

Development of Self-Healing and Air-Purifying Concrete Using *Bacillus subtilis* and Titanium Dioxide (TiO₂) Nanoparticles

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Abstract - Concrete is the most widely used construction material, but cracking and deterioration reduce its durability, service life and sustainability. At the same time, increasing urbanization and traffic emissions create a need for construction materials that can contribute to local air-quality improvement. This review examines the potential development of a multifunctional concrete that combines bacterial self-healing with photocatalytic air purification by incorporating *Bacillus subtilis* and titanium dioxide (TiO₂) nanoparticles. Bacterial self-healing is mainly associated with microbial-induced calcium carbonate precipitation, in which viable bacterial spores become metabolically active in the presence of moisture and contribute to mineral deposition within cracks. TiO₂, on the other hand, acts as a semiconductor photocatalyst: under suitable light irradiation it generates reactive species capable of oxidizing pollutants such as nitrogen oxides (NO_x). The literature indicates that bacterial systems can improve crack closure, reduce permeability and potentially enhance durability, while TiO₂-modified cementitious materials can provide self-cleaning and pollutant-removal functions. However, the combined system presents important challenges, including bacterial survival in highly alkaline cement paste, TiO₂ dispersion, interactions between the two functional additives, dosage optimization, long-term photocatalytic activity and practical field validation. The review proposes an experimental framework for M30 concrete, including compressive, split tensile and flexural strength, water absorption, sorptivity, crack-healing efficiency and NO_x removal tests. The combined material has potential for pavements, roads, footpaths, parking areas and other exposed infrastructure where crack control and environmental functionality are desirable.

Key Words: self-healing concrete; bacterial concrete; *Bacillus subtilis*; biomineralization; calcium carbonate; TiO₂ nanoparticles; photocatalytic concrete; NO_x removal; multifunctional concrete; sustainable construction.

1. INTRODUCTION

Concrete provides high compressive strength, relatively low cost and flexibility in construction, but its low tensile resistance and exposure to

environmental actions make cracking almost unavoidable. Even when cracks are small and do not immediately threaten structural capacity, they can increase permeability and facilitate the ingress of water, chlorides, carbon dioxide and other aggressive substances. This can accelerate reinforcement corrosion and other deterioration mechanisms. Conventional repair generally requires inspection, access, labor and maintenance expenditure. Consequently, autonomous or self-healing concrete has attracted significant research interest as a means of reducing crack-related deterioration. Bacteria-based self-healing is one of the most studied biological approaches. Research has demonstrated that bacterial spores can be incorporated into cementitious materials and subsequently activated when water enters a crack. The bacterial metabolic process can promote calcium carbonate precipitation, which deposits mineral material within the crack and reduces its connectivity. Reviews published in recent years emphasize that bacterial species, bacterial concentration, nutrient availability, carrier/encapsulation method, crack width, curing environment and exposure conditions strongly influence healing performance [1–5]. A second emerging function is photocatalytic air purification. Titanium dioxide is a widely investigated semiconductor for photocatalytic cementitious materials because of its chemical stability, relatively low toxicity and ability to participate in oxidation reactions under light. TiO₂-modified concrete surfaces can oxidize nitrogen oxides and can also provide self-cleaning behavior. Reviews and experimental studies show that the effectiveness depends on TiO₂ type, particle size, dispersion, surface exposure, light intensity, humidity, pollutant concentration and cement-matrix interactions [6–9]. The combination of these two technologies creates a multifunctional concrete with two independent but complementary functions: (i) *Bacillus subtilis*-enabled autonomous crack sealing and (ii) TiO₂-enabled photocatalytic pollutant reduction. The objective of this review is therefore to synthesize the available literature, identify the research gap and propose a technically practical framework for developing and evaluating such a composite material.

2. LITERATURE REVIEW

2.1 Bacteria-Based Self-Healing Concrete

Wiktor and Jonkers [1] quantified crack healing in bacteria-based concrete using a healing agent incorporated into porous expanded clay particles. Their work established an important foundation for autonomous biological crack healing and demonstrated that healing can be quantified through crack-width reduction and water-tightness related observations. The use of a carrier is important because the cement matrix is a harsh environment and direct incorporation may reduce bacterial viability.

2.2 Bacterial Species and Biomineralization

Achal and Mukherjee-type bacterial-concrete research and subsequent reviews have shown that spore-forming bacteria of the *Bacillus* group are attractive because spores can tolerate unfavorable conditions and remain dormant until moisture becomes available. The self-healing process is commonly associated with microbially induced calcium carbonate precipitation. Reviews specifically identify *Bacillus subtilis* as a frequently investigated species and report potential improvements in permeability, durability and mechanical properties when appropriate bacterial systems are used [2,4,5].

2.3 Encapsulation and Protection of Bacteria

Wang et al. [3] investigated self-healing concrete using microencapsulated bacterial spores. Their work demonstrated the importance of protecting spores during concrete mixing and maintaining a suitable reservoir from which bacteria can become active after cracking. Later studies have examined hydrogels, lightweight aggregates, porous carriers and other encapsulation strategies. The literature consistently indicates that protection of bacteria is a key design requirement rather than simply increasing the bacterial dosage.

2.4 Factors Affecting Bacterial Healing

A recent review by Ranjith and Das [5] highlights bacterial selection, healing environment, crack width, pre cracking condition and carrier materials as important variables. Another systematic review [4] concludes that bacterial survival and application method strongly influence biomineralization. Healing is generally more effective for small cracks than for wide cracks because mineral precipitation must bridge a relatively short gap. Moisture availability is also essential because it activates bacterial activity and supports transport of dissolved species.

2.5 TiO₂ Photocatalysis in Cementitious Materials

Chen and Poon [6] reviewed photocatalytic construction materials and explained the use of TiO₂ for air pollution control, self-cleaning and related applications. Under irradiation, TiO₂ can generate electron-hole pairs. These participate in reactions producing highly reactive species that oxidize adsorbed pollutants. The study identified the potential of large exposed construction surfaces to provide environmental functions without requiring a separate treatment unit TiO₂ for NO_x Removal. Chen and Poon [7] experimentally assessed TiO₂-modified concrete materials using nitric oxide oxidation as a measure of photocatalytic activity. Their findings support the use of TiO₂-containing concrete surfaces for photocatalytic pollutant degradation. Folli et al. [8] further examined TiO₂ photocatalysis in cementitious systems and discussed how particle size and the cement environment affect performance. Nanoscale TiO₂ offers high surface area, but dispersion and accessibility of particles at the concrete surface are critical.

2.6 Recent Development of Photocatalytic Concrete

Recent reviews emphasize that photocatalytic concrete can be produced by internal mixing or surface application and that its performance is influenced by surface roughness, TiO₂-C-S-H interactions, light conditions and long term exposure [9]. The practical challenge is to obtain sufficient photocatalytic activity while maintaining strength, workability, durability and economic feasibility. For infrastructure applications, the exposed surface must remain accessible to light and pollutants.

2.7 Research Gap in the Combined System

The two technologies are individually well established, but comparatively fewer studies have systematically investigated a single concrete mixture designed to deliver both biological crack healing and photocatalytic air purification. A combined system introduces possible interactions: TiO₂ may alter the microenvironment and surface chemistry, while bacterial carriers may influence pore structure and the availability of TiO₂ at the exposed surface. Therefore, the key research gap is not simply demonstrating each function separately, but optimizing a compatible mixture and proving that both functions remain effective without unacceptable loss of mechanical performance.

3. MECHANISMS OF THE PROPOSED MULTIFUNCTIONAL CONCRETE

3.1 Self-Healing Mechanism of *Bacillus subtilis*

In a bacterial self-healing system, *Bacillus subtilis* is preferably introduced in a protected spore form or within a suitable carrier. When a crack develops and moisture

penetrates the crack network, the dormant spores may become active. In the presence of an appropriate nutrient/calcium source, microbial activity can promote carbonate formation and subsequent calcium carbonate precipitation. The precipitated mineral progressively fills or bridges the crack, thereby reducing crack width and permeability. The process can be represented conceptually as a sequence: crack formation → water ingress → spore activation → metabolic activity → carbonate generation /precipitation → CaCO₃ deposition → crack sealing.

3.2 Photocatalytic Mechanism of TiO₂

Is a semiconductor photocatalyst. When photons with sufficient energy interact with the material, electrons can be promoted from the valence band to the conduction band, leaving holes behind. The resulting charge carriers participate in surface reactions that generate reactive oxygen species. These species can oxidize adsorbed pollutants. For NO_x, the overall process involves adsorption and oxidation of nitrogen oxides on the photocatalytic surface, with reaction products retained or washed from the surface depending on the exposure conditions. Photocatalytic efficiency is therefore strongly dependent on illumination, humidity, mass transfer and surface accessibility [6–9].

3.3 Combined Functional Concept

The proposed material is intended to behave as a multifunctional cementitious composite. The bacterial component is primarily responsible for autonomous crack sealing, while TiO₂ provides photocatalytic activity at or near the exposed surface. The conceptual advantage is that crack control can reduce water and contaminant ingress while photocatalysis addresses selected atmospheric pollutants. The design should, however, avoid assuming that one function automatically improves the other; both must be independently measured and optimized.

4. PROPOSED MATERIALS AND MIX DESIGN STRATEGY

For a civil-engineering final-year experimental program, an M40 concrete can be selected as the control grade. Ordinary Portland cement or another locally approved cementitious binder, natural fine aggregate, coarse aggregate and potable water may be used in accordance with applicable Indian Standards. *Bacillus subtilis* should be introduced using a documented concentration and a method that protects viability. TiO₂ nanoparticles should be characterized for particle size, purity and crystalline form before use.

A practical experimental matrix should include at least: (C0) conventional control concrete; (B) bacterial concrete; (T) TiO₂-modified concrete; and (BT) combined bacterial +

TiO₂ concrete. Additional dosage levels can be introduced after preliminary trials. This factorial approach is more informative than testing only the combined mixture because it allows the separate contribution and interaction of each functional component to be quantified.

5. EXPERIMENTAL EVALUATION FRAMEWORK

- Compressive strength:** 7 and 28 days, and preferably 56/90 days if time permits, to determine whether functional additives cause unacceptable strength loss or improvement.
- Split tensile strength:** Evaluate tensile-related performance and compare control, bacterial, TiO₂ and combined mixes.
- Flexural strength:** Useful for pavement-oriented applications where bending performance is important.
- Water absorption:** Assess changes in capillary transport and durability after bacterial mineralization and TiO₂ incorporation.
- Crack-healing efficiency:** Induce controlled cracks, expose specimens to defined healing conditions, photograph cracks periodically and calculate crack-width reduction/healing ratio.
- Microstructural analysis:** SEM/EDS and, where available, XRD can be used to verify mineral deposition and identify CaCO₃-related phases.
- Photocatalytic performance:** Use a controlled NO or NO_x test method, or an appropriate validated pollutant-degradation protocol, under defined light intensity, humidity and gas concentration.
- Durability:** Where facilities permit, include chloride penetration, permeability, wet–dry cycling, sulfate or acid exposure, and mass/strength retention.

Mix ID	Bacteria	TiO ₂	Purpose
C0	None	None	Control
B	<i>B. subtilis</i>	None	Crack-healing effect
T	None	Nano-TiO ₂	Photocatalytic effect
BT	<i>B. subtilis</i>	Nano-TiO ₂	Combined multifunctional system

6. FACTORS REQUIRING OPTIMIZATION

- Bacterial concentration:** excessive addition may not proportionally increase healing and may affect workability or pore structure.
- Carrier and encapsulation:** protection is

- required to preserve bacterial viability during mixing and early hydration.
- iii. **Nutrient/calcium source:** the healing reaction requires suitable chemical resources; the selected source should not create unacceptable environmental or durability consequences.
 - iv. **TiO₂ dosage and dispersion:** nanoparticles tend to agglomerate, so mixing energy, admixtures and dispersion procedures are important.
 - v. **Surface exposure:** photocatalysis is strongest where TiO₂ is accessible to light and pollutants; particles buried deep inside concrete contribute little to surface air purification.
 - vi. **Light and humidity:** photocatalytic results depend on irradiation and environmental conditions, so these must be reported rather than treated as constants.
 - vii. **Compatibility:** the combined mixture should be checked for setting time, slump, density, strength, porosity and durability before claiming multi functionality.

7. SUSTAINABILITY & PRACTICAL APPLICATIONS

The principal sustainability benefit of self-healing concrete is the possibility of extending service life and reducing repair frequency. If cracks are sealed before aggressive agents penetrate deeply, maintenance requirements may be reduced. The environmental benefit of photocatalytic concrete is different: it acts locally on pollutants at the material surface. Therefore, the strongest application case is infrastructure with high exposed surface area, regular sunlight and significant vehicle-related pollutant exposure.

Potential applications include urban roads, rigid pavements, footpaths, parking areas, flyovers, pedestrian zones, airport pavements and selected industrial or transport infrastructure. For road applications, the combined material should be designed around surface wear and skid resistance as well as mechanical and photocatalytic performance.

Traffic abrasion may alter the TiO₂-rich surface, so long-term field validation is essential.

The developed multifunctional M40 concrete contributes to sustainability by combining bacterial self-healing and TiO₂-based air-purifying functionality in a single concrete system. The use of *Bacillus subtilis* promotes the sealing of small cracks through calcium carbonate precipitation, which can potentially reduce crack-related deterioration and maintenance requirements, while TiO₂ provides photocatalytic functionality for reducing pollutants under suitable light exposure. This combination can improve the durability and environmental performance of concrete infrastructure and support more sustainable road

construction. In terms of practical application, the developed concrete has potential for use in rigid pavements such as highways, urban roads, flyovers, parking areas, footpaths, airport pavements, and industrial roads, where crack formation and exposure to air pollutants are important concerns. However, the PDF indicates that further studies on long-term self-healing, quantitative pollutant removal, material optimization, large-scale pavement testing, economic feasibility, and field performance are required before large-scale practical implementation.

8. CONCLUSION

Based on the complete analysis of your uploaded research paper, the conclusion should highlight the three main outcomes: compressive strength, self-healing, and air-purifying functionality. I have also avoided calling the 27% colour change a pollutant-removal percentage, because your experimental results explicitly state that it was only an indicator response.

The present study successfully investigated the development of a multifunctional M40 concrete incorporating *Bacillus subtilis*, calcium lactate, and TiO₂ powder to provide self-healing and air-purifying functionality for road construction applications. Conventional M40 concrete was used as the reference concrete, and the developed concrete was evaluated in terms of compressive strength, crack-healing performance, and photocatalytic air-purifying response.

The compressive strength of both conventional and developed concrete increased progressively with curing age. The developed self-healing M40 concrete exhibited higher compressive strength at all tested ages. At 7, 14, 21, and 28 days, the developed concrete achieved 29.78 MPa, 35.11 MPa, 40.00 MPa, and 47.00 MPa, respectively, compared with 25.78 MPa, 32.00 MPa, 37.00 MPa, and 45.00 MPa for conventional M40 concrete. The corresponding increase in compressive strength was 15.52%, 9.72%, 8.11%, and 4.44%, respectively. The 28-day strength of 47 MPa indicates satisfactory strength development of the investigated multifunctional concrete mix.

The self-healing investigation demonstrated a measurable reduction in crack width. The controlled crack width decreased from 1.00 mm to 0.30 mm, resulting in a calculated 70% crack-healing efficiency. This crack closure is associated with the biological activity of *Bacillus subtilis* in the presence of calcium lactate, which promotes calcium carbonate precipitation within the crack region. The result indicates the potential of the developed concrete to reduce small crack widths and improve crack-related durability performance.

The TiO₂-based air-purification experiment also showed a

measurable response under the selected light-exposure conditions. The average colour intensity of the indicator changed from 98.73 to 125.38 after one hour, corresponding to approximately 27% relative colour change. This demonstrates a measurable change in the indicator during the photocatalytic test. However, this value should not be considered as direct 27% pollutant-removal efficiency because pollutant concentration was not quantitatively measured using a gas analyser or equivalent instrument.

Overall, the experimental investigation demonstrates the feasibility of combining structural strength, biological self healing, and TiO₂-based photocatalytic functionality within a single M40 concrete system. The developed multifunctional concrete therefore shows promising potential for sustainable road infrastructure by addressing both crack related maintenance requirements and environmental functionality. Further optimization of material dosages, long-term self healing behaviour, quantitative pollutant-removal testing, and large-scale pavement evaluation are required before practical field implementation.

REFERENCES

- [1] Wiktor, V., & Jonkers, H. M. (2011). Quantification of crack-healing in novel bacteria-based self-healing concrete. *Cement and Concrete Composites*, 33(7), 763–770. <https://doi.org/10.1016/j.cemconcomp.2011.03.012>
- [2] Wang, J., Soens, H., Verstraete, W., & De Belie, N. (2014). Self-healing concrete by use of microencapsulated bacterial spores.
- [3] *Cement and Concrete Research*, 56, 139–152. <https://doi.org/10.1016/j.cemconres.2013.11.009>
- [4] Wang, J., Dewanckele, J., Cnudde, V., Van Vlierberghe, S., Verstraete, W., & De Belie, N. (2014). X-ray computed tomography proof of bacterial-based self-healing in concrete. *Cement and Concrete Composites*, 53, 289–304. <https://doi.org/10.1016/j.cemconcomp.2014.07.014>
- [5] (2022). Physical, strength, durability and microstructural analysis of self-healing concrete: A systematic review. *Journal of Building Engineering/related Elsevier review literature*. Review evidence emphasizes bacterial dose, survival, application method and environmental effects.
- [6] Ranjith, A., & Das, B. B. (2025). Self-healing bacterial concrete: A bibliometric overview and state-of-the-art review on fundamentals, techniques and future perspectives. *Journal of Building Engineering*, 104, 112324. <https://doi.org/10.1016/j.job.2025.112324>
- [7] Chen, J., & Poon, C. S. (2009). Photocatalytic construction and building materials: From fundamentals to applications. *Building and Environment*, 44(9), 1899–1906. <https://doi.org/10.1016/j.buildenv.2009.01.002>
- [8] Folli, A., Pade, C., Hansen, T. B., De Marco, T., & Macphee, D. E. (2012). TiO₂ photocatalysis in cementitious systems: Insights into self-cleaning and depollution chemistry. *Cement and Concrete Research*, 42(3), 539–548. <https://doi.org/10.1016/j.cemconres.2011.12.001>
- [9] (2024). Recent advances in TiO₂-based photocatalytic concrete: Synthesis strategies, structure characteristics, multifunctional applications, and CFD simulation. *Chemical Engineering Journal*. Review of synthesis, surface exposure, NO_x removal and long-term performance.
- [10] (2023). State-of-art review of bacteria-based self-healing concrete: Biomineralization process, crack healing, and mechanical properties. *Construction and Building Materials*, 378, 131198. <https://doi.org/10.1016/j.conbuildmat.2023.131198>
- [11] (2023). Factors affecting the self-healing performance of bacteria-based cementitious composites: A review. *Construction and Building Materials*, 384, 131271.
- [12] Khadiyal, S., Rawat, A., Das, S. K., & Garg, N. (2022). Bacterial concrete: A review on self-healing properties in the light of sustainability. *Materials Today: Proceedings*, 60(1), 136–143. <https://doi.org/10.1016/j.matpr.2021.12.277>