International Scientific Journal of Engineering and Management (ISJEM) **ISSN: 2583-6129**
Volume: 05 Issue: 04 | April – 2026 **DOI:10.55041/ISJEM06786**
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

A Review on Bacterial Concrete: Mechanisms, Applications and Performance Enhancement

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ABSTRACT

Cracking in concrete is an inevitable phenomenon caused primarily by its low tensile strength, resulting in increased permeability, reduced durability, and accelerated structural deterioration. Bacterial concrete has emerged as a sustainable material capable of autonomously healing cracks through Microbiologically Induced Carbonate Precipitation (MICP). In this process, specific bacterial strains precipitate calcium carbonate that seals cracks and densifies the concrete matrix. Research shows improvements in compressive strength, significant reductions in water absorption, and enhanced resistance to chemical attack when bacterial concrete is utilized. This review examines the mechanisms behind MICP, methods of bacterial incorporation, mechanical and durability performance, and current applications. Additionally, it highlights limitations—particularly ammonia generation by ureolytic bacteria—and identifies future research directions for sustainable implementation. Overall, bacterial concrete presents a promising pathway toward durable, maintenance-efficient, and environmentally friendly construction materials.

Keywords: Bacterial concrete, Bacilus subtilis, MICP, compressive strength, self-healing concrete

I. INTRODUCTION

Concrete is the most widely used construction material due to its relatively low cost, flexibility in design, and high compressive strength. Despite these advantages, a major drawback of concrete lies in its inherently low tensile strength, which makes it susceptible to cracking. These cracks—whether micro-cracks formed during curing or macro-cracks caused by external loads—serve as pathways for the ingress of water, chemicals, and harmful ions.

Recent advancements in sustainable construction materials have introduced bacterial concrete, an innovative self-healing technology inspired by biological processes. Bioconcrete integrates specific strains of bacteria and suitable nutrients into the concrete matrix. When cracks occur and moisture enters, these bacteria activate and initiate a process known as Microbiologically Induced Carbonate Precipitation (MICP). Through this mechanism, the microorganisms generate calcium carbonate deposits that fill and seal cracks naturally. This approach not only enhances durability but also aligns with the growing emphasis on environmentally friendly construction practices.

Over the past decade, extensive research has explored MICP-based techniques, bacterial encapsulation strategies, healing efficiencies, and mechanical improvements resulting from biological activity. This review paper synthesizes the current state of knowledge on bacterial concrete, focusing on its mechanism, applications, mechanical behavior, durability characteristics, and challenges. Special attention is given to limitations such as ammonia emissions from ureolytic bacteria and concerns regarding long-term viability and cost.

II. Litreature Review:

Henk M. Jonkers (2010), who introduced the concept of self-healing concrete using bacteria. His research demonstrated that Bacillus species embedded in concrete could precipitate calcium carbonate when activated by water ingress, effectively sealing cracks up to 0.5 mm. Jonkers also emphasized the importance of encapsulating bacteria in lightweight aggregates to ensure their survival in the highly alkaline concrete environment.

Ramachandran et al. (2001) investigated the role of microbial calcite precipitation in concrete improvement. Their study showed that bacterial treatment significantly enhanced compressive strength and reduced permeability.

They concluded that microbial mineral deposition could serve as an effective method for crack remediation and surface protection.

De Muynck et al. (2010) focused on the application of bacterial carbonate precipitation for improving the durability of cementitious materials. Their findings indicated that bacterial concrete exhibited reduced water absorption and increased resistance to chloride ion penetration. The study highlighted that the deposition of calcite crystals refines the pore structure, thereby enhancing long-term durability.

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Research by Achal et al. (2011) explored the use of ureolytic bacteria such as Sporosarcina pasteurii for crack healing. The authors reported improvements in compressive strength and a substantial decrease in water permeability. However, they also pointed out the environmental concern associated with ammonia production during the ureolysis process.

Wiktor and Jonkers (2011) examined the effectiveness of encapsulated bacterial spores in self-healing concrete. Their study confirmed that encapsulation techniques significantly improved bacterial viability and healing efficiency. They observed that cracks could be autonomously healed when moisture and oxygen triggered bacterial activity.

Ghosh et al. (2005) studied the enhancement of concrete strength using microbial activity. Their results showed that the addition of bacteria increased compressive strength and reduced porosity. The study attributed these improvements to the precipitation of calcium carbonate within the cement matrix.

Van Tittelboom and De Belie (2013) provided a comprehensive review of self-healing concrete technologies, including bacterial approaches. They compared different healing mechanisms and concluded that bacterial concrete is one of the most promising methods due to its ability to provide autonomous and long-term crack repair.

More recently, Seifan et al. (2016) reviewed the advancements in MICP and highlighted its potential for sustainable construction. The authors discussed various bacterial pathways and emphasized the need to develop non-ureolytic methods to overcome the issue of ammonia generation.

Wang et al. (2014) investigated the use of encapsulated bacteria in concrete and reported significant improvements in crack healing efficiency and durability properties. Their study demonstrated that the use of protective carriers enhances bacterial survival and prolongs healing activity.

III. Mechanism of Bacterial Concrete

A. Microbiologically Induced Carbonate Precipitation (MICP)

The fundamental mechanism behind bacterial concrete is the precipitation of calcium carbonate ($CaCO_3$) by microorganisms. Among several biochemical pathways that produce carbonate minerals, ureolytic MICP is the most studied and commonly applied. In this pathway, bacteria such as Sporosarcina pasteurii contain the enzyme urease, which catalyzes the hydrolysis of urea into ammonia and carbon dioxide. The reaction increases local alkalinity, enabling $CaCO_3$ to precipitate in the presence of calcium ions. When this process occurs inside cracks, the resulting minerals act as fillers that bond to the concrete matrix.

B. Conditions Required for MICP

Effective precipitation depends on favorable conditions, including nutrient availability, moisture, pH, and oxygen levels. Concrete’s naturally alkaline environment is suitable for many spore-forming bacteria, which can remain dormant until activated. Moisture infiltration through cracks triggers bacterial metabolism, creating an autonomous healing response.

C. Bacterial Selection

Ideal strains for MICP should tolerate high pH, survive mechanical mixing during casting, and produce urease efficiently. Spore-forming, non-pathogenic bacteria such as Bacillus and Sporosarcina species are preferred because they can remain viable for long durations. Genetic engineering approaches have also been explored to improve metabolic efficiency, though these methods raise regulatory and environmental concerns.

IV. Methods of Incorporating Bacteria in Concrete

A. Direct Addition Method

In this method, bacterial spores and nutrients are directly mixed into the concrete. Although easy to implement, survival rates may be reduced due to mechanical stress and high temperature during hydration. Nutrients such as urea or calcium lactate must be carefully proportioned to prevent adverse effects on fresh properties.

B. Encapsulation Techniques

Encapsulation protects bacteria from harsh conditions within the fresh concrete matrix. Carriers such as silica gel, lightweight aggregates, expanded clay, and polymeric capsules are commonly used. Encapsulation improves bacterial viability and provides controlled nutrient release, enhancing long-term healing potential.

C. Surface Treatment and Spraying

For existing structures, bacterial solutions can be sprayed onto surfaces or injected into cracks. This method is particularly useful for repair applications and for structures exposed to aggressive environments. The treatment forms a protective layer of $CaCO_3$ that reduces permeability and slows deterioration.

D. Vascular and Network Systems

Emerging approaches involve embedding microvascular networks within concrete. These hollow channels deliver bacterial cultures or nutrients upon crack formation. Although promising, such techniques are still experimental and increase construction complexity.

V. Mechanical Properties of Bacterial Concrete

A. Compressive Strength

Research consistently reports improvements in compressive strength due to MICP. Calcium carbonate deposition reduces pore connectivity and increases matrix density, which contributes to strength gains. Studies show increases ranging from moderate (10%) to significant (over 30%) depending on bacterial concentration, nutrient addition, and curing conditions. The densified microstructure also reduces micro-crack propagation, leading to improved load-bearing capacity.

B. Tensile and Flexural Strength

Concrete’s tensile performance remains a primary concern. Bacterial precipitation contributes to better crack resistance and reduced crack width, indirectly enhancing tensile and flexural properties. While increases in these properties are smaller than for compressive strength, they are still notable and contribute to improved durability.

C. Microstructural Modifications

Scanning electron microscopy often reveals needle-shaped or rhombohedral $CaCO_3$ crystals that bridge crack surfaces. These mineral formations bond to the hydrated cement matrix, reducing voids and improving overall microstructural integrity.

VI. Durability Enhancement

A. Water Absorption and Permeability

One of the most significant benefits of bacterial concrete is reduced water absorption. The $CaCO_3$ layer formed inside cracks and pores greatly diminishes permeability, which is essential for structures exposed to moisture and freeze-thaw cycles. Reductions of several- fold have been reported, demonstrating strong potential for protective applications.

B. Resistance to Chemical Attack

Concrete often deteriorates when exposed to acids, sulfates, or chloride ions. Bacterial self- healing provides an additional barrier that slows penetration of harmful substances. Improved resistance to acid attack results from the dense $CaCO_3$ deposits, which neutralize acidic environments and limit internal damage.

C. Reduced Corrosion of Reinforcement

By limiting crack width and sealing pathways for chloride ingress, bacterial concrete indirectly protects steel reinforcement. This is particularly beneficial for coastal structures, bridges, and wastewater systems. The self-healing mechanism is activated repeatedly as cracks form, providing long-term corrosion mitigation.

VII. Applications of Bacterial Concrete

A. Infrastructure and Transportation Structures

Highways, bridges, parking structures, and pavements benefit from bacterial concrete’s crack-healing ability. Autonomous healing reduces maintenance needs and extends service life without the need for frequent repairs.

B. Water Retaining and Hydraulic Structures

Canals, dams, and reservoirs require materials with low permeability. MICP-based healing significantly improves impermeability, making bacterial concrete suitable for water-retaining applications.

C. Precast Components

Precast industries can carefully control bacterial concentrations and curing conditions, making bacterial concrete attractive for precast blocks, slabs, pipes, and façade elements. Encapsulation methods fit well with controlled factory environments.

D. Heritage Conservation

$CaCO_3$ produced by bacteria is chemically similar to natural limestone, making it suitable for repairing historical stone structures. The gentle, biologically compatible healing process preserves the authenticity of ancient materials.

VIII. Limitations and Challenges

A. Ammonia Production

A major concern associated with ureolytic bacteria is the production of ammonia during urea hydrolysis. Ammonia is a potent pollutant that can impact air quality and lead to environmental toxicity. This has prompted exploration of non-ureolytic pathways such as denitrification or photosynthetic MICP, which produce $CaCO_3$ without harmful byproducts.

B. Cost and Scalability

Embedding bacteria and encapsulating agents increases material costs. Scaling production for large infrastructure projects requires significant investment. However, long-term savings from reduced maintenance may justify initial expenses.

D. Long-Term Viability of Bacteria

Maintaining bacterial viability over decades remains a challenge. Spores can survive long periods, but nutrient depletion, temperature variations, and hydration cycles may reduce effectiveness over time.

E. Standardization and Regulatory Barriers

Bacterial concrete is still in the research and development phase, and standardized guidelines for production, quality control, and implementation are limited. Widespread adoption requires robust codes and acceptance criteria.

IX. Future Prospects

Future research is shifting toward environmentally safe, cost-effective, and high-efficiency bacterial systems. Promising directions include:

- Developing non-ureolytic bacteria to eliminate ammonia emissions.
- Improving encapsulation materials to extend bacterial viability.
- Integrating nanomaterials to enhance precipitation efficiency.
- Designing smart vascular systems for repeated healing cycles.
- Exploring genetically engineered microorganisms for improved performance, while addressing safety concerns.

Advancements in biotechnology and materials engineering indicate strong potential for bacterial concrete to become a mainstream sustainable construction solution.

X. Conclusion

Bacterial concrete represents a significant innovation in sustainable construction materials. By utilizing microbial processes to precipitate calcium carbonate, this technology provides autonomous crack healing, improved durability, and enhanced mechanical properties. Its ability to reduce permeability, protect reinforcement, and strengthen the microstructure offers substantial advantages over conventional repair methods. Despite challenges such as ammonia production, cost, and questions regarding long-term viability, ongoing research continues to refine the technology. With further development and standardization, bacterial concrete has the potential to revolutionize the way infrastructure is designed, maintained, and preserved.

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