International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 09 Issue: 04 | Apr 2022 www.irjet.net p-ISSN: 2395-0072

Experimental Study of Photocatalytic Cement: New Approach to Reduce the Air Pollutants-A Review

Maheraj Harishkumar Rathod[1], Dr. R. L. Patel[2], Dr. J. R. Pitroda[3]

[1]M.Tech. (Civil) Construction Engineering and Management, BVM Engineering College, Vallabh Vidyanagar, Gujarat
[2]Associate Professor, Civil Engineering Department, BVM Engineering College, Vallabh Vidyanagar, Gujarat
[3]Associate Professor, PG Coordinator Construction Engineering and Management, Civil Engineering Department, BVM Engineering College, Vallabh Vidyanagar, Gujarat

---***---

Abstract - Interlacement Group created titanium dioxide (TiO_2), a proprietary cement content that is produced in United States by Essroc, a part of Interlacement Company. TX Active properties are photocatalytic materials that utilises UV photon energy to oxidize the vast majority of organic and inorganic substances. TX active product (TiO_2) removes pre-existing air pollutants from the environment, which are then washed away by rain. As a consequence, this new kind of Cement could be used in a variety of applications make concrete and drywall, reducing maintenance costs and providing a cleaner environment. This research demonstrates the idea of photocatalysis and its use in concrete, in addition to findings of research in the lab focusing on air purification. This type of material can be used in a variety of ways in industrial locations is not only environmentally benign but also beneficial to society.

Key Words: Air Purification, Self-Cleaning Surface, Titanium dioxide (TiO2), Photocatalysis Martials, Cement, Echo Friendly.

1. INTRODUCTION

A new and innovative approach to cut back the air pollutant in our area with the assistance of TX active (TiO_2) martial. within the present-day, pollution may be a major problem for us. On a day to day, industrial and military activities generate tons amount of organic and inorganic pollutants which are polluted our atmosphere, rivers, soil, and oceans. pollution abatement strategies are essentially supported by electrostatic filters and membranes to cut back fine suspension particulate matters, chemical derivatives, mutagens, and materials derived out of catalytic processes to get rid of air pollutants like CO, Sox, NOx, Carbon Partials, vaporized organics substances.

When a photocatalyst is present in concrete, it removes organic materials like dirt, mold, algae, bacteria, allergens, air pollutants, smoke, tobacco, etc. within the presence of sunshine. The catalyzed compounds break down into the water, carbonic acid gas, Nitrated, Oxygen, Sulfates that are either beneficial or have a comparatively minor effect on the environment. this sort of concrete having a photocatalyst in it called self-cleaning concrete, which could be a green construction material.

A photocatalytic cement together with its structural ability like a standard cement could be a strong depollutant. the pigment is that the photocatalyst material mixed with concrete. within the presence of UV light, titanium martial starts the method to wash the pollutant on the surface of the photocatalyst and reacts with external substances to get rid of organic compounds. The pollutants products can easily be washed with water. Rain can easily remove the pollutants products and also the building looks clean and delightful as a replacement one. the oxide will be mix with all sorts of cement, concrete, including plaster.

There are Various types photocatalysts such as ZINC OXIDE (ZnO), ZINC SULFIDE (ZnS), CADMIUM SULFIDE (CdS), STRONTIUM PEROXIDE (SrO_2) and TUNGSTEN TRIOXIDE (WO_3) have been used for treatment of air pollutants. The most popular among them is Titanium dioxide (TiO_2) due to its low cost, high stability, environmental friendliness. It is a semiconductor which is used for photo-induced redox reactions for degradation of Volatile organic compounds (VOCs).

Titanium dioxide (TiO_2) has been widely used as a photocatalyst in many environmental and energy applications due to its efficient photoactivity, high stability, low cost, and safety to the environment and humans.

1995-1998	R&D program on photocatalysis in cement-based systems First (Italian) patent application (1996) First publications First concrete trials
1999-2001	First project: "Dives in Misericordia" Church, Rome "Cité de la Musique et des Beaux Arts", Chambéry Rhodamine-B (discoloration) test (CSTB, France)
2002-2005	Start of PICADA Project (2002-2005) Street canyon experience Pilot depollution tests in Segrate, Calusco, Bergame Launch of first version of photocatalytic cement (TX Millennium®) Development of Laboratory Test methods
2006-2011	Launch of TX Active® Cements (Italy, France, Spain, USA, ...) Publication of first UNI standards (Italy) "Umberto I" Tunnel (Rome) (2007) License agreement with Heidelberg Cement Group (2008) Projects: *i.lab*, Bergamo - Vodafone Village, Milan

Fig.1. A short history on Photocatalytic cements

1.1 Need of Study:

Many cities around the world struggle with increasing car exhaust fumes, industrial smog and other forms of air pollution. Together they produce a mix of nitrogen oxides, volatile organic compounds, carbon monoxide, sulfur oxides. So, we use a TX Active's properties are photocatalytic components that use the energy from ultraviolet rays to oxidize most organic and some inorganic compounds. Air pollutants that would normally result in discoloration of exposed surfaces are removed from the atmosphere by the components, and their residues are washed off by rain.

This new cement can be used to produce concrete and plaster products that save on maintenance costs while they ensure a cleaner environment.

1.2 Objective of Study:

- The major objective of this project was to review of the available results of existing research on the use of photocatalysts for reduction of air pollutants.
- To compare the mechanical and physical properties of photocatalytic concrete and standard concrete.
- To compare the benefits between photocatalytic concrete and standard concrete.
- To carry the cost-benefit analysis of photocatalytic concrete and standard concrete.

2. Study of Photocatalytic Cement

2.1 Photocatalytic products for air cleaning

G. Hu¨ sken st al. (2009) The characteristics and evaluation of concrete products with photocatalytic active TiO_2 for air purification are the focus of this study. Commercial & self-developed mortars were also tested. A suitable test setup was established to examine the air-purifying capabilities of these cements, which is based just on NO degradation as stated in ISO 22197-1:2007. The set-up is used to investigate the variables that influence the degradation of NO. Because of large the number of influencing factors elements as well as the partially significant impact on measurement, a single test standard with similar boundary conditions is required. An acceptable process for determining the quality of concrete is presented based on these findings and also needs in the research and requirements.[1]

M.M. Ballari et al. (2010) In very polluted areas, the use of photocatalysts conventional concrete Tio2 in urban highways is an approach for improving air quality. A broad range of air pollutants can be degraded, such as nitrous oxide and nitrogen dioxide, which are mostly emitted by automobiles, using this approach. The photodegradation of nitric oxide is formed dioxide is investigated in the present study, as well as environmental processes involving nitrous oxides and solar radiation. Furthermore, the impact of various system variables such as input concentration of pollutants, humidity levels, and irradiance is thoroughly investigated.[2]

Thomas Martinez et al. (2011) This study looks at how a photocatalysts TiO2 nanoparticles embedded in a polymer matrix-based coating are used in an oxidation process may break down nitric oxide in the air. The flow-type reactor used in the experiment was based just on ISO 22197-1 standard. Final products included nitrogen oxides in the gaseous state and nitrogen atoms adsorbed on the photocatalysts surface. The coating formulation, substrate type, and starting nitric oxide concentration are all factors to consider, contaminated airflow, and humidity were all investigated as factors affecting oxidant degradation efficiency. The application of cement as a foundation increased the photocatalytic properties of reduces the thickness of coatings the formation of gas nitrogen oxides as an afterthought as compared to glass.[3]

Ming-Zhi Guoet al. (2013) On a global scale, the amalgamation of TiO_2 nanoparticles with concrete mixture to materials produce viable photocatalytic has gotten people's attention. A wide variety of admixtures will be applied to photocatalytic products in practical applications. The present study looked at how different factors affected the photocatalysts nitrogen dioxide removal efficiency of photocatalytic products. The researchers discovered that using glass culets instead of sand improved the photocatalysts nitrogen oxides percentage removal of concrete surface layers. Those cement surface layers with glass culets had a little better nitrogen dioxide removal capability than those with brilliant green glass culets. Furthermore, as compared to those manufactured with white cement and metakaolin, the layers of concrete on the surface formed utilizing white cement and crushed granulated blast furnace slag showed a somewhat higher photocatalytic nitrogen dioxide removal. In addition, incorporating different colored pigment into to the concrete cover layers pricing was drastically reduced of nitrogen dioxide removal. In terms of photocatalytic nitrogen dioxide removal, additionally it was discovered that intense abrasion caused there is no obvious degradation to the TiO_2 surface layers of intermixed concrete.[4]

KOTRESH K.M et al. (2014) The application of TiO_2 nanoparticles photocatalytic activity to cement concrete offers an expense strategy for all at the same trying to obtain: self-cleaning of building surfaces, retardation of base layer going to age, and air quality mitigation using sunlight, oxygen in the atmosphere, and water moisture or rain water. For two samples tested in concretes and mortars, performance in degrading inorganic Compounds, Rhodamine b, capacity to retard organic ageing caused by methods including such soiling as well as erosion, performance in oxidizing nitrous oxides toxic gases are presented, along with an understanding into the fundamental science of TiO_2 one day reactions responsible, are discussed in this paper.[5]

Elia Boonen et al. (2016) Photocatalytic building materials have been found to be a viable choice for NOx and VOC pollution treatment. However, issues and worries regarding the air purifying feature's long-term sustainability have been raised. BRRC is doing pre-normative research in this area as a first step toward evaluating how long photo-active air-purifying solutions will endure. This is accomplished by using standardized photocatalytic activity testing methodologies to combine and improve on existing durability evaluations for cement-based composites. The early findings of the research are reported here, including a prohibition on accelerated ageing experiments and the validation of ageing techniques that are suitable when used in combination with a standardized NOx elimination test for photocatalysts. Finally, suggestions are made for future study that includes photocatalytic building materials durability assessments.[6]

Julien G. Mahy et al. (2018) This research produced six distinct photocatalyst coatings on Tio2 that can be used on cement-able roadways. These coatings are meant to break breakdown pollutants created by vehicle traffic, such as nitrogen oxides. The coatings are made using a sol-gel process in an industrial or aqueous solution, or by functionalizing commercialized Titanium dioxide particles with hydroxybenzoic acid. Concrete slabs, brushing or uncovered aggregates roads cement, or brushed or exposed aggregates for roadwork are the three concrete substrates that all these solutions should be dipped or spray over. Each step has focused on the improvement of TiO_2 synthesis, which can now be easily repeated on a larger scale. Photocatalytic analysis on nitrogen decomposition, physical resistant studies, and cold cycle resilience in the lack of de-icing salts were used to characterize the samples. All other samples showed a NOx degradation of 10 to 45 percent, with the exception of those made by using sol-gel organic approach. In high resistance, the TiO_2 nanoparticles coating, which would be generated by surface functionalization Tio2, is indeed the best. The results show that nanocrystalline TiO_2 is plentiful on the sample's upper surface and also that the covering has a satisfactory TiO_2 loading. The qualities of titanium dioxide nanoparticles imply that they might be effective in road uses. [7]

R. Sakthivel et al. (2018) Pollution is a substantial risk factor for a variety of illnesses and health disorders linked to pollution. Self-cleaning concrete with technology for reducing NOX, SO_2, CO_2, and VOCs in the air from automotive traffic on roadways, industrial activity, and the urban environment. To minimize air pollution, photocatalytic elements are employed in ordinary concrete for urban structures and road pavements. Titanium dioxide, a white powder, is the major photocatalytic ingredient. Titanium dioxide is activated by sunlight or UV lights, and it decomposes external impurities on the concrete's surface, which are then washed away by wind and rain. Laboratory tests are used to track the presence and removal of contaminants. The self-cleaning concrete's workability and compressive strength are also examined. As a consequence, air pollution (also known as smog) is reduced, and self-cleaning activity occurs. Because of its widespread use, seslf-cleaning concrete contributes to a pollution-free environment and reduces global warming.[8]

Heyang Si et al. (2021) Use of such Photocatalyst in cement replacement is being studied as a viable strategy for reducing nitrogen oxide pollution. However, the impacts of the submission procedure on photocatalysts and catalytic lifespan should be extensively explored before widespread adoption. The photo electrocatalytic system was compared in this research. The effectiveness of Nitrogen degradation and the durability of traditional Tio2 nanoparticles dispersed in cementitious material, TiO_2 supported components mounted on concrete mixture surface, and TiO_2 supported remove loose in cementitious materials surface, while accounting for environmental parameters such as gas, nitrous oxide’s ability to focus, and relative humidity. The photocatalysts effectiveness results show that cementitious materials coatings have a nitrogen oxides extraction efficiency of 1.5 and 1.1 times higher than conventional concrete and cementitious materials surfaces, respectively, relating to a TiO_2 nanoparticles light absorption efficiency of 10 and 16 times bigger in concrete mix coatings than cementitious material and concretes mortar surfaces, respectively. As per the surface application of this method, the photocatalytic effectiveness of cement mortar is lower than those of concrete mixture after purifying the coating by more than 2 mm, depending on the thickness of the TiO_2 supporting aggregates installed. The results of this study might be used to develop new methods for adding Titanium dioxide-supported aggregate into concrete, taking into account their photocatalytic efficiency, price, and catalytic durability. [9]

2.2 Self-Cleaning Concrete by Using Titanium Di-Oxide

Weiguo Shen et al. (2014) By decreasing pollutant content in the atmosphere, self-cleaning cement has the potential of making cities cleaner. The photocatalytic properties of TiO_2 and the nanogranular character of the major hydrate of cement, Hydrated Calcium Hydrates, were coupled in this study to develop a photocatalytic cement with a smooth surface. Photocatalytic ultra-smooth concrete surface roughness;photo Because of its ultra-smooth texture and photocatalyst characteristics, which enable pollutants to be wiped away by rain, this new kind of concrete has the potential to be employed as just a self-cleaning finish product for urban buildings.[10]

Ranjit K. Odedra et al. (2014) Air pollution is a serious environmental issue that has serious health consequences for people and other living species. Nitrogen oxides, sulfur dioxide, and volatile organic compounds, which are generated from burning at high temperatures, are examples of major main pollutants caused by human activities. When photocatalytic materials absorb UV energy from the sun, they produce hydroxyl radicals and superoxide anions, which may react with pollution molecules like NOx and SOx, converting them to less hazardous compounds. The following concrete parameters were used in this paper: M25 concrete grade, 0.45 W/C ratio, Titanium dioxide + Ordinary Portland Cement = 3.5:96.5. All samples were covered with Rhodamine's dye solution on the top side after one day of curing, and observations of the dye reduction were made at various time intervals.[11]

T.Vignesh et al. (2018) The goal of this study is to use nano-liquid TiO_2 on concrete mixture in various potencies (0, 2.5, 5.0, 7.5 ml) as well as single, double, and tri coatings of nano-liquid tio2 on hardened concrete to start investigating the concrete strength power and self-properties of concrete. The self-cleaning abilities of the cement were examined to use the Rhodamine-B dye discoloration experiment under Sunlight eye monitoring in this study, which replaced 30% of the cement with fly ash. Concrete mixtures with photocatalytic nano-liquid TiO_2 mixed with new concrete revealed higher compression strength and increase dosages as comparing to nano-liquid Tio2 put on top of cured concrete. Hardened concrete samples have a greater self-cleaning capacity than concrete mixture variations in terms of cleaning capability. [12]

Luciano Cardellicchio et al. (2019) One of the first projects to use ultra-white concrete structures using self-cleaning photocatalysts cement was the Jubilee Church in Rome's southern suburbs. Unfortunately, 16 years after the building's completion, the TiO_2 particle in the concrete mix's self-cleaning and color scheme capabilities are no longer meeting the design specifications, and the concrete is exhibiting early signs of deterioration. While the form of the decay affects the structure's appearance more than its physical soundness, the ageing pattern of the building's components results in expensive expenditures, which are difficult to accommodate within a small parish's budget. This study covers the first phase in determining the causes of concrete's quick ageing pattern, with an emphasis on methods to improve the concrete's long-term durability and, as a result, lower the cost of the its maintenance. Furthermore, this research allowed for the evaluation of the Tio2's durability and effectiveness in real-world circumstances on a genuine structure with non-standard geometry. The findings show how the ageing pattern interacts significantly with the structure's form and how local weathering was neglected throughout the design process.[13]

Hritik S. Behare et al. (2021) Concrete is the most frequently utilized building supplies for building technologies. But cement manufacturing produces significant quantities of carbon dioxide to the environment that contributes to increasing the globe or global warming. Thus, another, ecologically beneficial building material such as photocatalytic concrete has been created. Photocatalysts cement applies a greener replacement binder, which is a modern construction ingredient that substitutes Conventional cement. This approach introduced microparticles such as nano clay into the concrete mixture in order to increase their mechanical qualities. The concrete materials also have been created to be performed as self-cleaning building materials. The self-cleaning capabilities of the cement are induced with the use of photocatalytic elements such as titanium Di-oxide. Self-cleaning concrete that includes those photocatalysts will be stimulated by UV light and quickens the breakdown of organic particles. Thus, the spotlessness of the building surfaces may be preserved and the air around environmental pollution can be decreased. This article briefly discusses self-cleaning concrete.[14]

3. Photocatalytic Process

Catalyst is a substance that accelerate a reaction, enhances the rate of a chemical reaction, without even being consumed within this method. Photocatalysis is simply characterized as light.

The photocatalytic method is a kind of Advanced Oxidation Technology that may be used to clean water and air. As seen in the picture, this approach uses a solid semiconductors catalyst, generally Tio2, that is activated by UV light of a certain wavelengths.

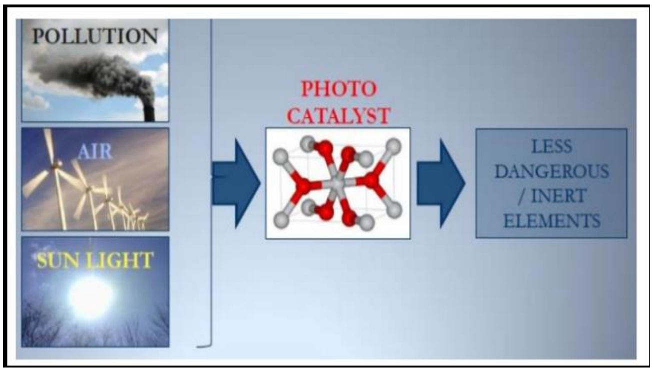

Fig.2. Photocatalytic Process

TiO_2 is multiplied in the natural world. The intermolecular interactions of oxygen TiO_2 are rutile, anatase, and brookite. Rutile is commonly used in white paints; however, its photocatalytic reactivity is low. Anatase is favored for use as a photocatalytic cell.

Photocatalysis requires UV light at a wavelength of less than 387mm. The intensity of sunshine has an effect on photocatalytic activity. In normal daylight, the photocatalysts process can be carried out. The utilization of visible light active TiO_2 nanoparticles is under investigation. Apart from cleaning the air, where pollutants are oxidized or decreased due to the presence of a photo - catalyst, Titanium dioxide is also known for its self-cleaning properties. The use of TiO_2 photocatalyst with concrete mixture and other construction materials has been shown to increase nitrogen oxide removal.

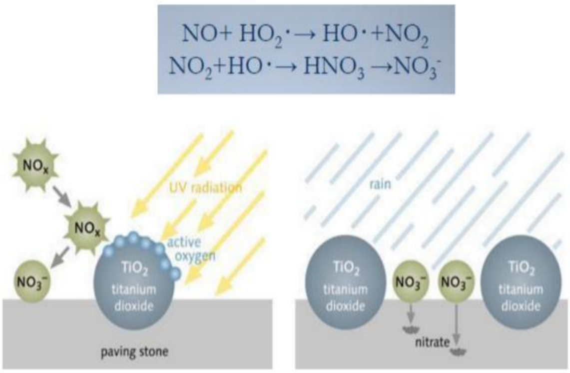

Fig.3.Chemical reaction in Cement

3.1 Environmental Advantages

1. Atmosphere and Energy

The advantages of concrete's heat capacity, as well as the intricate interaction between solar radiation, emissivity, and thermal mass, may be shown via whole-building energy simulations utilizing computer models.

2. Design and Innovation

Concrete built with TX is self-cleaning because to its self-cleaning properties. The heat island impact will be reduced since active cement will remain clean and reflect for a longer amount of time.

3. Job Opportunities in **Air Pollution Abatement** in TX Concrete with active cement reduces pollution by removing organic and inorganic impurities.

4. Job possibilities in TX Active concrete will tend to provide cement for a longer amount of time if protective coatings are not used.

3.2 Product Limitations

Because the entire photocatalytic process is exposed to UV light from the sun, TX Active is not recommended for indoor installation unless sufficient light of the appropriate wavelength is available.

The majority of chemical components produced by the photocatalytic activity are harmless. However, carbonates and calcium nitrates, that are simply simple salts washed away by rain, are possible side-products of several chemical processes.

Furthermore, trace amounts of CO_2 are produced. These subsequent compounds are produced in much lower quantities and do far less environmental damage than the initial substances did.

3.3 Application of Photocatalytic Cement

Fig.4.Hospital in Mexico City

Fig.5. The Milan Expo 2015 pavilion, built by Roma studio Nemesis & Partners, has an air-cleaning exterior.

Fig.6.Umberto Tunnel Italy (2007)

Fig.7. Jubilee Church in Rome

The following fig 4,5,6 and 7 are the actual example in which photocatalytic cement was used for air purifier.

4. Conclusions

According to the study, created concretes demonstrate photocatalytic activity and may cleanse air by eliminating nitrous oxides and organic compounds. The introduction of TiO_2 to cement increased the concrete's mechanical properties.

Despite this advantage, there are certain disadvantages to be aware of.

1. By extracting its by on the surface of photo - catalysts until they are totally mineralized, the by-products formed during photocatalysts degradation of pollution might sometimes be more damaging than the substrates.

2. Because commercial photoactive cements are usually activated by UV light, the researchers aimed to find a photocatalytic activity effective under visible light irradiation.

3. Increasing the quantity of photocatalyst applied to cement boosted its photocatalytic properties, but the changed cement's mechanical and physical properties worsened whenever the amount was greater than 5%.

4. Commercial photosensitive cements (including such TioCEM® from Gorazde in Poland and TXActive® from Italcement Group in Italy) are still eight to 10 times more expensive than pure cement.

Apart from these disadvantages, the advantages of innovative concrete mixtures, such as cleaner air, enhanced mechanical characteristics, and self-cleaning capabilities, make covering approximately concretes the future's building materials.

REFERENCES

[1] Y. Xu *et al.*, "Experimental investigation of photocatalytic effects of concrete in air purification adopting entire concrete waste reuse model," *J. Hazard. Mater.*, vol. 353, no. 2, pp. 421–430, 2018, doi: 10.1016/j.jhazmat.2018.04.030.

[2] G. Hüsken, M. Hunger, and H. J. H. Brouwers, "Experimental study of photocatalytic concrete products for air purification," *Build. Environ.*, vol. 44, no. 12, pp. 2463–2474, 2009, doi: 10.1016/j.buildenv.2009.04.010.

[3] T. Martinez, A. Bertron, E. Ringot, and G. Escadeillas, "Degradation of NO using photocatalytic coatings applied to different substrates," *Build. Environ.*, vol. 46, no. 9, pp. 1808–1816, 2011, doi: 10.1016/j.buildenv.2011.03.001.

[4] M. Z. Guo and C. S. Poon, "Photocatalytic NO removal of concrete surface layers intermixed with TiO2," *Build. Environ.*, vol. 70, pp. 102–109, 2013, doi: 10.1016/j.buildenv.2013.08.017.

[5] K. K. . KOTRESH K.M, D. B. S. PATTNAIK, and M. PATEL, "Study on Photocatalytic Cement as Solution for Pollution Control," *Indian J. Appl. Res.*, vol. 4, no. 3, pp. 166–169, 2011, doi: 10.15373/2249555x/mar2014/49.

[6] E. Boonen, A. Beeldens, I. Dirkx, and V. Bams, "Durability of Cementitious Photocatalytic Building Materials," *Catal. Today*, vol. 287, pp. 196–202, 2017, doi: 10.1016/j.cattod.2016.10.012.

[7] J. G. Mahy, C. A. Paez, J. Hollevoet, L. Courard, E. Boonen, and S. D. Lambert, "Durable photocatalytic thin coatings for road applications," *Constr. Build. Mater.*, vol. 215, pp. 422–434, 2019, doi: 10.1016/j.conbuildmat.2019.04.222.

[8] R. Sakthivel, T. Arun Kitcha, B. E. Student, and S. Aravindh, "Experimental Study of Photocatalytic Concrete using Titanium Dioxide," *IJIRST-International J. Innov. Res. Sci. Technol.*, vol. 4, no. 11, 2018, [Online]. Available: www.ijirst.org.

[9] H. Si, M. Zhou, Y. Fang, J. He, L. Yang, and F. Wang, "Photocatalytic concrete for NOx degradation: Influence factors and durability," *Constr. Build. Mater.*, vol. 298, p. 123835, 2021, doi: 10.1016/j.conbuildmat.2021.123835.

[10] M. Chen and J. W. Chu, "NOx photocatalytic degradation on active concrete road surface - From experiment to real-scale application," *J. Clean. Prod.*, vol. 19, no. 11, pp. 1266–1272, 2011, doi: 10.1016/j.jclepro.2011.03.001.

[11] R. K. Odedra and K. A. P. N. K. Arora, "Photocatalytic Self cleaning Concrete," *Int. J. Sci. Res. Dev.*, vol. 1, no. 11, pp. 2–4, 2014.

[12] T. Vignesh, A. Sumathi, and K. Saravana Raja Mohan, "Study on Self-Cleaning Concrete Using Nano-liquid TiO2," *Int. J. Eng. Technol.*, vol. 7, no. 3.12, p. 860, 2018, doi: 10.14419/ijet.v7i3.12.16551.

[13] L. Cardellicchio, "Self-cleaning and colour-preserving efficiency of photocatalytic concrete: case study of the Jubilee Church in Rome," *Build. Res. Inf.*, vol. 48, no. 2, pp. 160–179, 2020, doi: 10.1080/09613218.2019.1622405.

[14] H. S. Behare, A. N. Bhosale, J. C. Kadale, S. B. Kale, and D. W. Gawatre, "Investigation of Self Cleaning Concrete by Using Titanium Di-Oxide," vol. 8, no. 6, pp. 548–554, 2021.