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# Microbially Induced Calcium Carbonate Precipitation in Self-Healing Concrete: A Review

Rashmi P. Wade[1], Dr. A. W. Kharche[2], Dr. A. A. Malokar[3]
[1]*Research Scholar, Department of Civil Engineering , Padm. Dr. V. B. Kolte College of Engineering Malkapur, India*
[2]*Professor, Department of Civil Engineering , Padm. Dr. V. B. Kolte College of Engineering Malkapur, India*
[3]*Assistant Professor, Department of Civil Engineering , Padm. Dr. V. B. Kolte College of Engineering Malkapur, India*

***Abstract: Microbially Induced Calcium Carbonate Precipitation (MICP) has emerged as a promising bio-based technology for developing self-healing concrete capable of autonomously repairing cracks and enhancing structural durability. This review presents a comprehensive analysis of recent advancements in microbial self-healing concrete, focusing on biomineralization mechanisms, bacterial and fungal species, carrier materials, encapsulation techniques, endospore technology, and calcium carbonate-precipitating biomass additives. The role of MICP in improving mechanical properties, reducing permeability, enhancing durability, and extending the service life of concrete structures is critically examined. Furthermore, the application of microbial mineralization in low-carbon cementitious materials, environmental remediation, heavy metal immobilization, and historical structure restoration is discussed. The findings indicate that MICP-based self-healing systems offer significant environmental and economic benefits by reducing maintenance requirements and supporting carbon-neutral construction practices. Despite substantial progress, challenges related to microbial survival, large-scale implementation, and long-term field performance remain. Future research directions for improving the efficiency and commercialization of MICP technology are also highlighted.***
***Keywords: Microbially Induced Calcium Carbonate Precipitation (MICP), Self-healing concrete, Biomineralization, Calcium carbonate precipitation, Bioconcrete, Sustainable construction.***

## I. INTRODUCTION

Concrete is the most widely used construction material in the world due to its high compressive strength, versatility, durability, and cost-effectiveness. It is extensively utilized in residential buildings, bridges, highways, tunnels, dams, and other infrastructure projects. Despite its numerous advantages, concrete is inherently susceptible to cracking because of shrinkage, thermal stresses, mechanical loading, environmental exposure, and aging. The formation of cracks not only compromises the structural integrity of concrete but also facilitates the ingress of water, chlorides, sulfates, and other aggressive agents. These substances accelerate reinforcement corrosion, increase permeability, reduce durability, and ultimately shorten the service life of structures. Consequently, regular inspection, maintenance, and repair activities are required, resulting in substantial economic costs and environmental impacts throughout the lifespan of infrastructure.

In recent years, self-healing concrete has emerged as an innovative and sustainable solution to address the challenges associated with crack formation and durability deterioration. Self-healing concrete possesses the ability to autonomously repair cracks without external intervention, thereby restoring its original performance and extending service life. Various self-healing approaches have been investigated, including autogenous healing, encapsulated healing agents, shape memory materials, and biological healing methods. Among these techniques, Microbially Induced Calcium Carbonate Precipitation (MICP) has attracted considerable attention due to its eco-friendly nature, effectiveness, and long-term healing potential.

MICP is a biomineralization process in which microorganisms induce the precipitation of calcium carbonate ($CaCO_3$) through their metabolic activities. Specific bacterial species, particularly those belonging to the *Bacillus* genus, can survive under highly alkaline conditions and produce carbonate ions that react with calcium ions to form calcite crystals. These calcium carbonate precipitates accumulate within cracks, pores, and voids of concrete, effectively sealing the damaged regions and reducing permeability. The precipitated calcite exhibits strong compatibility with the cement matrix and contributes to the recovery of mechanical and durability properties. As a result, MICP-based self-healing concrete has emerged as a promising alternative to conventional repair techniques. The growing interest in microbial self-healing concrete is closely associated with global sustainability and carbon neutrality objectives. Traditional concrete repair and rehabilitation activities consume significant quantities of materials, energy, and financial resources while generating additional carbon emissions.

By enabling autonomous crack repair and extending structural lifespan, MICP technology can reduce maintenance requirements, conserve resources, and minimize the environmental footprint of infrastructure systems. Furthermore, the biomineralization process itself contributes to carbon sequestration through the formation of stable carbonate minerals, thereby supporting sustainable construction practices and circular economy principles.

Recent research has focused on enhancing the efficiency and reliability of microbial self-healing systems through the development of advanced bacterial strains, endospore technologies, carrier materials, encapsulation techniques, biomass-based healing agents, and predictive modeling approaches. In addition, the application of MICP has expanded beyond crack healing to include soil stabilization, environmental remediation, heavy metal immobilization, restoration of historical structures, and low-carbon cementitious materials. These developments demonstrate the versatility and multidisciplinary nature of microbial biomineralization technology.

Although substantial progress has been achieved in understanding the mechanisms and applications of MICP, several challenges remain related to bacterial survival, healing efficiency, large-scale implementation, and long-term performance under field conditions. Therefore, a comprehensive review of recent advancements is essential to evaluate the current state of knowledge and identify future research opportunities. This review aims to critically examine the principles, mechanisms, influencing factors, carrier systems, biomineralization processes, and practical applications of microbial-induced calcium carbonate precipitation in self-healing concrete, while highlighting its potential contribution toward durable, sustainable, and carbon-neutral infrastructure development.

## II. LITERATURE REVIEW

### *1) Overview of Microbially Induced Calcium Carbonate Precipitation (MICP) for Self-Healing Concrete*

The increasing demand for sustainable and durable construction materials has accelerated research on bio-based self-healing concrete technologies. Among these technologies, Microbially Induced Calcium Carbonate Precipitation (MICP) has emerged as one of the most promising approaches for autonomous crack repair in cementitious materials. MICP utilizes microbial metabolic activities to precipitate calcium carbonate ($CaCO_3$), which fills cracks and pores within concrete, thereby restoring mechanical properties and reducing permeability. The technology contributes to improved service life of structures, reduced maintenance requirements, and enhanced environmental sustainability.

Garg et al. (2023) conducted a comprehensive review of microbial-induced calcite precipitation for self-healing concrete and highlighted that bacterial strains capable of biomineralization can effectively produce calcium carbonate deposits within cracks. The study reported that microbial concrete, often referred to as bioconcrete, demonstrates significant improvements in durability, crack-sealing efficiency, and resistance to water ingress. The authors emphasized that the selection of suitable bacterial species and nutrient sources remains critical for successful field implementation.

### *2) MICP and Carbon Neutrality*

The role of MICP extends beyond crack healing and structural durability. Chang et al. (2024) reviewed the application of MICP in concrete self-healing and environmental restoration with a focus on carbon neutrality. The study explained that carbonate mineral precipitation induced by microbial activity can contribute to carbon sequestration while simultaneously enhancing concrete performance. The review demonstrated that MICP has the potential to reduce the environmental impact of construction by extending infrastructure lifespan and minimizing the need for repair materials. Furthermore, microbial biomineralization was identified as a sustainable alternative to conventional chemical repair methods due to its lower carbon footprint and compatibility with circular economy principles.

### *3) Bacterial Species and Biomineralization Mechanisms*

The effectiveness of MICP largely depends on the bacterial strains employed and their biomineralization capabilities. Li et al. (2024) investigated the $CaCO_3$ precipitation process induced by *Bacillus mucilaginosus* and evaluated its potential application in microbial self-healing concrete. The study demonstrated that the bacterium effectively precipitated calcium carbonate through metabolic activity, leading to substantial crack-filling capability. The authors concluded that incorporating microbial healing agents into concrete mixtures could significantly improve self-healing performance while maintaining structural integrity.

Similarly, Jiang et al. (2024) reviewed microbial-induced carbonate precipitation methods for concrete crack repair and discussed the role of various bacterial species, including sulfate-reducing bacteria. Their findings suggested that microbial diversity can influence the morphology, quantity, and durability of precipitated calcium carbonate. The study further emphasized the importance of selecting microorganisms capable of surviving the highly alkaline concrete environment.

*4) Enhancement of Bacterial Survival through Encapsulation and Immobilization*

One of the primary challenges associated with MICP-based self-healing concrete is maintaining bacterial viability during concrete mixing and throughout the service life of structures. To address this issue, several researchers have explored bacterial encapsulation and immobilization techniques.

Xu et al. (2024) investigated cellulose-immobilized bacteria for self-healing concrete applications. The study demonstrated that cellulose-based immobilization provided protective environments for bacterial cells, enhancing their survival and calcium ion adsorption capacity. Improved bacterial viability resulted in increased calcium carbonate precipitation and more effective crack closure. The authors reported that immobilized bacterial systems offer a practical approach for long-term self-healing performance.

Rahmaninezhad and co-workers (2026) further examined the impact of cell encapsulation on microbial-induced calcium carbonate precipitation. Their research focused on optimizing exogenous carbonate sources and bacterial encapsulation methods to improve precipitation efficiency. The findings revealed that encapsulated bacterial cells acted as nucleation sites for calcium carbonate formation, thereby enhancing crack-healing performance and mineral yield.

*5) Endospore-Based Self-Healing Systems*

The use of bacterial endospores has gained considerable attention due to their exceptional resistance to harsh environmental conditions. Rahmaninezhad et al. (2024) developed enhanced endospores through thermal shock treatment for application in microbial-induced calcium carbonate precipitation. The study demonstrated that thermally conditioned endospores exhibited superior durability and remained viable under challenging concrete environments. Experimental results indicated increased calcium carbonate production and improved crack-healing efficiency compared to conventional bacterial cultures.

The research highlighted that endospore-based systems represent a promising solution for overcoming the limitations associated with bacterial survival in cementitious matrices. The enhanced resilience of endospores ensures long-term healing functionality even after extended periods of dormancy.

*6) Prediction and Modeling of MICP Performance*

Accurate prediction of microbial self-healing behavior is essential for large-scale engineering applications. Lee et al. (2025) developed predictive models for microbial-induced calcium carbonate precipitation in cementitious materials. The study utilized experimental datasets to establish relationships between microbial activity, calcium carbonate production, and crack-healing efficiency. The developed models successfully predicted self-healing performance and recovery of material properties.

The authors suggested that predictive modeling could facilitate optimization of bacterial concentration, nutrient dosage, and environmental conditions, thereby improving the reliability of MICP technology in practical construction applications.

*7) MICP Performance under Extreme Environmental Conditions*

The effectiveness of MICP can be influenced by environmental factors such as temperature, salinity, and pH. Abdelwahed et al. (2026) investigated microbial-induced calcium carbonate precipitation under extreme environmental conditions and evaluated its effects on biomineralization and concrete performance. The study demonstrated that environmental stress significantly affects microbial metabolism and calcium carbonate precipitation rates. Nevertheless, certain bacterial strains maintained effective biomineralization capabilities even under adverse conditions.

The findings indicated that understanding environmental influences is essential for designing robust self-healing concrete systems suitable for diverse climatic regions and infrastructure applications.

*8) High-Temperature Performance and Bond Enhancement*

In addition to crack healing, MICP technology has been explored for improving concrete properties following exposure to elevated temperatures. Chen et al. (2024) applied microbial-induced calcium carbonate precipitation technology to enhance the bond strength of lightweight aggregate concrete subjected to high-temperature conditions. The results revealed that microbial biomineralization improved interfacial bonding and contributed to partial recovery of mechanical properties after thermal damage.

The study demonstrated the potential of MICP not only as a self-healing mechanism but also as a rehabilitation strategy for thermally damaged concrete structures.

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*9) MICP*

Despite significant advancements, several challenges remain in the implementation of MICP-based self-healing concrete. Current research indicates the need for:

*1)* Development of cost-effective bacterial encapsulation techniques.
*2)* Improvement in long-term bacterial viability within concrete matrices.
*3)* Standardization of testing methods for evaluating self-healing efficiency.
*4)* Investigation of field-scale applications and long-term durability.
*5)* Integration of artificial intelligence and predictive modeling for optimization of biomineralization processes.
*6)* Assessment of carbon sequestration potential and lifecycle environmental benefits.
*7)* Evaluation of MICP performance under varying climatic and loading conditions.

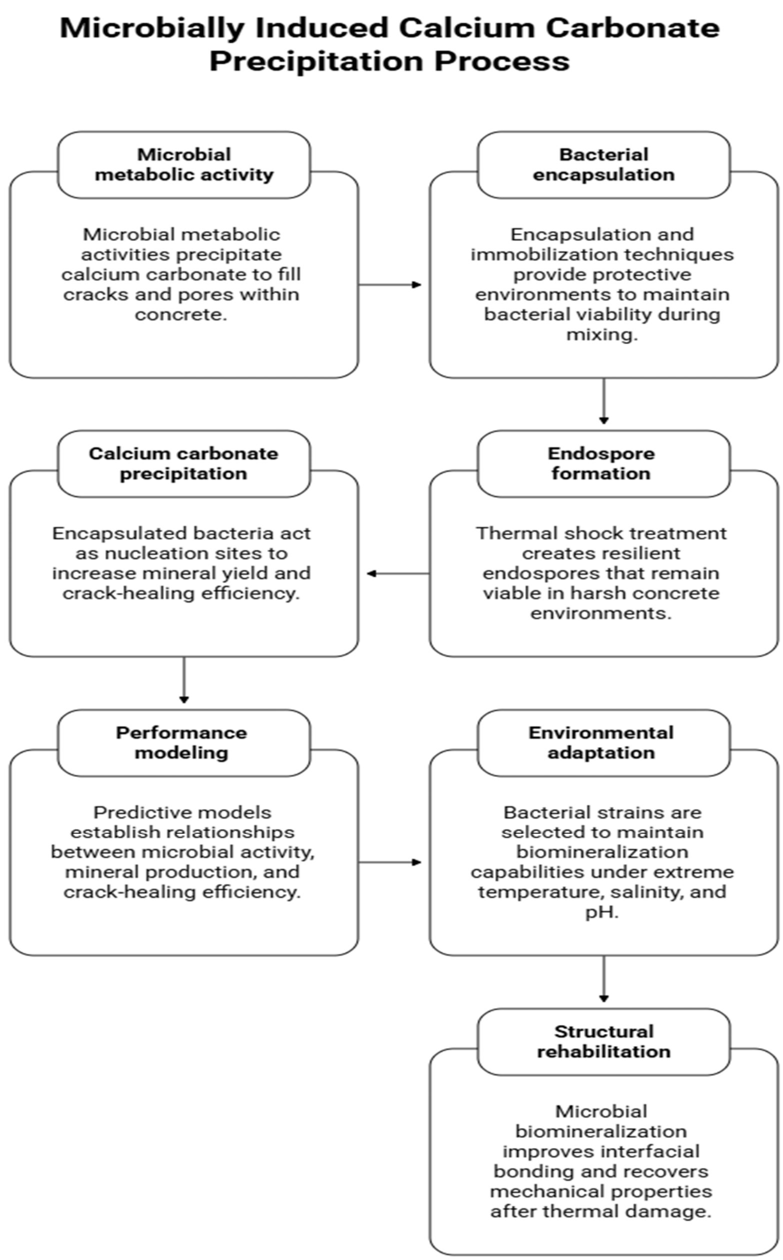


Figure 1: Microbially Induced Calcium Carbonate Precipitation Process

*10) Mineralization Mechanisms and Microstructural Characterization*

Recent studies have focused on understanding the mineralization mechanisms associated with MICP and their influence on crack-healing efficiency. Li et al. (2026) investigated the mineralization effects of microbially induced calcite precipitation in Strain-Hardening Cementitious Composites (SHCC). The study systematically evaluated the relationship between influencing factors, microstructural development, and self-healing performance. The results demonstrated that microbial calcite precipitation effectively filled microcracks and pore networks, resulting in improved mechanical properties and reduced permeability. Microstructural analyses revealed that the morphology and distribution of calcite crystals significantly affected healing efficiency. The authors concluded that optimized biomineralization processes can substantially enhance the durability of SHCC materials.

*11) Bio-Based Solutions for Sustainable Concrete Infrastructure*

The growing emphasis on sustainable construction has increased interest in bio-based repair technologies. Omoregie et al. (2025) presented a comprehensive review of microbial-induced carbonate precipitation as a bio-based solution for concrete infrastructure. The review highlighted the evolution of concepts such as bacterial concrete, bioconcrete, and self-healing concrete. The study discussed various microbial pathways responsible for calcium carbonate formation and emphasized their role in autonomous crack repair. The authors reported that MICP-based technologies offer significant environmental advantages by reducing maintenance interventions, extending service life, and lowering lifecycle carbon emissions. Consequently, microbial biomineralization was identified as a promising strategy for achieving sustainable and resilient infrastructure systems.

*12) MICP for Infrastructure Durability and Sustainability*

Rollakanti and Srinivasu (2022) reviewed the role of MICP in enhancing infrastructure durability and sustainability. Their study highlighted the widespread application of microbial-induced calcium carbonate precipitation in construction technology. The review demonstrated that self-healing concrete developed through MICP significantly improves resistance to crack propagation, water penetration, and chemical deterioration. Furthermore, the technology contributes to sustainable construction practices by reducing repair frequency and conserving construction resources. The authors suggested that large-scale implementation of MICP could play an important role in extending the operational lifespan of civil engineering structures.

*13) Fungal-Induced Calcium Carbonate Mineralization*

Although bacterial species dominate MICP research, fungal biomineralization has also emerged as a viable self-healing approach. Elkhateeb et al. (2022) investigated fungal calcium carbonate mineralization for concrete self-healing applications. The study demonstrated that fungal species can induce substantial calcium carbonate precipitation through biological processes similar to bacterial mineralization. Due to their filamentous growth patterns and greater tolerance to harsh environmental conditions, fungi exhibited enhanced survival within concrete matrices. The resulting biomineralization effectively sealed cracks and improved the durability of cementitious materials. The authors concluded that fungal self-healing systems represent a promising alternative to bacterial-based approaches.

*14) Environmental Applications of Self-Healing MICC Materials*

Beyond structural repair, MICP technology has shown considerable potential in environmental remediation. Xue et al. (2023) investigated self-healing microbial-induced calcium carbonate (MICC) materials for preventing $Pb^{2+}$ migration under harsh circular environmental conditions.

The study demonstrated that calcium carbonate precipitates generated through microbial activity effectively immobilized heavy metal ions by forming stable mineral complexes. The self-healing characteristics of MICC materials simultaneously repaired structural defects while reducing contaminant mobility. These findings highlight the potential integration of MICP technology into environmental protection and waste containment systems. In a related study, Xue et al. (2023) developed the first microcapsule-based self-healing MICC material for controlling lead ion migration. The microcapsule system protected microbial agents and ensured controlled release during crack formation. Experimental results indicated enhanced calcium carbonate precipitation, improved crack-sealing capability, and effective heavy metal immobilization. The research demonstrated the versatility of MICP technology in addressing both infrastructure maintenance and environmental challenges.

*15) MICP in Low-Carbon Cement Systems*

The development of low-carbon cementitious materials has become a major research priority in sustainable construction. Wei et al. (2024) explored the application of MICP technology in Limestone Calcined Clay Cement (LC3), a low-carbon alternative to ordinary Portland cement.

Bacillus pasteurii was employed to induce calcium carbonate precipitation and improve the self-healing capacity of LC3-based composites. The study reported substantial crack closure, enhanced durability, and improved resistance to water penetration. The findings suggest that combining MICP with low-carbon binders can further reduce the environmental footprint of concrete while maintaining satisfactory structural performance.

*16) Novel Alkaliphilic Bacterial Strains for Self-Healing Bio-Mortar*

The search for highly effective microbial strains remains an active area of research. Ibrahim et al. (2026) introduced a novel alkaliphilic Bacillus albus strain capable of inducing calcite precipitation under highly alkaline conditions. The study evaluated the performance of bio-mortar specimens incorporating the bacterial strain and reported significant improvements in compressive strength, crack-healing efficiency, and durability. The enhanced performance was attributed to the strain's ability to survive within cementitious environments and generate substantial quantities of calcium carbonate. The research demonstrated the importance of microbial selection in optimizing self-healing concrete systems.

*17) Mechanical Strength Enhancement through Microbial Calcite Induction*

Ali et al. (2023) reviewed the role of microbial calcite induction in strengthening and healing concrete structures. The authors described bio-concrete as an innovative material based on microbial-induced calcium carbonate precipitation capable of improving both mechanical performance and durability. The review reported that microbial calcite formation densifies the concrete microstructure, reduces porosity, and increases compressive strength. In addition, the self-healing capability minimizes crack propagation and extends service life. The study concluded that microbial calcite induction offers a multifunctional approach to enhancing structural performance while supporting sustainable construction objectives.

*18) MICP for Historical Architecture Restoration*

Applications of MICP are not limited to modern concrete structures. Wang and Wang (2025) reviewed the use of microbial-induced calcium carbonate precipitation in the restoration and preservation of historical architecture. The study highlighted the compatibility of microbial biomineralization with heritage materials, particularly stone and masonry structures. Unlike conventional repair techniques, MICP provides a non-invasive restoration method that maintains the original appearance and material integrity of historic buildings. The authors reported successful applications in crack repair, surface consolidation, and weathering resistance enhancement. These findings demonstrate the broader applicability of MICP technology beyond contemporary civil infrastructure.

*19) Calcium Carbonate-Precipitating Biomass as a Self-Healing Additive*

The development of bio-based healing agents has emerged as an effective strategy for improving the performance of self-healing concrete. Zhu et al. (2023) investigated the production of calcium carbonate-precipitating biomass (CPB) powder as a self-healing additive for cementitious materials. The study evaluated the effectiveness of CPB in mortar specimens subjected to cracking conditions. Experimental results demonstrated that the biomass powder promoted substantial calcium carbonate precipitation, leading to effective crack closure and improved durability. Furthermore, the incorporation of CPB enhanced resistance against aggressive environmental conditions while maintaining the mechanical integrity of the mortar. The authors concluded that CPB represents a practical and sustainable bio-additive for autonomous crack repair in concrete structures.

*20) Role of Carrier Materials in Microbial Self-Healing Systems*

One of the major limitations of MICP technology is the reduced survival of microorganisms within the highly alkaline concrete environment. To overcome this challenge, researchers have explored the use of carrier materials capable of protecting bacterial cells and nutrients.

Feng et al. (2022) reviewed the application of carrier materials in self-healing cement-based materials utilizing microbial-induced mineralization. The study highlighted various carriers, including lightweight aggregates, hydrogels, expanded clay, silica gel, diatomaceous earth, and polymeric capsules. These materials provide protective microenvironments that enhance microbial viability and ensure long-term healing functionality.

The review demonstrated that carrier-assisted systems significantly improve calcium carbonate precipitation efficiency, crack-healing performance, and durability of cementitious composites. The authors emphasized that the selection of suitable carrier materials is critical for successful field implementation of microbial self-healing technologies.

*21) Microbially Induced Self-Healing Bioconcrete for Sustainable Development*

The contribution of microbial self-healing concrete toward sustainable development has attracted increasing research attention. Vanjinathan et al. (2024) investigated the development of microbial self-healing bioconcrete and evaluated its crack-healing performance through microstructural and chemical analyses. Due to the high alkalinity of concrete, bacterial strains capable of surviving extreme conditions were incorporated into the cement matrix. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) analyses confirmed the formation of calcium carbonate crystals within cracks and voids.

The study reported significant crack-healing efficiency and improved durability characteristics resulting from microbial mineralization. The precipitation of calcium carbonate effectively reduced permeability and increased resistance to environmental degradation. The authors concluded that microbial self-healing bioconcrete offers a sustainable alternative to conventional repair approaches by reducing maintenance requirements and extending structural service life.

*22) Comprehensive Review of Microbial Self-Healing Concrete*

Li et al. (2026) presented a comprehensive review of microbial self-healing concrete, covering mechanisms, applications, performance evaluation, and future research directions. The review discussed the fundamental principles of microbial-induced calcium carbonate precipitation and summarized recent advances in bacterial selection, encapsulation technologies, biomimetic approaches, and healing efficiency assessment.

The authors highlighted that biomimetic self-healing systems inspired by natural biological processes have demonstrated considerable potential in improving crack repair performance. Furthermore, advances in hierarchical healing structures, nutrient delivery systems, and intelligent microbial carriers were identified as key developments driving the next generation of self-healing concrete technologies. The review emphasized that integration of biotechnology, material science, and digital monitoring systems could significantly accelerate commercialization of microbial self-healing concrete.

*23) Improvement of Mechanical Properties and Durability through Bacterial Calcium Carbonate Precipitation*

Rajendiran et al. (2025) investigated the enhancement of durability and mechanical properties of self-compacting concrete through bacterial calcium carbonate precipitation. The study evaluated the influence of microbial activity on compressive strength, durability, and self-healing performance of concrete specimens. Results indicated that bacterial-induced calcium carbonate effectively filled pores and microcracks, leading to a denser microstructure and reduced permeability.

The researchers observed notable improvements in compressive strength and resistance to water penetration compared with conventional concrete. In addition, microbial mineralization enhanced crack-sealing capability, contributing to improved long-term durability. The findings confirmed that bacterial calcium carbonate precipitation represents a viable technique for developing high-performance and durable self-healing concrete systems.

*24) Synthesis of Recent Developments*

The recent literature demonstrates a clear progression from basic microbial crack-healing mechanisms toward advanced engineered self-healing systems. Current developments focus on:

- Calcium carbonate-precipitating biomass powders as bio-healing agents.
- Advanced carrier materials for microbial protection and nutrient delivery.
- Sustainable bioconcrete systems with enhanced durability.
- Biomimetic and hierarchical self-healing approaches.
- Improvement of mechanical properties through controlled biomineralization.
- Integration of microbial technologies with sustainable construction practices.

These advancements collectively indicate that microbial self-healing concrete is evolving into a mature technology capable of addressing durability, sustainability, and carbon-reduction objectives in modern civil engineering infrastructure.

## III. CONCLUSIONS

Although significant progress has been achieved in microbial self-healing concrete, several challenges remain unresolved. Most studies have focused on laboratory-scale investigations, while limited information is available regarding field-scale implementation and long-term performance under real service conditions. The influence of environmental factors such as cyclic loading, temperature fluctuations, and chemical exposure on microbial activity requires further investigation. Additionally, optimization of bacterial carriers, nutrient delivery mechanisms, and large-scale production of bio-healing agents remains an important research area. Future studies should also focus on life-cycle assessment, economic feasibility, and integration of artificial intelligence-based monitoring systems to facilitate practical adoption of MICP technology in sustainable infrastructure development.

The reviewed literature demonstrates a rapid expansion of MICP research across multiple domains, including self-healing concrete, low-carbon construction materials, environmental remediation, historical structure preservation, and advanced biomineralization systems. Current investigations are increasingly focused on:

1) Development of novel bacterial and fungal strains.
2) Advanced encapsulation and microcapsule technologies.
3) Integration of MICP with low-carbon cementitious materials.
4) Predictive modeling and artificial intelligence applications.
5) Heavy metal immobilization and environmental restoration.
6) Long-term durability assessment under extreme conditions.
7) Field-scale implementation and commercialization.

Collectively, these advancements indicate that MICP technology has evolved from a laboratory-scale self-healing mechanism into a multifunctional and sustainable engineering solution capable of addressing structural, environmental, and carbon-neutrality challenges in modern infrastructure development.

The reviewed literature demonstrates that Microbially Induced Calcium Carbonate Precipitation is an effective and sustainable technology for self-healing concrete. Studies have confirmed its capability to seal cracks, restore durability, improve mechanical performance, and contribute to carbon-neutral construction practices. Advances in bacterial immobilization, endospore technology, predictive modeling, and environmental adaptation have significantly enhanced the feasibility of MICP systems. However, further research is required to address challenges related to scalability, long-term performance, and economic viability before widespread industrial implementation can be achieved.

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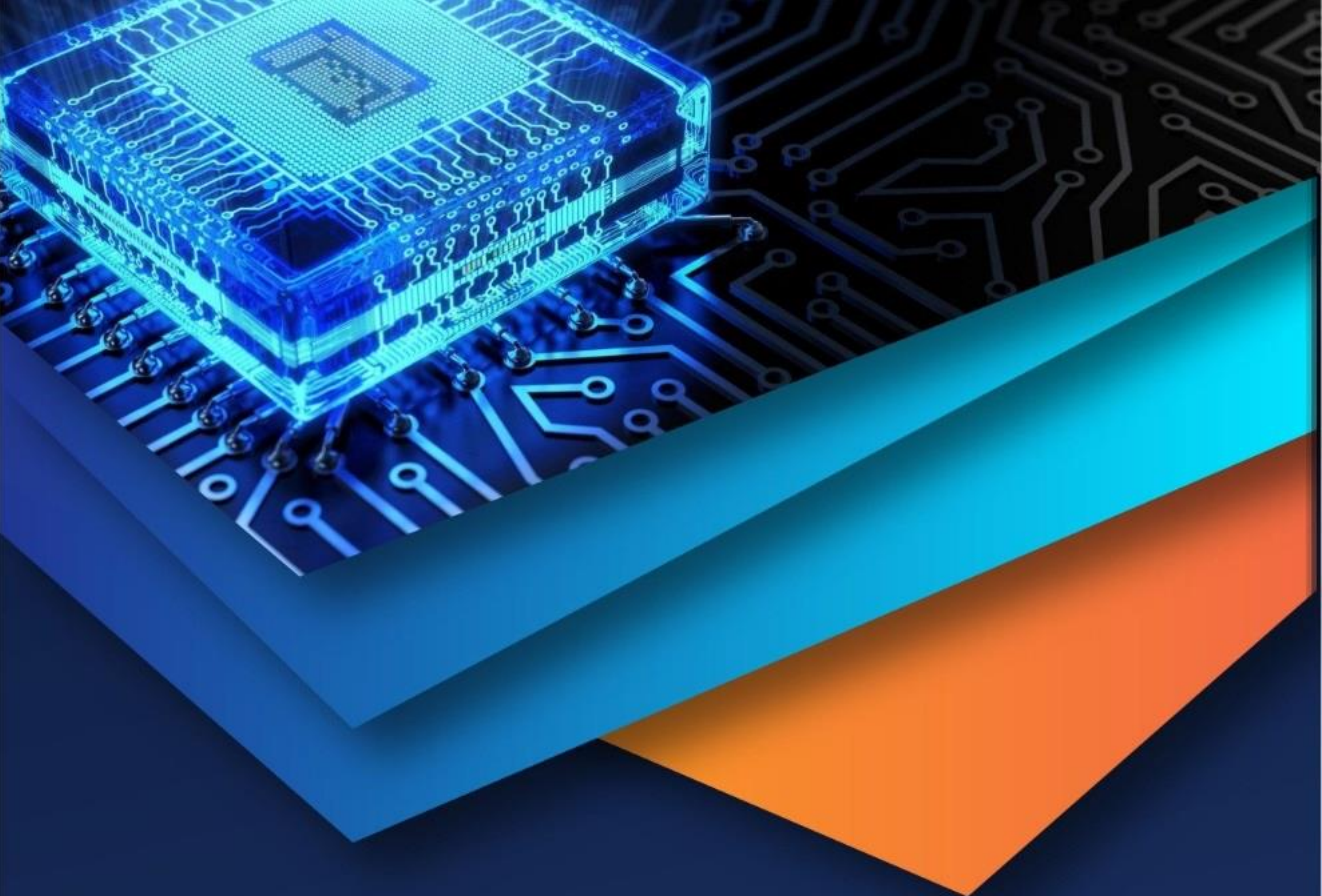


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