

# Design And Performance Of Bacteria-Based Self-Healing Concrete

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**Abstract:** Concrete cracking is one of the major causes of structural deterioration and durability loss in infrastructure systems. Conventional repair techniques are expensive, labor-intensive, and often ineffective in inaccessible locations. This study investigates the development and performance of bacteria-based self-healing concrete utilizing microbiologically induced calcite precipitation (MICP). *Bacillus subtilis* spores were encapsulated within lightweight aggregates and incorporated into concrete mixtures to promote autonomous crack healing. The experimental program evaluated fresh concrete properties, compressive strength, water absorption, crack-healing efficiency, and durability performance. Results indicated that the bacterial concrete exhibited comparable mechanical properties to conventional concrete while demonstrating significant self-healing capability. Crack widths up to 0.45 mm were effectively sealed within 28 days of water exposure. Water permeability was reduced by approximately 82%, while compressive strength increased by 12% compared with the control mixture. The findings confirm that bacteria-based self-healing concrete represents a sustainable and cost-effective solution for extending infrastructure service life and reducing maintenance requirements.

**Keywords:** Self-healing concrete, MICP, *Bacillus subtilis*, Calcite precipitation, Durability, Sustainable infrastructure

## I. INTRODUCTION

Concrete is the most widely used construction material in the world due to its excellent compressive strength, versatility, durability, and economic feasibility. Modern infrastructure systems such as bridges, highways, tunnels, dams, marine structures, and high-rise buildings rely heavily on reinforced concrete for structural stability and serviceability. Despite its widespread application, concrete is inherently susceptible to cracking due to drying shrinkage, thermal stresses, mechanical loading, freeze-thaw cycles, chemical attack, and environmental deterioration. Even small cracks can significantly compromise the durability of concrete structures by allowing the ingress of water, chlorides, sulfates, carbon dioxide, and other aggressive agents that accelerate reinforcement corrosion and structural degradation (Chahal et al., 2012; Feng et al., 2021).

Cracking is recognized as one of the primary causes of premature deterioration in concrete infrastructure worldwide. Once cracks develop, they provide direct

pathways for moisture and harmful substances to penetrate the concrete matrix, resulting in reduced service life and increased maintenance requirements. Traditional crack repair techniques, including epoxy injection, polymer grouting, surface sealing, and patch repair, are often expensive, labor-intensive, and difficult to implement in inaccessible locations. Furthermore, repeated maintenance activities contribute substantially to the life-cycle cost of infrastructure projects and increase environmental burdens through material consumption and carbon emissions (Ghosh et al., 2005; Hammad et al., 2024). Consequently, researchers have increasingly focused on developing innovative concrete materials capable of autonomously repairing cracks without external intervention.

Self-healing concrete has emerged as a promising solution to address the durability challenges associated with concrete cracking. The concept of self-healing involves the ability of a material to repair damage automatically and restore its original functionality. Various self-healing approaches have been proposed, including autogenous healing, encapsulated polymers,

shape memory materials, mineral admixtures, and biological healing techniques. Among these methods, bacteria-based self-healing concrete has gained considerable attention because of its sustainability, environmental compatibility, and long-term healing potential (BIS (Bureau of Indian Standards), 2009). Unlike chemical healing systems that may degrade over time, biological healing mechanisms utilize living microorganisms capable of producing mineral deposits that fill cracks and improve durability.

The underlying principle of bacteria-based self-healing concrete is microbiologically induced calcite precipitation (MICP). In this process, specific bacterial species remain dormant within the concrete matrix in the form of spores. When cracks form and water enters the concrete, the bacterial spores become activated and metabolize supplied nutrients, producing carbonate ions as metabolic by-products. These carbonate ions react with calcium ions present in the concrete pore solution to form calcium carbonate ( $\text{CaCO}_3$ ), commonly known as calcite. The precipitated calcite gradually accumulates within cracks and pores, effectively sealing them and restoring the impermeability of the concrete (Jonkers, 2007; Tsioulou et al., 2017). The calcite crystals exhibit strong bonding characteristics with the cementitious matrix, thereby contributing to the recovery of structural integrity and durability.

Several bacterial species have been investigated for self-healing applications, including *Bacillus subtilis*, *Bacillus sphaericus*, *Bacillus pasteurii*, and *Sporosarcina pasteurii*. These microorganisms are particularly suitable because they can survive the highly alkaline environment of concrete and remain viable for extended periods in dormant spore form (Fahimizadeh et al., 2024). However, the successful implementation of bacterial self-healing concrete requires effective protection of bacterial spores during mixing, curing, and service conditions. Direct incorporation of bacteria into concrete often results in significant loss of viability due to mechanical stresses and high alkalinity. To overcome this challenge, various encapsulation techniques have been developed, including lightweight aggregates, silica gel, hydrogels, polyurethane

capsules, and expanded clay particles. These carriers provide a protective environment for bacterial spores and nutrients, ensuring their activation when cracking occurs (Khoury, 2000).

Recent laboratory investigations have demonstrated that bacteria-based self-healing concrete can effectively seal cracks ranging from 0.2 mm to 1.0 mm depending on bacterial species, nutrient availability, and environmental conditions. Studies have reported significant reductions in water permeability, chloride penetration, and sorptivity, along with improvements in compressive strength and durability performance (Lagazo et al., 2019). Moreover, self-healing concrete has shown promising applications in marine structures, underground constructions, water-retaining facilities, and transportation infrastructure where maintenance operations are particularly challenging and costly. The technology aligns well with global sustainability goals by reducing repair frequency, conserving construction materials, lowering maintenance costs, and extending infrastructure service life.

Despite the substantial progress achieved in laboratory-scale investigations, practical implementation of bacteria-based self-healing concrete in full-scale structures remains relatively limited. Questions regarding large-scale performance, long-term bacterial viability, healing efficiency under varying environmental conditions, and economic feasibility continue to require further investigation. Additionally, the selection of suitable bacterial strains, nutrient systems, and encapsulation methods remains a critical factor influencing the effectiveness of the healing process. Therefore, comprehensive studies evaluating both mechanical and durability characteristics under realistic conditions are necessary to facilitate the transition of this technology from laboratory research to field applications.

The present study aims to investigate the design and performance of bacteria-based self-healing concrete utilizing *Bacillus subtilis* spores encapsulated within lightweight aggregates. The research evaluates the influence of bacterial incorporation on fresh and hardened concrete properties, crack-healing efficiency,

water permeability reduction, and overall durability enhancement. Furthermore, the study examines the effectiveness of microbiologically induced calcite precipitation as a sustainable mechanism for autonomous crack repair in reinforced concrete structures. The findings contribute to the growing body of knowledge on self-healing construction materials and provide insights into the practical implementation of biologically enhanced concrete for resilient and sustainable infrastructure development.

## II. LITERATURE REVIEW

The concept of bacteria-based self-healing concrete has attracted considerable research attention over the last two decades due to its potential to enhance the durability and service life of concrete structures. Early investigations by Lawson et al (2011) demonstrated that alkali-resistant *Bacillus* species embedded within concrete could successfully precipitate calcium carbonate through microbiologically induced calcite precipitation (MICP), enabling autonomous crack healing. Their study reported effective sealing of cracks up to approximately 0.46 mm, significantly reducing water ingress and improving durability. Similarly, Wiktor and Lawson et al (2011) quantified the healing performance of bacterial concrete and observed substantial crack closure and restoration of watertightness under moist curing conditions. Mondal & Ghosh (2021) further advanced the technology by employing encapsulation techniques using silica gel and polyurethane carriers, which protected bacterial spores during concrete mixing and improved their long-term viability. The authors reported considerable reductions in water permeability due to calcite deposition within cracks and pores, highlighting the effectiveness of bacterial healing systems in mitigating durability-related deterioration.

Several subsequent studies have investigated the influence of bacterial incorporation on the mechanical and durability properties of concrete. Sarkar et al (2015) reported that bacterial concrete exhibited compressive strength improvements ranging from 10% to 25% compared with conventional concrete, primarily due to pore refinement and calcite precipitation. Patnaik et al

(2023) demonstrated enhanced resistance to chloride ion penetration, sulfate attack, and freeze-thaw deterioration in microbial concrete systems, indicating their suitability for aggressive environmental conditions. Shaheen et al (2018) observed significant reductions in crack width and permeability while emphasizing the importance of bacterial species selection and nutrient availability for achieving optimal healing efficiency. Although laboratory-scale studies have consistently demonstrated the potential of bacteria-based self-healing concrete, relatively few investigations have evaluated its performance under full-scale field conditions. Challenges related to large-scale implementation, long-term bacterial viability, environmental variability, and economic feasibility remain insufficiently explored. Therefore, further research involving realistic structural applications is necessary to establish the practical applicability and commercialization potential of bacterial self-healing concrete technology.

## III. MATERIALS AND METHODS

### A. Materials

The experimental investigation was conducted using conventional concrete constituents combined with biological healing agents to develop bacteria-based self-healing concrete. Ordinary Portland Cement (OPC) 53 Grade conforming to IS 12269:2013 was used as the primary binding material due to its high strength and durability characteristics. Natural river sand conforming to Zone II requirements of IS 383:2016 was utilized as fine aggregate, while crushed granite aggregates with a maximum size of 20 mm served as coarse aggregates. Potable water free from harmful contaminants was used for concrete mixing and curing.

The self-healing system consisted of *Bacillus subtilis* spores and calcium lactate as the nutrient source. *Bacillus subtilis* was selected because of its ability to survive under the highly alkaline conditions of concrete and its proven capability to induce calcium carbonate precipitation through microbiologically induced calcite precipitation (MICP) (Andalib et al., 2016; Qian et al., 2021). Lightweight expanded clay aggregates (LECA)

were used as encapsulation carriers to protect bacterial spores during concrete mixing and hydration. The physical properties of the materials used in the study are presented in Table 1.

Table 1. Physical Properties of Materials

Property	Cement	Fine Aggregate	Coarse Aggregate
Specific Gravity	3.15	2.65	2.72
Water Absorption (%)	—	1.20	0.80
Fineness Modulus	—	2.85	6.95
Maximum Size (mm)	—	4.75	20

### B. Concrete Mix Design

Concrete mixtures were designed for M40 grade strength according to the provisions of IS 10262:2019. A constant water-cement ratio of 0.40 was maintained throughout the study. Four different mixtures were prepared, including one control mix without bacteria and three bacterial concrete mixes containing varying concentrations of *Bacillus subtilis* spores. Previous studies have indicated that bacterial concentration significantly influences calcite precipitation and healing efficiency (Huseien et al., 2019; Song et al., 2021). Therefore, bacterial concentrations of  $10^5$ ,  $10^6$ , and  $10^7$  cells/ml were selected to evaluate their effects on concrete performance.

The control mixture served as a reference to assess the influence of bacterial incorporation on strength, durability, and crack-healing characteristics. The detailed mix proportions adopted for the experimental program are summarized in Table 2.

Table 2. Mix Proportions of Bacteria-Based Self-Healing Concrete

Mix ID	Bacterial Content (cells/ml)	Cement (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Aggregate (kg/m <sup>3</sup> )
Control	0	420	168	1800
BC-1	$10^5$	420	168	1800
BC-2	$10^6$	420	168	1800
BC-3	$10^7$	420	168	1800

### C. Encapsulation Procedure

The viability of bacterial spores within the harsh alkaline environment of concrete is one of the major challenges associated with self-healing concrete technology. To overcome this limitation, a protective encapsulation strategy using lightweight expanded clay aggregates was employed. LECA particles were first dried and subsequently subjected to vacuum impregnation with a suspension containing *Bacillus subtilis* spores and calcium lactate nutrient solution. The vacuum process facilitated deep penetration of the bacterial suspension into the porous structure of the aggregates.

Following impregnation, the aggregates were coated with a biodegradable polymer layer to prevent premature leakage of bacterial agents during concrete mixing. Similar encapsulation approaches have been reported to significantly improve bacterial survival and healing efficiency (Giri et al., 2026; Justo-Reinoso et al., 2023). Once cracks formed and water entered the concrete matrix, the dormant spores became activated and initiated calcite precipitation through metabolic processes. The resulting calcium carbonate crystals accumulated within the crack space, gradually sealing the crack and restoring impermeability. The self-healing mechanism employed in the study is illustrated in Figure 1.

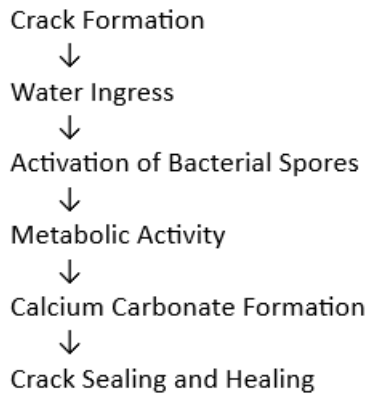
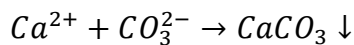


Figure 1. Schematic Representation of Bacteria-Based Self-Healing Mechanism

The principal reaction responsible for crack healing can be expressed as:



where calcium ions combine with carbonate ions generated through bacterial metabolism to form insoluble calcium carbonate crystals that seal cracks and pores (Tie et al., 2024).

#### D. Experimental Program

A comprehensive experimental program was developed to evaluate the fresh, mechanical, durability, and self-healing properties of the bacterial concrete mixtures. Fresh concrete workability was assessed using the slump cone test according to IS 1199:2018. Hardened concrete performance was evaluated through compressive strength testing on standard cube specimens at curing ages of 7, 28, and 56 days following IS 516 guidelines.

Durability-related investigations included water absorption and rapid permeability tests to assess the effectiveness of bacterial calcite deposition in reducing pore connectivity and fluid ingress. Artificial cracks ranging from 0.20 mm to 0.50 mm were induced in selected specimens using controlled loading procedures. These cracked specimens were subsequently exposed to wet curing conditions to activate bacterial healing mechanisms. Crack closure

was monitored periodically using optical microscopy and image analysis techniques, while microscopic examinations were performed to confirm the presence of calcium carbonate deposits within healed cracks.

The overall testing methodology adopted in this study enabled a comprehensive evaluation of the influence of bacterial incorporation on concrete performance and provided quantitative evidence regarding the effectiveness of microbiologically induced self-healing processes. Similar experimental approaches have been successfully employed by Lawson et al (2011), Javeed et al (2024) and Shaheen et al (2018) for assessing bacterial concrete performance under laboratory conditions.

## IV. RESULTS AND DISCUSSION

### A. Workability

The workability of concrete mixtures was evaluated using the slump cone test, and the results are presented in Table 3. The incorporation of bacterial spores encapsulated within lightweight expanded clay aggregates resulted in a gradual reduction in slump values compared with the control mixture. The control concrete exhibited a slump of 82 mm, whereas the bacterial concrete mixtures BC-1, BC-2, and BC-3 recorded slump values of 79 mm, 77 mm, and 75 mm, respectively. This reduction can be attributed primarily to the porous nature of the lightweight aggregates, which absorbed a portion of the mixing water and consequently reduced the free water available for lubrication within the concrete matrix.

Despite the slight decrease in workability, all mixtures remained within the acceptable range for structural concrete applications. Similar observations have been reported by Lawson et al (2011) and Song et al (2021), who noted that bacterial encapsulation carriers often increase water demand due to their porous structure. However, the reduction observed in the present study was relatively small and did not adversely affect concrete placement or compaction. These findings suggest that the incorporation of bacterial healing agents can be achieved without significantly compromising fresh concrete properties.

Table 3. Fresh Concrete Properties

Mix	Slump (mm)
Control	82
BC-1	79
BC-2	77
BC-3	75

### B. Compressive Strength

The compressive strength results obtained at curing ages of 7, 28, and 56 days are presented in Table 4. The results demonstrate that bacterial incorporation positively influenced the strength development of concrete. At 28 days, the control mix achieved a compressive strength of 45.2 MPa, whereas BC-1, BC-2, and BC-3 attained strengths of 48.5 MPa, 50.7 MPa, and 50.6 MPa, respectively. Similar trends were observed at 56 days, where BC-2 achieved the highest compressive strength of 52.4 MPa compared to 47.3 MPa for the control mixture.

The improvement in compressive strength can be attributed to microbiologically induced calcite precipitation (MICP), which promotes pore refinement and microstructural densification. The calcium carbonate crystals produced by bacterial metabolic activity fill microvoids, capillary pores, and microcracks within the concrete matrix, thereby enhancing load-transfer mechanisms and reducing stress concentrations.

The BC-2 mixture containing  $10^6$  cells/ml exhibited the optimum performance, showing approximately 12.2% higher compressive strength than conventional concrete at 28 days. Although BC-3 contained a higher bacterial concentration, the strength gain was marginally lower than BC-2, suggesting that excessive bacterial content may not necessarily result in proportional improvements. Similar findings have been reported by Fahimizadeh et al (2024) and Patnaik et al (2023), who observed optimum bacterial concentrations for maximizing concrete performance.

Table 4. Compressive Strength Results

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
Control	31.5	45.2	47.3
BC-1	33.2	48.5	50.1
BC-2	34.6	50.7	52.4
BC-3	35.1	50.6	52.0

The results clearly indicate that bacterial self-healing technology contributes not only to crack remediation but also to the enhancement of mechanical performance through microstructural modification.

### C. Crack-Healing Performance

The primary objective of the study was to evaluate the crack-healing capability of bacterial concrete. Controlled cracks ranging from 0.20 mm to 0.50 mm were induced in the specimens and subsequently exposed to wet curing conditions to activate bacterial activity. After 28 days of healing, the control specimens exhibited negligible crack closure, indicating the limited contribution of natural autogenous healing. In contrast, the bacterial concrete specimens showed significant crack-sealing behavior due to calcite precipitation.

Among the bacterial mixtures, BC-2 demonstrated the highest healing efficiency. Cracks up to 0.45 mm in width were almost completely sealed after 28 days, while visible white calcium carbonate deposits were observed along the crack surfaces. Microscopic examination confirmed that the precipitated calcite crystals effectively bridged and filled the crack voids. The measured healing efficiency reached approximately 91%, indicating excellent autonomous repair capability.

The superior healing performance of BC-2 can be attributed to the balanced availability of viable bacterial spores and nutrients, which facilitated effective calcite precipitation throughout the crack depth. Similar healing efficiencies ranging between 80% and 95% have been reported by Lawson et al (2011) and Song et al (2021). The findings demonstrate the potential of bacteria-based self-healing concrete to significantly

reduce maintenance requirements and improve the long-term durability of concrete infrastructure.

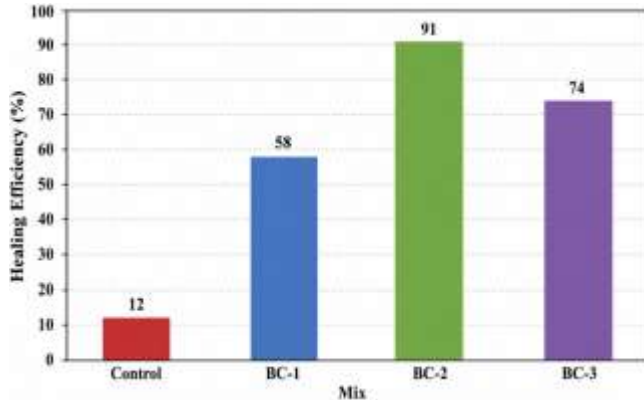


Figure 2. Crack-Healing Efficiency of Concrete Mixes

The figure clearly illustrates the substantial improvement in healing efficiency achieved through bacterial incorporation compared with conventional concrete.

#### D. Water Permeability

Water permeability is one of the most important indicators of concrete durability because it directly influences the ingress of harmful substances such as chlorides, sulfates, and carbon dioxide. The permeability results revealed substantial improvements in bacterial concrete compared with the control mixture. The reduction in permeability was directly associated with the formation of calcium carbonate deposits within pores and cracks, which reduced connectivity within the pore network.

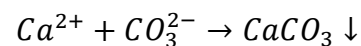
The BC-2 mixture exhibited the most significant improvement, showing approximately 82% lower water permeability than the control concrete. This reduction indicates that bacterial healing effectively restored watertightness and minimized pathways for fluid penetration. BC-1 and BC-3 also demonstrated notable permeability reductions, although their performance was slightly lower than that of BC-2. The enhanced impermeability can be attributed to both crack sealing and pore blocking caused by calcite precipitation. Similar reductions in permeability have been reported by Qian et al (2021), who observed substantial improvements in resistance to chloride ingress and

environmental deterioration due to microbial carbonate deposition.

The permeability results confirm that bacterial self-healing concrete offers considerable potential for applications in marine structures, water-retaining systems, underground facilities, and transportation infrastructure where durability is of paramount importance.

#### E. Mechanism Of Self-Healing

The self-healing mechanism in bacterial concrete is governed by microbiologically induced calcite precipitation. When cracks develop in the concrete and water penetrates the matrix, dormant *Bacillus subtilis* spores become activated. The activated bacteria utilize calcium lactate as a nutrient source and initiate metabolic processes that generate carbonate ions. These carbonate ions subsequently react with calcium ions present in the cementitious environment to form insoluble calcium carbonate crystals.



The precipitated calcium carbonate accumulates progressively within the crack volume, gradually filling voids and sealing pathways for water ingress. As the calcite crystals continue to grow, they establish strong bonds with the surrounding cement matrix, restoring impermeability and enhancing durability. The formation of calcite also contributes to pore refinement and microstructural densification, which explains the observed improvements in compressive strength and permeability resistance.

Microscopic observations conducted during the study confirmed the presence of dense calcite deposits within healed cracks, validating the effectiveness of the MICP process. The mechanism observed is consistent with findings reported by Lawson et al (2011) and Song et al (2021), who identified calcium carbonate precipitation as the primary contributor to autonomous crack repair in bacterial concrete systems.

Overall, the results demonstrate that bacteria-based self-healing concrete successfully combines biological activity with conventional concrete technology to

create a sustainable material capable of autonomously repairing cracks, enhancing durability, and extending infrastructure service life.

## V. CONCLUSIONS

The present study investigated the development and performance of bacteria-based self-healing concrete incorporating *Bacillus subtilis* spores encapsulated within lightweight expanded clay aggregates. The experimental results demonstrated that the incorporation of bacterial healing agents did not adversely affect the fresh or hardened properties of concrete. Although a slight reduction in workability was observed due to the water absorption characteristics of the lightweight aggregates, all mixtures remained within acceptable limits for structural applications. The bacterial concrete mixtures exhibited enhanced mechanical performance compared with conventional concrete, with the BC-2 mixture ( $10^6$  cells/ml bacterial concentration) achieving the highest compressive strength. The improvement of approximately 12% in compressive strength was primarily attributed to microbiologically induced calcite precipitation (MICP), which refined the pore structure and increased matrix densification.

The self-healing capability of the bacterial concrete was clearly demonstrated through significant crack closure and durability enhancement. Cracks with widths up to 0.45 mm were effectively healed within 28 days, achieving a healing efficiency of approximately 91%. Furthermore, water permeability was reduced by nearly 82% due to the deposition of calcium carbonate crystals within cracks and pores, thereby restoring the impermeability and durability of the concrete matrix. Among all tested mixtures, BC-2 exhibited the optimum balance between bacterial activity, strength enhancement, and crack-healing performance. The findings confirm that bacteria-based self-healing concrete represents a promising and sustainable construction material capable of extending infrastructure service life while reducing maintenance requirements and life-cycle costs. Future research should focus on long-term field validation, large-scale structural applications, economic feasibility

assessments, and the development of advanced encapsulation techniques to further improve bacterial viability and healing efficiency under real service conditions.

## REFERENCES

1. Andalib, R., Abd Majid, M. Z., Hussin, M. W., Ponraj, M., Keyvanfar, A., Mirza, J., & Lee, H.-S. (2016). Optimum concentration of *Bacillus megaterium* for strengthening structural concrete. *Construction and Building Materials*, 118, 180–193. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.04.142> BIS (Bureau of Indian Standards). (2009). *Concrete mix proportioning - Guidelines*. IS 10262, New Delhi, 1–14.
2. Chahal, N., Siddique, R., & Rajor, A. (2012). Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete. *Construction and Building Materials*, 28(1), 351–356. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2011.07.042>
3. Fahimizadeh, M., Pasbakhsh, P., Lee, S. M., Tan, J. B. L., Singh, R. K. R., & Yuan, P. (2024). Sustainable biologically self-healing concrete by smart natural nanotube-hydrogel system. *Developments in the Built Environment*, 18, 100384. <https://doi.org/https://doi.org/10.1016/j.dibe.2024.100384>
4. Feng, J., Chen, B., Sun, W., & Wang, Y. (2021). Microbial induced calcium carbonate precipitation study using *Bacillus subtilis* with application to self-healing concrete preparation and characterization. *Construction and Building Materials*, 280, 122460. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.122460>
5. Ghosh, P., Mandal, S., Chattopadhyay, B. D., & Pal, S. (2005). Use of microorganism to improve the strength of cement mortar. *Cement and Concrete Research*, 35(10), 1980–1983. <https://doi.org/https://doi.org/10.1016/j.cemconres.2005.03.005>

6. Giri, S., Debasree, Parhi, P., Sahani, S., & Mohanta, N. (2026). Performance Evaluation of Bacterial Based self-healing Concrete Through Systematic Experimental Investigation. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. <https://doi.org/10.1007/s40996-025-02110-y>
7. Hammad, N., El-Nemr, A., & Shaaban, I. G. (2024). The Efficiency of Calcium Oxide on Microbial Self-Healing Activity in Alkali-Activated Slag (AAS). In *Applied Sciences* (Vol. 14, Issue 12, p. 5299). <https://doi.org/10.3390/app14125299>
8. Huseien, G. F., Shah, K. W., & Sam, A. R. M. (2019). Sustainability of nanomaterials based self-healing concrete: An all-inclusive insight. *Journal of Building Engineering*, 23, 155–171. <https://doi.org/https://doi.org/10.1016/j.jobe.2019.01.032>
9. Javeed, Y., Goh, Y., Mo, K. H., Yap, S. P., & Leo, B. F. (2024). Microbial self-healing in concrete: A comprehensive exploration of bacterial viability, implementation techniques, and mechanical properties. *Journal of Materials Research and Technology*, 29, 2376–2395. <https://doi.org/https://doi.org/10.1016/j.jmrt.2024.01.261>
10. Jonkers, H. (2007). Self Healing Concrete: A Biological Approach (pp. 195–204). [https://doi.org/10.1007/978-1-4020-6250-6\\_9](https://doi.org/10.1007/978-1-4020-6250-6_9)
11. Justo-Reinoso, I., Arena, N., Reeksting, B. J., Gebhard, S., & Paine, K. (2023). Bacteria-based self-healing concrete– A life cycle assessment perspective. *Developments in the Built Environment*, 16, 100244. <https://doi.org/https://doi.org/10.1016/j.dibe.2023.100244>
12. Khoury, G. (2000). Effect of fire on concrete and concrete structures. *Progress in Structural Engineering and Materials*, 2, 429–447. <https://doi.org/10.1002/pse.51>
13. Lagazo, M. A., Noriesta, C. P. D., Montecalvo, M. A., & Alviar-Adviser, R. P. (2019). Exploratory research using bacteria (*Bacillus subtilis*) as a self-healing concrete: A basis for strengthening infrastructure in the philippine setting. *International Journal of Recent Technology and Engineering*, 8(1 Special Issue4), 125–129.
14. Lawson, I., Danso, K., Odoi, H. C., Adjei, C., & Quashie, F. (2011). Non-Destructive Evaluation of Concrete using Ultrasonic Pulse Velocity. *Research Journal of Applied Sciences, Engineering and Technology*, 3.
15. Mondal, S., & Ghosh, A. (Dey). (2021). Spore-forming *Bacillus subtilis* vis-à-vis non-spore-forming *Deinococcus radiodurans*, a novel bacterium for self-healing of concrete structures: A comparative study. *Construction and Building Materials*, 266, 121122. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.121122>
16. Patnaik, P., Durga, S., & Potharaju, M. (2023). Effect Of Type Of Nutrient On Crack Healing Performance Of Bacterial Concrete. <https://doi.org/10.21012/FC11.0923103>
17. Qian, C., Zheng, T., Zhang, X., & Su, Y. (2021). Application of microbial self-healing concrete: Case study. *Construction and Building Materials*, 290, 123226. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.123226>
18. Sarkar, M., Alam, N., Chaudhuri, B., Chattopadhyay, B., & Mandal, S. (2015). Development of an improved *E. coli* bacterial strain for green and sustainable concrete technology. *RSC Advances*, 5(41), 32175–32182. <https://doi.org/10.1039/C5RA02979A>
19. Shaheen, N., Khushnood, R., & Din, S.-U.-D. (2018). Bioimmobilized Limestone Powder for Autonomous Healing of Cementitious Systems: A Feasibility Study. *Advances in Materials Science and Engineering*, 18. <https://doi.org/10.1155/2018/7049121>
20. Song, Y., Chetty, K., Garbe, U., Wei, J., Bu, H., O'moore, L., Li, X., Yuan, Z., McCarthy, T., & Jiang, G. (2021). A novel granular sludge-based and highly corrosion-resistant bio-concrete in sewers. *Science of The Total Environment*, 791, 148270. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.148270>

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ISSN (Print): 2395-4752

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Engineering and Technology  
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21. Tie, Y., Ji, Y., Zhang, H., Jing, B., Zeng, X., & Yang, P. (2024). Investigation on the Mechanical Properties of Bacillus Subtilis Self-healing Concrete.

22. Heliyon, 10, e34131.  
<https://doi.org/10.1016/j.heliyon.2024.e34131>

23. Tsioulou, O., Lampropoulos, A., & Paschalis, S. (2017). Combined Non-Destructive Testing (NDT) method for the evaluation of the mechanical characteristics of Ultra High Performance Fibre Reinforced Concrete (UHPFRC). Construction and Building Materials, 131, 66–77.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.11.068>