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ARTICLE

Photo Catalytic Degradation of Concrete Containing Titanium Dioxide Nanoparticles—A Review

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ABSTRACT

Concrete is one of the key component in the construction field. The importance of concrete is because of its strength and long lasting properties. The incorporation of nano materials in concrete helps to improve the characteristics of conventional concrete. Titanium dioxide (TiO_2) is one such nanomaterial that helps to increase the performance of concrete by enhancing self-cleaning, anti-microbial and anti-bacterial activities. This paper briefly explains about the reaction of titanium dioxide nano particle N-TiO_2 on cement materials which in turn changes the mechanical and physical properties of concrete against chemical, climatic changes and abrasion. The review presented here includes the features of titanium dioxide nano particles basically, its dosage in concrete, its impact on concrete on both fresh and hardened properties, photo catalytic effect and anti-microbial. This review explores the photo catalytic degradation of concrete enhanced with N-TiO_2, which presents a promising method for improving the durability and sustainability of concrete structures. The addition of N-TiO_2, recognized for its photo catalytic properties when exposed to UV light, has demonstrated potential in tackling various environmental and structural challenges associated with concrete. The paper provides a detailed analysis of the mechanisms involved in the photo catalytic process, the way N-TiO_2 particles aid in breaking down pollutants (including organic compounds, NOx, and CO_2), and its contributions to self-cleaning, antimicrobial functions, and the degradation of harmful pollutants.

Keywords: Antibacterial; Concrete; Nano Titanium Dioxide; Photocatalytic Property; Self-Cleaning Concrete

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1. Introduction

The construction industry, known for its high energy consumption, is increasingly moving toward sustainable materials and technologies to lessen its environmental impact. Concrete, the most widely used construction material worldwide, significantly contributes to the environmental footprint due to CO_2 emissions during its production and its performance under various environmental conditions. Recently, N-TiO_2 has gained attention as a valuable additive to improve the properties of concrete, by utilizing its photocatalytic and environmental remediation abilities [1,2]. When added to concrete, N-TiO_2 has demonstrated the potential to enhance durability, reduce pollution, and even provide self-cleaning effects, all of which support sustainable urban development [3–5]. For high-scale infrastructure development, such as highways, bridges, and city facades, the total expense of including nano-additives at even modest concentrations (e.g., 1–3% by cement weight) might considerably outweigh regular material budgets. In the absence of a serious analysis of long-term economic return, such as decreased maintenance expenses, longer service life, or environmental credits for pollution mitigation, the viability of the installation of N-TiO_2 concrete on a mass scale is speculative. Titanium dioxide, a semiconductor with a wide band gap, shows strong photocatalytic activity when exposed to ultraviolet (UV) light [6]. This property allows N-TiO_2 to decompose pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the air, making it a desirable ingredient for photocatalytic concrete [7,8]. The addition of N-TiO_2 not only tackles the pressing issue of urban air pollution but also boosts the self-cleaning capabilities of concrete surfaces, leading to better aesthetics and lower maintenance costs [9,10]. Furthermore, N-TiO_2's ability to facilitate the breakdown of organic pollutants can significantly prolong the lifespan of concrete structures by reducing the impact of environmental contaminants.

In addition to its environmental advantages, N-TiO_2 has been found to enhance the mechanical and chemical characteristics of concrete [11]. Reports indicate that it improves the material's resistance to degradation from environmental factors such as UV radiation, acid rain, and carbonation [12,13]. Moreover, N-TiO_2 can enhance concrete performance by increasing compressive strength and decreasing water absorption, which ultimately leads to greater durability [14,15]. The incorporation of N-TiO_2 into concrete can take different forms, including the use of nano-sized TiO_2 particles, which offer enhanced photocatalytic properties due to their larger surface area. Despite these promising benefits, there remain challenges associated with the practical use of N-TiO_2 in large-scale construction projects, such as issues related to dispersion in the cement matrix, cost, and long-term performance [16]. Addressing these challenges requires ongoing research to refine N-TiO_2 -based concrete formulations and optimize their photocatalytic efficiency and durability under real-world conditions [17–19]. The self-cleaning property of N-TiO_2 enhances the concrete to clean off the dirt which settles on the surface. So that the environmental pollutants which settles on the surface will be washed off when the reaction of N-TiO_2 takes place in the presence of sunlight [20–24].

In buildings, nano TiO_2 is added to concrete and coatings to give them self-cleaning and pollution-controlling abilities. It is also commonly employed in sunscreens, paints, water purification, and antimicrobial coatings. Its antimicrobial property is another valuable property when triggered by light, the generated ROS of nano TiO_2 can kill bacterial cell walls and DNA, resulting in efficient microbial inactivation. This makes it beneficial in healthcare, sanitation, and building materials where hygienic surfaces are essential. Overall, nano TiO_2 is a multifunctional material combining environmental, structural, and biological benefits, making it promising as an additive in sustainable and smart material technologies. Although various studies have shown the photocatalytic NO_x degradation potential of nano titanium dioxide (TiO_2) in concrete, much research remains that cannot be practically implemented in actual environments. Most current studies are mainly focused on laboratory tests under optimized UV irradiation, typically without consideration for the fluctuating light intensities and pollutant concentrations found in urban environments. The interconnection between TiO_2 dispersion, concrete microstructure, and photocatalytic activity. Dosage, binder composition, and surface treatment techniques are rarely standardized, and as such, variations in these yield inconsistent results. Few studies also assess the reduction in NO_x removal efficiency with time through surface fouling or loss of active sites. Economic and lifecycle analyses are most importantly never conducted, which raises questions regarding the cost-effectiveness and scalability of TiO_2-enhanced concrete. Closing these gaps is necessary in order to bridge the gap between laboratory testing and sustainable application of NO_x-degrading concrete technologies in urban infrastructure [25].

This paper provides a comprehensive review of the current research on N-TiO_2-incorporated concrete, discussing the photocatalytic mechanisms, performance enhancement, environmental impact, and practical challenges. Furthermore, it highlights recent advances in nanotechnology that have contributed to the development of advanced N-TiO_2 -based concrete materials, aiming to improve the sustainability and resilience of urban infrastructures.

2. Titanium Dioxide Nano Particles

2.1. Fundamentals of Titaniumdioxide

Titanium dioxide (TiO_2) is a widely used photocatalyst, valued for its stability, non-toxicity, and high photocatalytic efficiency [26]. TiO_2 exists in three polymorphs: anatase, rutile, and brookite. Among these, anatase, with its tetragonal crystal structure, is the most effective for photocatalytic applications due to its high surface area and low electron-hole recombination rate [27]. These properties make anatase suitable for air purification, water purification, self-cleaning surfaces, and solar energy applications. Anatase contributes to reactive oxygen species like hydroxyl radicals (.OH) and superoxide anions ($O_2\cdot^-$) that oxidize pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), thereby converting them into less toxic compounds like nitrates and sulfates [27,28,29]. Anatase is also able to fully oxidize compounds into carbon dioxide and inorganic salts. Rutile is denser, highly chemically inert, and one of the commonly used forms for pigments, coatings, and heat-resistant materials because of its high refractive index and opacity; Brookite is metastable and one of the least abundant forms in an orthorhombic structure and synthesizes through complex techniques [30]. Anatase and brookite can be transformed into rutile by heat treatment; however, their doping or combining often enhances the desired application. It is certain that anatase, being the phase that is largely accountable for TiO_2's enhanced photocatalytic activity, starts to convert into the thermodynamically stable rutile phase at temperatures above 600 °C. During this conversion, there is a significant loss of photocatalytic efficiency owing to the reduced surface reactivity and mobility of charge carriers in rutile. In actual urban outdoor environments, concrete buildings are subjected to variable and, in some cases, high temperatures from solar irradiation, urban heat islands, fire accidents, or thermal cycling. The lack of information or discussion on the long-term thermal stability of anatase TiO_2 in the concrete matrix is a cause of concern regarding the longevity and continued functionality of the photocatalytic effects. Moreover, the effect of such phase transitions on mechanical soundness, pore structure, and general durability of the concrete is uninvestigated.

TiO_2 nanoparticles (N-TiO_2) have gained much prominence in cementitious composites. It has a range of applications, including self-cleaning, air purification, and pollutant decomposition [31,32]. These composites harness the photocatalytic properties of N-TiO_2 to break down organic and inorganic pollutants by UV light. NO_x concentrations are lowered by as much as 50% by such composites [33]. Researchers have been able to prove that NO_x concentrations could be reduced to more than 70% using N-TiO_2 -modified concrete [34]. Organic contaminants on glass, tile, and concrete materials are eradicated under UV light with the presence of TiO_2-coated surfaces and maintain their cleanliness even in outdoor exposure for long periods Unlike the other photocatalytic materials like zinc oxide or cadmium sulfide, TiO_2 is safer, cost-effective, and chemically more stable even after long UV exposure periods [35,36]. Additionally, N-TiO_2 is an antimicrobial agent well known to inhibit fungi such as *Cladosporium* sp. [37] pathogens like Legionella pneumophila [38], and bacteria such as Escherichia coli under UV light. These antimicrobial properties make TiO_2 suitable for public infrastructure, including hospitals, schools, and public transit facilities [39]. Advanced techniques such as ultrasonication and surface functionalization are often used to improve the dispersion and reactivity of N-TiO_2 [40]. In general, the multifunctionality of N-TiO_2 in concrete, from air purification and self-cleaning to antimicrobial benefits, places it as a critical material for sustainable urban development and environmental protection.

2.2. Applications of N-TiO_2

The main functional benefits that the photocatalytic properties of N-TiO_2 make it an ingredient widely used in concrete include keeping concrete surfaces clean by breaking organic matter, dirt, and pollutants through UV light [41]. This self-cleaning property has been successfully applied in structures like the Jubilee Church in Rome, where N-TiO_2 -coated concrete panels have maintained their bright white appearance over the years despite exposure to urban grime [42]. These applications reduce maintenance costs, prolong the lifespan of structures, and enhance aesthetic durability. It has the additional capability of degrading environmental pollutants, including NO_x and VOCs, thereby improving the quality of air in cities [43]. Case studies support its real-life efficacy; for example, in Milan, pavements and building facades treated with TiO_2 lowered the levels of NO_x by a considerable margin [44]. Laboratory experiments give further evidence:obtained a maximum degradation efficiency of 73.82% for methyl orange pollutants using nano-TiO_2 concrete under UV light . Also showed substantial reductions in NO_x and SO_2 concentrations during laboratory and field-testing of N-TiO_2 -based photocatalytic concrete blocks. These results show the potential of N-TiO_2 -modified concrete in pollution mitigation, especially in high-traffic urban areas and industrial zones.

Another important feature of N-TiO_2 is its antimicrobial property. Upon activation with UV light, N-TiO_2 generates reactive oxygen species that act as inhibitors of bacterial, fungal, and other microorganisms, thereby preventing the formation of biofilms and degradation of surfaces [45]. It is especially advantageous in humid conditions. Laboratory experiments by showed that N-TiO_2 in cement mixes significantly restrained fungal growth, especially *Cladosporium* sp. The antimicrobial properties of N-TiO_2 -modified concrete make it suitable for public infrastructure such as hospitals, schools, and transportation hubs, where hygiene is a priority. Moreover, the antimicrobial properties of N-TiO_2 can be used in water treatment applications have shown the effective inactivation of Escherichia coli using TiO_2-loaded cement under UV irradiation. Hence the various applications of nano titanium dioxide plays a significant role in concrete which enhance the strength and durability.

N-TiO_2 also improves the aesthetic quality and sustainability of concrete. TiO_2 decreases the amount of harmful organic matter that settles on surfaces, hence reducing degradation with time [46]. TiO_2-treated concrete also inhibits discoloration and staining resulting from organic matter and pollutants [47]. It is graffiti-proof, since photocatalytic breakdown of organic pigment molecules makes easier the cleaning task tested further that also after severe weathering, it maintained a high removal efficiency up to 95% for toluene by coatings on autoclaved aerated concrete. N-TiO_2 plays a role in enhancing the thermal efficiency of concrete. It reflects the sun's radiation, thus reducing urban heat island effects and cooling energy demands, and hence improves the energy efficiency in cities [48]. It also enhances the deicing efficiency by breaking ice-melting chemicals faster in the presence of UV, making it very efficient in colder climates [49]. The various applications of nano titanium dioxide is shown in **Figure 1**.

Figure 1. Applications of N-TiO_2.

3. Functional Properties

3.1. Antimicrobial Activity

N-TiO_2 is a multifunctional material that not only removes air pollutants and provides self-cleaning properties but also exhibits strong antimicrobial action, making it effective in preventing microbial growth on concrete surfaces . During photocatalysis, the reactive oxygen species (ROS) generated can kill bacteria, fungi, and other microbes, preventing biofilm formation and surface degradation. This antimicrobial capability enhances the durability and hygiene of N-TiO_2 -coated materials, making them ideal for various applications. The effectiveness of N-TiO_2 against fungal growth in cement mixes [50] has wide impact on concrete. Their study demonstrated that N-TiO_2 strongly inhibited fungal growth, specifically the fungus *Cladosporium sp.*, during laboratory experiments. This makes N-TiO_2 -based concrete particularly suitable for critical public infrastructures, such as hospitals, schools, and transport facilities, where hygiene is of utmost importance. Without such measurements, it is impossible to assess the effectiveness, replicability, or relative advantage of N-TiO_2 concrete compared with traditional antimicrobial coatings or treatments. Photocatalytic inactivation of microorganisms is extremely sensitive to factors like light intensity, exposure duration, humidity, surface topography, and initial microbial concentration. Thus, in the absence of comprehensive experimental information such as rate constants or time-resolved CFU measurements, the antimicrobial assertion is unsubstantiated and unsound.

In addition to its antibacterial properties, N-TiO_2 also prevents the growth of fungi, algae, and other microorganisms [51]. The antimicrobial activity of N-TiO_2 is especially beneficial in water treatment. For example, Diamond et al. [52] reported the effective inactivation of *Escherichia coli* using N-TiO_2 -loaded cement under UV irradiation [53]. This dual functionality of air purification and microbial inhibition enhances the versatility and application scope of N-TiO_2 in concrete. The antibacterial activity of N- TiO_2 is attributed to its photocatalytic properties. ROS produced under UV light activation penetrate bacterial cell walls, leading to cell death [54]. N-TiO_2 can inhibit a wide range of bacteria, including human pathogens, making it a potential disinfectant for use in hospitals, schools, and other sensitive environments. Its ability to maintain clean and hygienic surfaces under prolonged UV exposure ensures its effectiveness in mitigating microbial risks in both outdoor and indoor settings. Hence, N-TiO_2 concrete has significant antibacterial activity, and it has the potential to be used as a material for applications where hygiene and cleanliness are critical. The antibacterial action of N- TiO_2 in concrete is mainly due to its photocatalytic behavior. When subjected to ultraviolet (UV) radiation, N- TiO_2 gets photoactivated, generating reactive oxygen species (ROS) like hydroxyl radicals and superoxide anions [32]. These ROS are capable of degrading the cell walls of bacteria, interfering with their metabolic functions, and finally causing cell death. In concrete, N-TiO_2 is normally introduced as an additive to the cement paste or sprayed as a surface coating. With UV illumination, the N-TiO_2-treated surface of the concrete becomes inhibitive to microbial activity, efficiently discouraging bacterial adhesion and biofilm development.

3.2. Photocatalytic Effect

The photocatalytic features of N-TiO_2 are ascribed to the property of absorbing ultraviolet light with a band gap of 3.2 eV that generates electron-hole pairs and consequently redox reactions required for the annihilation of many organic and inorganic pollutants, hence N-TiO_2 is very efficient for air cleaning purposes. It degrades harmful pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs), thus leaving the air in urban environments significantly cleaner [55,56]. In addition to air cleaning, N-TiO_2 -coated surfaces have self-cleaning properties. These coatings degrade organic matter efficiently, preventing its accumulation on surfaces and thus reducing maintenance costs. Hence, buildings, pavements, and other constructions in urban environments remain attractive for longer periods of time, even in polluted environments [57]. In addition, N-TiO_2 films have proven to be effective in cleaning the air, even after being exposed to the environment for long periods of time. This durability makes them ideal for use on building walls, roadways, and other areas that are frequently exposed to pollution. Another application of the photocatalytic activity of N-TiO_2 is in water purification. N-TiO_2 effectively degrades organic pollutants and kills microorganisms, making water treatment systems more sustainable [58].

The ability to purify both air and water makes N-TiO_2 versatile and crucial in addressing urban pollution. It also has an additional environmental and public health benefit since it reduces VOCs, such as toluene. Investigations into N-TiO_2 coatings will, therefore, inform optimal content levels for N-TiO_2 and optimize methods of applying coatings so as to increase performance with minimal cost in material usage. The photocatalytic properties of N-TiO_2 will emerge as an important asset in the fight against urban pollution and in fostering environmental sustainability. Its remarkable capacity to keep surfaces clean and purify both air and water will significantly extend the functional lifespan of construction materials, making N-TiO_2 an indispensable element for contemporary, eco-friendly urban development [59]. The advantages of Photocatalytic activity of N-TiO_2 is shown in **Figure 2**.

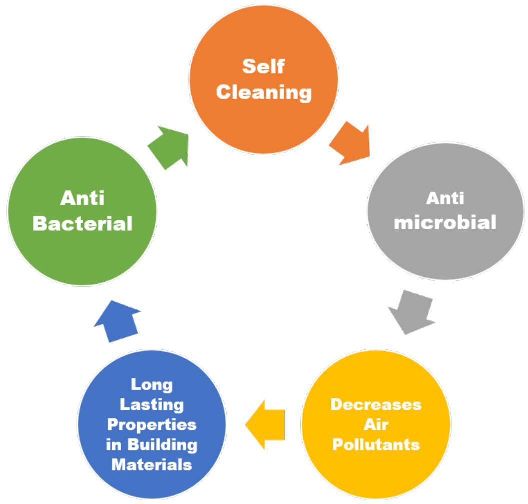

Figure 2. Advantages of Photocatalytic effect.

4. Nano Titanium Dioxide in Concrete

4.1. Impact of N-TiO_2 on Hardened Properties

4.1.1. Compressive Strength of N-TiO_2 Concrete

The qualities of concrete in mechanical aspects has an adverse effect by the addition of nano titanium dioxide [60–65]. It helps to improve the strength of the material and long lasting property. The rigidity of the material have been increased by the closure of pore structures in concrete by the formation of C-S-H gel [66]. This is because of the addition of nano materials in concrete. **Table 1** shows the compressive strength of concrete with different proportion of N-TiO_2.

Table 1. Compressive Strength of N-TiO_2 Concrete.

Reference	W/C Ratio	Percentage of N-TiO_2 Added	Optimum Percentage	Strength in 28 Days (MPa)
[60]	0.5	0.5, 1	1	40.47
[61]	0.3	0.5,1,1.5,2	0.5	67.1
[62]	0.5	0.5,0.75,1,1.25,1.5	1	85
[63]	0.48	2	2	22.71
[64]	0.3	1,2,3	2	17
[65]	0.34	0.5,1,1.5,2,2.5	2	55.35
[66]	0.35	1,2,3,4	2	78.44
[67]	0.33	0.5,1,1.5	1	64.65
[68]	0.42	1,3,5	1	18.03
[69]	0.4	1,3,5	3	23.6

A number of research studies have investigated the impact of introducing N-TiO_2 on the strength of concrete at 28 days of curing. From the findings, it is evident that both the proportion of N-TiO_2 introduced and the water-to-cement (W/C) ratio are determinative factors in how strong the concrete will be. Overall, when utilized in the appropriate proportion, N-TiO_2 has the potential to enhance the strength of concrete substantially. But beyond the optimum percentage, it does not always result in improved outcomes and may even decrease strength at times.

It was found that [60], 0.5 W/C ratio was employed with 0.5% and 1% N-TiO_2. The optimal dose was 1%, which yielded a compressive strength of 40.47 MPa. Another research [61], with a reduced W/C ratio of 0.3, discovered that optimum results were obtained with only 0.5% N-TiO_2, which had a significantly higher strength of 67.1 MPa. This indicates that a lower W/C ratio and a minute amount of N-TiO_2 can prove to be highly effective. The highest strength reported among the studies was 85 MPa in reference [62], where 1% N-TiO_2 was added to a mix with a W/C ratio of 0.5. This demonstrates that even at a moderate W/C ratio, a well-balanced amount of N-TiO_2 can lead to excellent results. On the other hand, some mixes with higher dosages did not perform as well. For example, 2% N-TiO_2 was added to a composition having a W/C ratio of 0.48, but strength was achieved up to only 22.71 MPa [63]. The same pattern was observed in another literature [64], where there was a very low W/C ratio of 0.3 but 2% N-TiO_2 achieved only 17 MPa. There were other works demonstrating improved performance slightly differently. The W/C ratio of 0.34 and 2% N-TiO_2 provided a strength of 55.35 MPa [65]. Even stronger value of 78.44 MPa by employing the same content of TiO_2 but with a W/C ratio of 0.35 [66]. Employing a W/C ratio of 0.33 and 1% N-TiO_2 provided a strong value of 64.65 MPa [67]. These results show just how crucial it is to get the correct amount of water and N-TiO_2 for optimal performance. The work experimented with higher concentrations of TiO_2 (up to 5%) with W/C values of approximately 0.4. Their outcomes were comparatively low, at 18.03 MPa and 23.6 MPa even at their optimum [68,69]. In short, N-TiO_2 can make a considerable enhancement in concrete strength if it is applied in an appropriate amount with an appropriate water-cement ratio. The optimal results generally are achieved through 1–2% application of N-TiO_2 combined with a W/C value ranging from 0.3 to 0.35. Extending beyond these values doesn't always provide an added advantage and may, on occasion, compromise performance. The results are encouraging for N-TiO_2 application in high-performance and environmentally friendly concrete technologies. **Figure 3** describes the various compressive strengths with different optimum percentages of the studies.

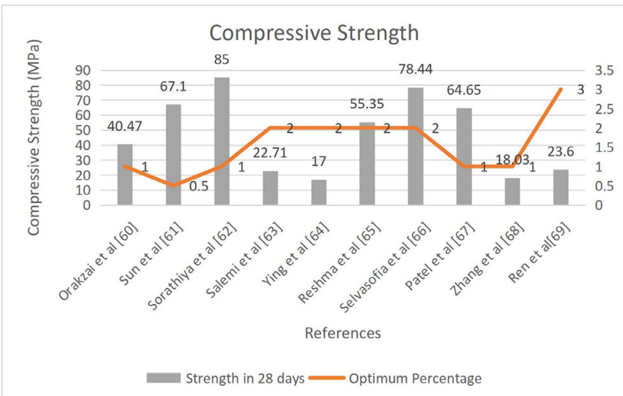

Figure 3. Compressive Strength of N-TiO_2 Concrete.

4.1.2. Split Tensile Strength of N-TiO_2 Concrete

The incorporation of N-TiO_2 in concrete has been found to enhance its mechanical characteristics, such as split tensile strength. Split tensile strength is an important characteristic, as it reflects the capacity of the concrete to resist cracking under tensile stress. A number of studies have proved that the inclusion of N-TiO_2 particles can improve the microstructure of concrete by favoring the creation of a denser, more durable network of calcium silicate hydrate (C-S-H) gel, which is significant in the development of tensile strength [70]. The nanoparticles enhance the cement particles' bonding together, enhancing the material's cracking resistance [65]. In addition, the photocatalytic properties of N-TiO_2, particularly when exposed to UV, have been investigated for their ability to enhance the long-term strength of concrete, which indirectly affects tensile strength [71]. Nevertheless, the performance of N-TiO_2 to increase split tensile strength is based on particle size, concentration, and water-to-cement ratio [72–74]. Optimization of the quantity of N-TiO_2 is critical because high dosing levels can negatively impact the workability and early-age strength of concrete [10,75]. The variations in strength is shown in **Table 2**. Generally speaking, N-TiO_2 possesses great potential to enhance split tensile strength as well as the performance of concrete.

Table 2. Split Tensile strength of N-TiO_2 concrete.

Reference	W/C Ratio	Percentage of TiO_2 Added	Optimum Percentage	Strength in 28 Days (MPa)
[60]	0.5	0.5, 1	1	5.84
[65]	0.34	0.5,1,1.5,2,2.5	2	5.34
[76]	0.413	1,2,3,4,5	3	3.9
[66]	0.35	1,2,3,4	2	5.28
[63]	0.48	2	2	5.1

A number of research studies have investigated how the addition of N-TiO_2 influences concrete tensile strength at 28 days of curing. The findings indicate that both the dose of N-TiO_2 used and the water-to-cement (W/C) ratio have a significant influence on what the strength of the concrete will be. Overall, if used at the correct dosage, N-TiO_2 has been proven to greatly enhance concrete strength [73,74]. Yet, surpassing the optimal percentage is not always accompanied by improved outcomes and may sometimes diminish strength as well. The results of the research indicate that TiO_2 can improve split tensile strength to an optimum dosage, after which the performance might plateau or decrease slightly.

For example, in an experiment with a W/C ratio of 0.5 and testing 0.5% and 1% TiO_2 [60], the optimum dosage was 1%, and the split tensile strength increased marginally compared to control mixes. This improvement is due to the micro-filler effect of TiO_2 particles, which occupy pores in the cement matrix, creating a denser, more compact structure. The fine particles also enhance the bond between the cement paste and aggregates, which can enhance the tensile performance. In a different investigation [65] where the W/C ratio was lower at 0.34 and the amounts of TiO_2 varied between 0.5% and 2.5%, the optimal tensile strength was noted at 2%. The enhanced packing density and interparticle interaction at this dosage level were probably responsible for the gains in tensile capacity observed. But it is not always a linear relationship. Sometimes [75,76], where more concentrated dosages of TiO_2 were used (up to 5%) with a W/C ratio of 0.413, the highest split tensile strength was at 3%. After this, more TiO_2 would have begun to disrupt cement hydration or caused nanoparticle clustering, detracting from the consistency of the matrix and lowering bond strength. Trends similar to the above were also reported in [66], with 2% TiO_2 providing optimum performance at a W/C ratio of 0.35. What is particularly relevant from this finding is that more of an attempt to increase strength was being made without properly optimizing the TiO_2 content.

Compared to this, only 2% TiO_2 was tried with a W/C ratio of 0.48, and the split tensile strength was reasonably enhanced but not appreciably higher than normal [63]. This indicates that increased water content might limit the efficiency of TiO_2 particles by facilitating a less dense microstructure. In all the studies, the improvements in split tensile strength tended to be modest, with most enhancements within the range of 5–15% compared to control samples. In summary, TiO_2 added to concrete improves split tensile strength when used in optimal amounts, usually between 1% and 2%. The improvement is primarily due to better particle packing and matrix densification. However, excessive amounts may hinder performance because of agglomeration or interference with hydration. TiO_2 is not a strength-boosting additive in the classical sense, but it can provide moderate improvements in tensile strength along with its well-known environmental and durability benefits. The split tensile strength with varying percentage of N-TiO_2 is shown in **Figure 4**.

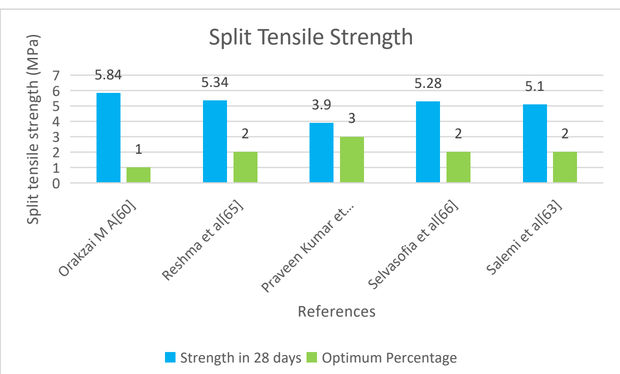

Figure 4. Split Tensile Strength of N-TiO_2 Concrete.

4.1.3. Flexural Strength of N-TiO_2 Concrete

The incorporation of N-TiO_2 into concrete has demonstrated promising enhancement in flexural strength, which is important for the material's resistance to bending or fracture under load. N-TiO_2 particles improve the cement particle bonding, resulting in a denser microstructure and improved load distribution, enhancing flexural strength Research also indicates that N-TiO_2 photocatalytic activity contributes to enhanced long-term durability and, indirectly, flexural performance [72]. The flexural strength of concrete with different percentages is shown in **Table 4** and **Figure 5**. Optimizing the content of N-TiO_2, though, is important since overmuch content can impair workability and overall strength [10]. A number of studies have investigated this, typically demonstrating that N-TiO_2 enhances flexural strength up to an optimal percentage, and then the benefits begin to reduce through particle agglomeration or interference with cement hydration.

Table 4. Flexural strength of N-TiO_2 concrete.

Reference	W/C Ratio	Percentage of TiO_2 Added	Optimum Percentage	Strength in 28 Days (MPa)
[60]	0.5	0.5, 1	1	5.84
[67]	0.33	0.5,1,1.5	1	7.27
[65]	0.34	0.5,1,1.5,2,2.5	2	4.41
[76]	0.413	1,2,3,4,5	3	7.2
[66]	0.35	1,2,3,4	2	6.52
[77]	0.4	0.25,0.75,1.25,1.75	0.75	6.1

In a research [60], at a W/C ratio of 0.5, 1% TiO_2 resulted in a flexural strength of 5.84 MPa. More significant enhancement was realized in work [67] (W/C = 0.33) when 1% TiO_2 attained a maximum of 7.27 MPa, the highest reported. This implies that a lower W/C ratio in conjunction with the right TiO_2 amount can yield denser, stronger concrete. Employing 2% TiO_2 with a W/C of 0.34 resulted in 4.41 MPa [65], whereas research [76] reported 3% TiO_2 with a W/C of 0.413 to yield a good result of 7.2 MPa, indicating that slightly higher dosages are effective in certain mixes. It was discovered 2% to be best with 6.52 MPa strength and 6.1 MPa at only 0.75% TiO_2 [66,77]. Generally, the findings indicate that flexural strength is enhanced by TiO_2 between 0.75% and 2%, chiefly by improving microstructure and bonding between aggregates and paste. Beyond optimal dosage, though, the performance drops with inadequate dispersion or particle clumping. The varying percentage of N-TiO_2 is shown in **Figure 5**. Flexural strength is extremely sensitive to mix design variables, microstructural evolution, curing protocol, and testing procedure. Differences in nanoparticle dispersion, compatibility of admixtures, and even specimen shape can considerably influence mechanical performance.

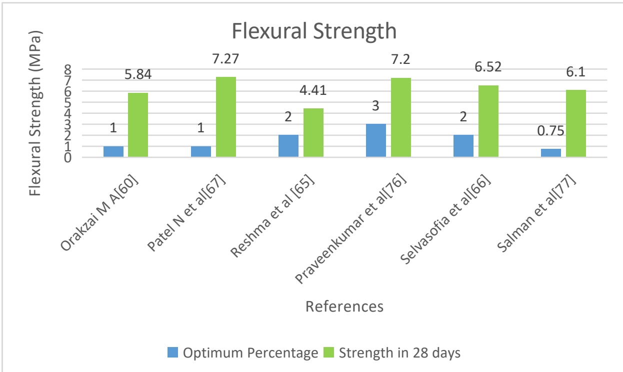

Figure 5. Flexural strength of N-TiO_2 Concrete.

5. Impact of N-TiO_2 on Fresh Properties

The fresh characteristics of concrete, such as setting time, consistency, and workability, have a greater impact on the addition of N-TiO_2 [78]. The smaller size and amount of N-TiO_2 in concrete improves the fresh nature of the concrete. The factors such as slump and slump flow were triggered by the incorporation of N-TiO_2 [79]. In concrete technology, maintaining consistent workability is essential for casting, compaction, and surface finish quality. The high surface area of N-TiO_2 not only increases water demand but also alters the rheological behavior of the mix. There was a decrease in slump flow by the augumentation percentage of N-TiO_2 in concrete [80]. On comparison with normal concrete, the value of the slump was 145 mm by the addition of 1% N-TiO_2 [81]. The addition of N-TiO_2 to concrete has been researched for its potential to modify the setting time and improve the overall properties of the material. N-TiO_2 particles with their small particle size and high surface area can speed up the hydration of cement, especially during the early stages of setting. Research indicates that N-TiO_2 has the ability to serve as a catalyst, promoting the decomposition of water molecules and promoting the development of calcium silicate hydrate (C-S-H) gel, which plays an important role in strengthening [82]. This catalysis accelerates the setting time of concrete, with the potential to result in quicker construction processes. In addition, the photocatalytic activity of N-TiO_2 when exposed to ultraviolet (UV) light can also provide enhanced durability and resistance to environmental conditions, which is desirable for use in outdoor applications [83]. Nevertheless, the degree of influence of N-TiO_2 on setting time varies with particle concentration and the water-to-cement ratio of the mixture [84]. Although N-TiO_2 has been found to have beneficial effects on setting time and strength, it is necessary to optimize its application to avoid premature hardening or loss of workability [10]. Therefore, the incorporation of N-TiO_2 in concrete is a promising route for enhancing both the setting time and long-term performance of the material. A dramatic decrease in workability is among the most perceptible consequences of the incorporation of N-TiO_2. Owing to its highly developed surface area and ultrafine particle size, N-TiO_2 enhances the mixing water demand of the concrete blend. This makes the mix harder and lower-slump, making it less workable in the absence of using more water or plasticizers. For proper flowability to be sustained, the mixes containing N-TiO_2 routinely contain superplasticizers or water-reducing admixtures. N-TiO_2 can also have an effect on the setting time of concrete [83]. According to certain research, it can cause a slight increase in the initial setting time because it has high surface energy and supports nucleation sites for the hydrating products. The effect's magnitude is reliant on the N-TiO_2 dosage, cement type, and other mix components, though. The porosity of N-TiO_2 concrete could also vary due to the fine nature of the particles, which can attract more air into the mix. Again, this effect tends to be negligible and may be managed by proper adjustments to the mix design.

In general, although N-TiO_2 delivers some functional benefits, in particular with respect to photocatalysis and environmental performance, its influence on fresh properties must be treated with caution. Changes in mix proportions, water amount, and admixture dosages are usually required in order to obtain the required workability and performance in the plastic state. By adequate mix design, N-TiO_2 concrete can have both satisfactory fresh behavior and improved durability, as well as environmental advantages.

6. Conclusions

The conclusions derived from the above research papers suggest the following points.

- The addition of nano titanium dioxide has a greater effect in concrete because of its photocatalytic, self-cleaning and self-healing effects.
- The concrete surface with N-TiO_2 when exposed to sunlight, triggers a chemical reaction that converts harmful substances like NOx to harmless ones like nitrates. This means that the concrete with N-TiO_2 helps to clean the air in urban environment.
- The photocatalytic action of these nano particles break down the organic dirt on the surface of the concrete, which settles on it. This can be washed off in rain or water, which makes the surface clean leading to self-cleaning performance.
- Addition of N-TiO_2 creates anti-microbial activity by breaking down of the cell walls of bacteria and generating reactive oxygen species
- The literatures revealed that the mechanical characteristics of concrete with titanium dioxide nano particles showed good improvement. The more amount of titanium dioxide nano particles in concrete leads to decrease in strength characteristics. This is because of the improper distribution of nano particles.
- The studies also revealed that the addition of N-TiO_2 alters the behaviour of concrete in its fresh state. It makes the concrete workable and easy to pour because of the nano sized particles provided the mix is properly modified with the addition of super plasticizer.

Future Scope

The application of nano titanium dioxide (TiO_2) in concrete offers promising potential for reducing urban air pollution by photocatalytic decomposition of nitrogen oxides (NO_x). Nevertheless, future studies need to focus on several key aspects for improving both the scientific knowledge and the practical applicability.

- Extended field exposure experiments are critical to assess the durability and long-term photocatalytic activity of N-TiO_2 under authentic environmental factors, such as fluctuating sunlight exposure, pollution intensity, temperature swings, and surface wear.
- Research into optimizing N-TiO_2 dose and dispersion processes in various binder systems will lead to consistency and efficiency enhancement for applications. In addition, investigations need to examine the complementarity between N-TiO_2 and additives like fly ash or slag to create sustainable, multifunctional concretes.
- New surface modification approaches like doping with metals or non-metals might also optimize visible light stimulation, enhancing performance under low-UV situations. In addition, incorporating sensors for in situ monitoring of NO_x degradation could also provide avenues for intelligent infrastructure.
- Life-cycle studies should be conducted in order to assess the viability of mass-scale adoption in public infrastructure. These future considerations will be essential to bringing N-TiO_2-based photocatalytic concrete from the laboratory to the usable urban environmental product.

Author Contribution

J.D.-Project Administartion, Methodolgy, Conceptualization and Validation; S.S., S.P.-Investigation, Resources, Data curation, Original Draft Preparatio, Writing review and Editing; M.P.- Supervision, Visulization, Resources and Writing Review.

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The authors declare no conflict of interest.

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