, particularly in urban areas. A possible answer is provided by the combination of concrete and photocatalytic compounds. The concentration of NOx in the air, a primary cause of smog and acid rain, may be decreased by concrete surfaces treated with photocatalytic chemicals. Concrete surfaces coated with ZnO or TiO_2 react with sunshine to break down nitrogen oxides in the air and transform them into innocuous chemicals like nitrates. In addition to improving air quality, this procedure helps reduce the urban heat island effect, which is the phenomenon wherein traditional materials like concrete and asphalt absorb and reradiate heat, raising temperatures in constructed areas.

The research will focus on the following key aspects: 1.**Pollutant Degradation Efficiency**: The ability of TiO_2 and ZnO-infused concrete to break down pollutants including NOx and VOCs will be evaluated under controlled UV light exposure that replicates real-world conditions. The degradation efficiency over a specified time period will be measured to establish each material's photocatalytic capability.

2. **Mechanical Properties**: An analysis will be conducted to determine how TiO_2 and ZnO affect the mechanical strength, workability, and durability of concrete. It is crucial to make sure that adding these components doesn't weaken the concrete's structural integrity.

Furthermore, this study will compare the costs, environmental impact, and overall efficiency of TiO_2 and ZnO in photocatalytic concrete applications. The goal is to provide practical recommendations for the use of these materials in the construction industry, particularly for urban infrastructure, which has the potential to significantly reduce pollution levels and improvethe sustainability of built environments.

The findings of this study should support the broad use of photocatalytic concrete in practical applications and add to the expanding corpus of information on sustainable building materials. Cities may improve the visual appeal of their buildings and proactively improve environmental health and air quality by incorporating ZnO and TiO_2 into concrete. The creation of photocatalytic concrete is an important step toward the creation of cleaner, more sustainable urban areas, as environmental degradation and climate change remain major global concerns. In order to facilitate the adoption of greener building technologies that support sustainability and environmental stewardship, this study attempts to close the gap between laboratory research and real-world implementation.

2. MATERIALS AND METHODS

This study examines the usage of ZnO and TiO_2 in cementitious composites, evaluating their mechanical and photocatalytic capabilities in a controlled laboratory setting. The work mimics actual environmental exposure, including the interaction of UV light with the deterioration of air pollutants. The results will be useful in metropolitan settings where air pollution is a major issue. To ensure adaptability for wider deployment in various geographic locations, more testing in a range of climatic situations will be conducted to evaluate durability and efficiency under differing environmental stressors.

2.1 Methodology

Material Identification and Collection: Consistent material quality was ensured by obtaining high-purity TiO_2 and ZnO from reputable sources.

Mixing and Casting: Concrete samples were prepared with TiO_2 and ZnO in varyingpercentages (0%, 1%, 2%, 3%) to analyze their respective effects

Testing Procedures:

Mechanical Testing: To assess the samples' structural integrity, compressive strength tests were carried out utilizing a universal testing apparatus.

Photocatalytic Testing: Under UV light, the rate at which CO2, NOx, and VOCs degraded was determined.

Air Purification Analysis: CO2 reduction tests were performed in a controlled chamber to assess the real-time effectiveness of the samples in improving air quality.

3. RESULTS AND DISCUSSIONS

3.1 Slump Test

Table 1. Slump Test values

Sample	Slump value(mm)
0%	10
TiO2 1%	7
TiO2 2%	5
TiO2 3%	4
ZnO 1%	6
ZnO 2%	5
ZnO 3%	4

The concrete mix is rigid and appropriate for uses such as footings, pavements, and reinforced structures with low water-cement ratios, according to the slump test findings, which range from 4 to 10 mm. A somewhat constant blend is suggested by the small range in values. Water content or admixtures may need to be changed if greater workability is required.

3.2 Compressive Strength Analysis

Table 2. Compressive strength

Samples	Area(mm2)	Load(kN)		Compressive srength (N/mm2)	
		7 days	28 days	7 days	28 days
Normal concrete	22500	470	570	20.88	25.33
	22500	480	580	21.33	25.77
	22500	460	600	20.44	26.66
Titanium dioxide 1/%	22500	490	600	21.77	26.66
	22500	490	610	21.77	27.11
	22500	490	600	21.77	26.66
Titanium dioxide 2/%	22500	510	620	22.66	27.55
	22500	500	640	22.22	28.44
	22500	500	650	22.22	28.88
Titanium dioxide 3/%	22500	480	610	21.33	27.11
	22500	480	600	21.33	26.66
	22500	480	590	21.33	26.22
Zinc oxide 1/%	22500	490	600	21.77	26.66
	22500	490	620	21.77	27.55
	22500	500	610	22.22	27.11
Zinc oxide 2/%	22500	490	610	21.77	27.11
	22500	490	600	21.77	26.66
	22500	480	580	21.33	25.77
Zinc oxide 3/%	22500	450	560	20	24.88
	22500	440	550	19.55	24.44
	22500	460	550	20.44	24.44

Table 3. Showing best maximum output

Samples	Area(mm2)	Load (kN)	Compressive strength (N/mm2)	Average
		28 days	28 days	
Normal concrete	22500	570	25.33	25.92
	22500	580	25.77	
	22500	600	26.66	
Titanium dioxide 2/%	22500	620	27.55	28.29
	22500	640	28.44	
	22500	650	28.88	
Zinc oxide 1/%	22500	600	26.66	27.10
	22500	620	27.55	
	22500	610	27.11	

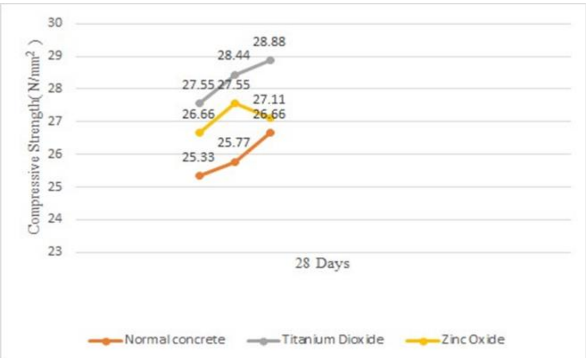

Figure 1. Graph showing Compressive Strength vs days

1. Improvement in Strength: The highest strength was observed with 2% Titanium Dioxide, making it the most effective among the tested samples.1% Zinc Oxide also performed well, indicating its potential as a concrete strength enhancer.

2. Optimal Additive Percentage: Titanium Dioxide 2% is the most effective; beyond this, strength slightly decreases.Zinc Oxide 1% gives the best result, while increasing to 3% leads to a decline in strength.

3. Effect of Excessive Additives: Increasing the percentage beyond the optimal value leads to a decrease in strength, likely due to changes in the internal microstructure or reduced bonding efficiency. For improved concrete strength, 2% Titanium Dioxide or 1% Zinc Oxide can be considered optimal. These additions enhance performance without compromising structural integrity.

3.3 Photocatalytic Efficiency

Figure 2. Normal cube

Figure 3. Concrete cube with TiO_2

Figure 4. Concrete cube with ZnO

The result show that adding zinc oxide (ZnO) and titanium dioxide (TiO_2) to concrete greatly increases its photocatalytic activity.

After an hour, the methylene blue dye was still visible, indicating that normal concrete had no discernible photocatalytic action. The dye almost vanished in an hour, demonstrating the high photocatalytic activity of concrete containing zinc oxide and titanium dioxide. Increased TiO_2 and ZnO dosages enhanced the self-cleaning effectiveness, allowing the modified concrete to effectively decompose organic contaminants in the presence of sunshine.

TiO_2 and ZnO are added to concrete to improve its self-cleaning qualities and environmental sustainability, which makes it appropriate for uses requiring both aesthetically pleasing durability and pollutant resistance.

3.4 Self-Cleaning Performance

According to the study, adding zinc oxide (ZnO) and titanium dioxide (TiO_2) to concrete greatly improves its ability to clean itself.

1. Normal concrete did not exhibit any discernible self-cleaning properties due to the lack of photocatalytic elements.

2. The self-cleaning performance of concrete treated with titanium dioxide (TiO_2) increased as the TiO_2 level increased from 1% to 3%.

3. At greater dosages, zinc oxide (ZnO) modified concrete demonstrated a high level of self-cleaning efficiency, demonstrating its high effectiveness.

When exposed to sunshine, concrete treated with TiO_2 and ZnO may efficiently decompose organic contaminants, making it a low-maintenance and sustainable building material, particularly in metropolitan areas where pollution and discoloration are common.

3.5 Air Pollution Test

In this experimental setup, a sealed glass chamber was created to provide a controlled environment for testing. To provide reliable readings, photocatalytic concrete cubes were positioned inside the chamber and a sensor was installed. To simulate air pollution, a particular polluting gas was supplied, and the chamber was promptly sealed to stop leaks. An MQ-135 air quality sensor was employed to measure the concentration of the gas. To track variations in gas intensity, readings were made at various intervals. This made it possible to assess how well the photocatalytic concrete degraded contaminants over time.

Figure 5. Experimental setup for air pollution test

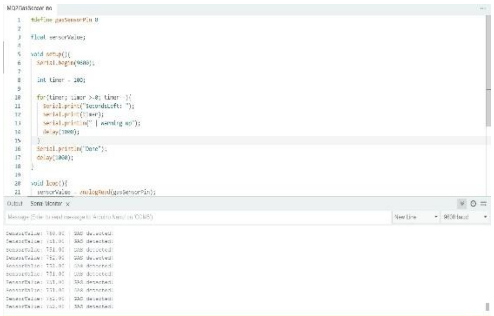

Figure 6. Output of Gas Sensor

Table 4. Output values of Gas Sensor

Sample	Time(Minutes)	Gas Concentration (ppm)
Chamber with Gas only	0	751
	30	740
	60	735
Chamber with Normal Concrete	0	776
	30	759
	60	732
Chamber with Titanium Dioxide	0	725
	30	674
	60	614
Chamber with Zinc Oxide	0	717
	30	677
	60	636

1.Gas Only: Natural dispersion is indicated by a slight drop from 751 ppm to 735 ppm.

2. Normal Concrete: The gas concentration slightly decreases from 776 ppm to 732 ppm, but there is no noticeable gas reduction.

3. TiO_2 Concrete: Showed effectiveness in air filtering, notably decreasing from 725 parts per million to 614 parts per million.

4. ZnO Concrete: Decrease from 717 ppm to 636 ppm, efficient, but not as good as TiO_2.

In conclusion, the test findings show that adding zinc oxide and titanium dioxide to concrete enhances its air purifying properties. Concrete with titanium dioxide has a better gas reduction effectiveness than concrete containing zinc oxide.

Table 5. Percentage Reduction (Based on Time Interval)

Sample	0 min	30 min	60 min
Chamber with Gas only	0.00%	1.46%	2.13%
Chamber with Normal Concrete	0.00%	2.19%	5.67%
Chamber with Titanium Dioxide	0.00%	7.03%	15.31%
Chamber with Zinc Oxide	0.00%	5.58%	11.30%

- Percentage Reduction

$$=\frac{Initial\ Value - Current\ Value}{Initial\ Value} \times 100$$

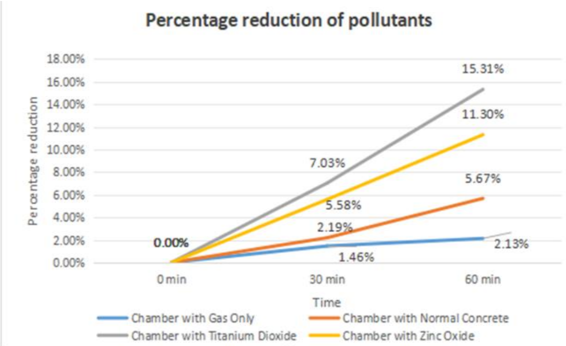

Figure 7. Percentage reduction of pollution

1.Gas Only Chamber : shows extremely little decrease over time, suggesting that natural dissipation has very little effect.

2.Normal Concrete : limited ability to reduce gas, with a slight improvement at 30 minutes (2.19%) and 60 minutes (5.67%).

3.Titanium Dioxide : A considerable reduction at 30 minutes (7.03%) and a remarkable reduction at 60 minutes (15.31%) showed its excellent photocatalytic efficiency.

4.Zinc Oxide : Moderate reduction at 30 minutes (5.58%) and reasonable reduction at 60 minutes (11.30%), show decent but lower efficiency compared to TiO_2.

Conclusion: Since titanium dioxide consistently exhibits the biggest percentage reduction over time, it is the most effective material for air purification out of all the samples that were studied.

Zinc oxide likewise shows a noticeable decline, however it lags behind titanium dioxide. Ordinary concrete has very little effect.

4. CONCLUSIONS

The integration of TiO_2 and ZnO in concrete enhances sustainability by providing air purification and self-cleaning properties.ZnO provides better mechanical qualities, however TiO_2 performs better in photocatalytic applications. Combining these resources offers a well-rounded strategy that capitalizes on each one's advantages. The use of these materials in environmentally friendly building is encouraged by these findings.

The study also demonstrates that adding TiO_2 and ZnO to cementitious composites can be extremely important for pollutant degradation and urban air purification. These materials' long-term efficiency is guaranteed by their longevity, which makes them suitable for widespread use in smart and green cities. By striking a balance between mechanical strength and photocatalytic activity, hybrid formulations of ZnO and TiO_2 exhibit encouraging potential to improve the overall efficacy of sustainable building techniques.

From an economic perspective, it is best to integrate these materials in building in a way that maximizes benefits and minimizes expenses. In order to ensure affordability for large-scale applications, future research should concentrate on creating economical synthesis techniques for ZnO and TiO_2. To ascertain the materials' long-term sustainability, studies should also examine the effects of extended exposure to these substances on the ecosystem.

Additional research ought to examine how different environmental elements, such temperature swings and air quality, affect the functionality of TiO_2 and ZnO composites. The creation of novel strategies, such as doping methods or formulations for nano composite materials, may improve their functionality and suitability for use in building.
All things considered, the study emphasizes how TiO_2 and ZnO-based photocatalytic materials can revolutionize environmentally friendly building and air purification. Through the incorporation of these materials into contemporary infrastructure, cities may actively lower air pollution and promote a more sustainable and healthy environment

REFERENCES

[1] Chen, Kailun, et al. "Advancing photocatalytic concrete technologies for design, performance and sustainable futures." Advanced Nanocomposites (2024).
[2] Adebanjo, Abiola Usman, et al. "Effect of nano sized titanium dioxide and zinc oxide as antimicrobial agents on early compressive strength of high-

performance concrete." E3S Web of Conferences. Vol. 488. EDP Sciences, 2024.

[3] Dhanapal, Jegatheeswaran, et al. "Eco-Friendly Concrete Solutions: The Role of Titanium Dioxide Nanoparticles in Enhancing Durability and Reducing Environmental Pollutants-A Review." J. Environ. Nanotechnology 13.3 (2024): 332-344.

[4] .Farooq, Miss Sofian, Miss Mehreena Manzoor, and Mr Tajamul Islam Zargar. "Self-cleansing of rigid pavements by using flyash and titanium dioxide." (2024).

[5] Nematov, Dilshod. "Titanium dioxide and photocatalysis: A detailed overview of the synthesis, applications, challenges, advances and prospects for sustainable development." Applications, Challenges, Advances and Prospects for Sustainable Development (October 02, 2024) (2024).

[6] .Mostafa, Fatma El-Zahraa M., et al. "Analyzing the effects of nano-titanium dioxide and nano-zinc oxide nanoparticles on the mechanical and durability properties of self-cleaning concrete." Materials 16.21 (2023): 6909.

[7] Rawat, Garima, Sumit Gandhi, and Yogesh Iyer Murthy. "Durability aspects of concrete containing nano-titanium dioxide." ACI Mater. J 120 (2023): 25-36

[8] Ramadan, M., et al. "Exploration of mechanical performance, porous structure, and self-cleaning behavior for hydrothermally cured sustainable cementitious composites containing de-aluminate metakaolin waste and TiO2 nanoparticles." Journal of Materials Research and Technology 25 (2023): 3998-4019.

[9] .Khannyra, Souad, et al. "Self-cleaning durability assessment of TiO2/SiO2 photocatalysts coated concrete : effect of indoor and outdoor conditions on the photocatalytic activity." Building and Environment 211 (2022): 108743.

[10] Amor, Fouad, et al. "Effect of TiO2 and ZnO powder mixtures on mechanical and photocatalytic performance of high performance concrete." (2022).

[11] .Kelechi, A. Hilary, et al. "Design of a low-cost air quality monitoring system using arduino and thing speak." Compute. Mater. Contin 70 (2022): 151-169.

[12] Rebello, Nalini, et al. "Development of Arduino Prototype for the Detection of Fire, Smoke, and Carbon Monoxide from Open Waste Burning." International Conference on Civil Engineering Trends and Challenges for Sustainability. Singapore: Springer Nature Singapore, 2021.

[13] Hamidi, Fatemeh, and Farhad Aslani. "TiO2-based photocatalytic cementitious composites: Materials, properties, influential parameters, and assessment techniques." Nanomaterials 9.10 (2019): 1444.

[14] Loh, K., C. C. Gaylarde, and M. A. Shirakawa. "Photocatalytic activity of ZnO and TiO2 'nanoparticles' for use in cement mixes." Construction and Building Materials 167 (2018): 853-859.

[15] Siwińska-Stefańska, Katarzyna, et al. "TiO2-ZnO binary oxide systems: Comprehensive characterization and tests of photocatalytic activity." Materials 11.5 (2018): 841.