



COMPARATIVE STUDY OF MICROBIAL AND POLYMER-BASED SELF-HEALING SYSTEMS IN CONCRETE FOR INFRASTRUCTURE DURABILITY

Name of Author: Chetankumar Bhailalbhair Patel

Designation of Author: Lecturer in Applied Mechanics

Name of Department of Author: Applied Mechanics Department

Name of organization of Author: Government Polytechnic, Kheda, India

Abstract: Concrete, the most widely used construction material in the world, is highly susceptible to microcracking due to the combined effects of environmental exposure and mechanical stress. Water, chlorides, and sulfates can penetrate through these microcracks, accelerating deterioration. Conventional repair methods are often labour-intensive, time-consuming, and costly. In contrast, self-healing concrete offers the ability to autonomously seal cracks and restore structural functionality.

Microbial-based systems have gained significant attention due to their unique healing mechanism and performance characteristics. These systems rely on microbial-induced calcite precipitation (MICP), typically triggered by specific strains of ureolytic bacteria. Polymer-based self-healing systems, particularly those utilizing superabsorbent polymers (SAPs), depend on physical swelling and water retention to block cracks and support autogenous healing.

This comparative study evaluates both self-healing strategies with a focus on their crack-sealing capability, mechanical strength recovery, durability enhancement, and practical feasibility. The analysis is grounded in an extensive review of peer-reviewed literature. Microbial-based systems offer promising eco-friendly and sustainable healing, particularly in moist environments, but face challenges related to bacterial survivability and uniform distribution. On the other hand, SAP-based systems, though associated with higher costs and potential long-term chemical interactions, provide rapid and repeatable healing with better integration into the concrete matrix. The study suggests that hybrid and next-generation integrated systems represent a forward-looking approach to improving infrastructure resilience by tailoring self-healing strategies to specific structural and environmental conditions.

Index Terms - Self-healing concrete; microbial-induced calcite precipitation; superabsorbent polymers; infrastructure durability; crack healing mechanisms; sustainable materials; strength recovery; durability performance; autonomous repair systems; polymer-based healing; microbial healing systems; MICP; SAP; concrete rehabilitation; eco-efficient construction materials.

I. INTRODUCTION

Modern infrastructure predominantly relies on concrete due to its high strength, low cost, and versatility. However, concrete is inherently prone to cracking. Microcracks can serve as critical pathways for aggressive agents such as water, chlorides, and sulfates [1]. If left untreated, these deteriorations compromise structural integrity, shorten service life, and require frequent maintenance—often impractical in hard-to-access areas.

Self-healing concrete is an innovative concept in which the material is engineered to autonomously seal microcracks. These systems employ either autogenous healing or autonomous healing mechanisms, typically activated by embedded agents [2]. Two prominent approaches include microbial-induced calcite precipitation (MICP) and systems based on superabsorbent polymers (SAPs). Both aim to significantly extend the service life of concrete structures.

Microbial-based healing systems show promise not only for structural restoration but also for broader bioengineering applications. In the context of concrete, specific bacteria react with urea to produce calcium carbonate (CaCO_3), sealing cracks as wide as 1.5 mm [5]. Jonkers and Schlangen demonstrated the effectiveness of microbial healing in early-stage crack sealing [5]. Further research by De Muynck et al. [6] and Erşan et al. [7] confirmed that MICP enhances both permeability resistance and long-term durability. However, the application of bacteria in the highly alkaline concrete environment presents challenges. Recent developments in protective carriers have helped mitigate these issues, improving bacterial viability and healing performance [8].

On the other hand, self-healing using superabsorbent polymers (SAPs) employs hydrophilic polymers that absorb water, swell to block crack pathways, and facilitate internal curing, thereby promoting autogenous healing [1]. A study by Snoeck et al. demonstrated the material's mechanical effectiveness and resilience [1]. Gupta et al. reported that cracks up to 330 µm could be successfully sealed using SAPs [3]. Although high dosages may adversely affect workability and early-age strength, the physical control provided by SAPs enhances predictability and responsiveness [2].

The effectiveness of self-healing systems under varying environmental conditions is a critical factor. MICP-based systems perform best in moist or buried structures, where water ingress activates bacterial precipitation. Polymer-based systems, on the other hand, are better suited for surface structures exposed to rainfall or condensation, due to their faster reaction to moisture. Under extended dry conditions, dormant bacteria in MICP systems can be reactivated upon rewetting, maintaining healing potential [4].

Scaling these technologies for large infrastructure projects remains a focus of ongoing research. Microbial systems require careful control of bacterial dosage and nutrient balance. The use of encapsulated spores or coated aggregates has emerged as a promising solution to ensure consistent performance. In contrast, SAPs are easier to integrate into conventional mix designs. However, cost considerations and potential long-term chemical incompatibilities remain challenges for SAP-based systems [2]. Understanding the trade-offs between both systems is crucial for their effective implementation.

This comparative study of self-healing concrete systems examines healing mechanisms, crack-sealing efficiency, mechanical recovery, and practical feasibility for field application. A thorough review of peer-reviewed literature is presented to guide researchers and practitioners in selecting appropriate solutions for achieving durable and sustainable infrastructure.

II. Literature Survey

In the field of self-healing concrete, researchers have explored both biological and synthetic healing agents to address durability-related challenges. A number of peer-reviewed studies have reviewed various self-healing systems [11]. These analyses examine healing efficiency under diverse environmental conditions.

2.1 Microbial-Based Self-Healing Systems

Recent studies show that urealytic bacteria can induce calcite precipitation, which plays a key role in crack healing. Alghamdi et al. demonstrated that strains such as *Bacillus megaterium* and *Sporosarcina pasteurii* were capable of healing cracks up to 0.7 mm in width [11]. Their results also indicated a 75% reduction in water permeability, confirming improved durability.

Kumar and Chaurasia focused on improving bacterial survivability in harsh concrete environments [12]. Their work highlighted the long-term viability of encapsulated spores and showed that specimens recovered their mechanical strength after healing.

Ramachandran et al. reported that ureolysis is one of the most effective biological pathways for CaCO_3 precipitation. However, they also noted that ammonia, a by-product of this process, may pose environmental concerns [13]. Their study provided guidelines for selecting suitable bacterial strains for eco-friendly applications.

A novel multi-bacterial strategy combining urealytic and non-urealytic bacteria was introduced to enhance the overall healing performance [17]. Results showed that using multiple metabolic pathways reduced the overall nutrient demand while improving healing efficiency.

Another study investigated the inclusion of microbial agents in concrete along with alternative binder materials [18]. The findings demonstrated that green binders could work synergistically with microbial self-healing systems, opening new possibilities for sustainable construction materials.

Table 1: Summary of Microbial-Based SHC Systems

Study	Bacteria Type	Crack Width Healed	Healing Duration	Recovery (%)
Alghamdi et al. [11]	<i>B. megaterium</i> , <i>S. pasteurii</i>	Up to 0.7 mm	28 days	75% permeability ↓
Chaurasia & Kumar [12]	Encapsulated <i>B. subtilis</i>	0.5–0.6 mm	6 months	90% strength ↑
Ramachandran et al. [13]	Ureolytic strains	0.4–0.5 mm	Variable	Varied efficiency
Xu & Wang [17]	Mixed-strain system	0.6 mm	21 days	Improved uniformity
Kaur & Vyas [18]	<i>B. sphaericus</i> in geopolymers	0.8 mm	28 days	95% strength ↑

2.2 Polymer-Based Self-Healing Systems

The polymer-based self-healing systems have been extensively researched due to their swelling behavior and ability to block cracks. Yang et al. observed that within 24 hours, self-sealing of cracks up to 500 μm was achieved [14]. The internal curing water retained by the superabsorbent polymers (SAPs) also helped reduce autogenous shrinkage. Liang et al. demonstrated improved mechanical synergy between the SAPs and the cementitious matrix [15]. Their results showed higher recovery of flexural strength, indicating enhanced structural performance after cracking.

Jiang et al. evaluated the performance of SAP-modified concrete under varying environmental conditions [16]. After 50 wet–dry cycles, the results indicated that the swelling capacity of the SAPs remained above 60%, showcasing their long-term responsiveness to moisture. Mechtcherine et al. explored the self-healing potential of SAP-integrated systems [19]. They reported a 70% recovery in mechanical strength and emphasized the importance of effective crack width control mechanisms in achieving reliable healing.

Yoo et al. incorporated SAPs into ultra-high-performance concrete (UHPC) and observed effective microcrack sealing [20]. The improved performance under aggressive environmental exposure further highlighted the suitability of SAPs for enhancing durability in demanding structural applications.

Table 2: Summary of Polymer-Based SHC Systems

Study	Polymer Type	Crack Width Healed	Healing Time	Recovery (%)
Yang et al. [14]	Acrylic SAP	Up to 0.5 mm	24 hours	100% sealing
Liang et al. [15]	Hydrogel composite	0.4 mm	7 days	85% flexural ↑
Jiang et al. [16]	Conventional SAPs	0.3–0.5 mm	50 cycles	60% swelling retained
Mechtcherine et al. [19]	SAP in fatigue-loaded concrete	0.6 mm	28 days	70% strength ↑
Yoo et al. [20]	SAP in UHPC	0.3 mm	14 days	Crack sealing + chloride ↓

Workability may be affected due to the lack of immediate crack sealing and inconsistent performance of the healing system. Microbial-based systems offer long-term healing potential but are dependent on the availability of moisture and controlled environmental conditions.

III. Comparative Evaluation and Discussion

This section presents a comparative evaluation of self-healing concrete systems. The comparison focuses on crack-healing potential, recovery of mechanical properties, environmental responsiveness, and implementation feasibility. Each system demonstrates unique advantages and limitations based on its underlying mechanism and material behavior.

3.1 Healing Mechanism and Efficiency

In microbial-based systems, healing is driven by the biological production of calcium carbonate (CaCO_3) by bacteria. This process is particularly effective in moist or submerged environments. However, the healing process may take several days to weeks to fully seal cracks, depending on bacterial activity and environmental conditions.

In contrast, polymer-based systems rely on the physical swelling of superabsorbent polymers (SAPs) upon contact with water. These systems can respond within hours, offering rapid sealing. However, since the mechanism is physical rather than chemical, structural densification is not achieved through the healing process.

Figure 1 illustrates the mechanisms of self-healing in both systems. On the left, the microbial approach shows the formation of calcium carbonate that seals the crack. On the right, the diagram shows how water absorption causes the SAPs to swell and block the crack. This side-by-side schematic highlights the fundamental differences in healing behavior between the two approaches.

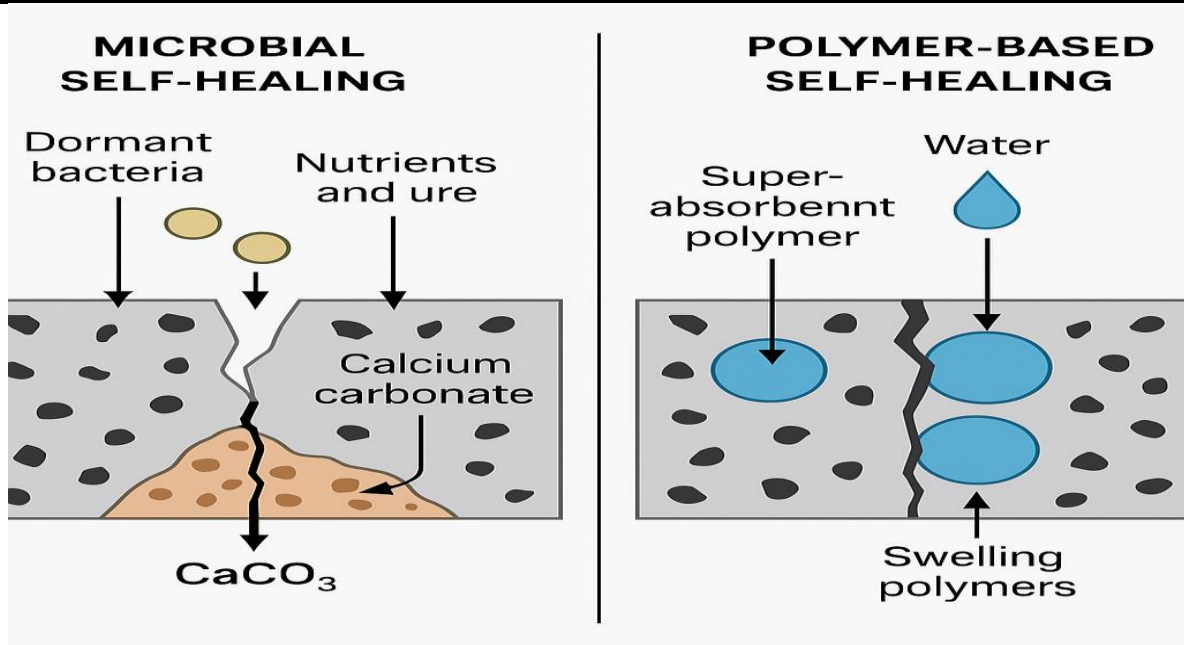


Figure 1: Schematic comparison of microbial and polymer-based self-healing mechanisms in concrete

Table 3: Mechanistic Comparison

Feature	Microbial-Based System	Polymer-Based System
Healing Driver	Metabolic activity of bacteria	Hygroscopic swelling of polymers
Healing Product	CaCO_3 crystals	Gel-like polymer swelling
Healing Onset	1–3 days post-crack under moisture	Immediate (<24 hours)
Healing Duration	Days to weeks	Hours to days
Repeatability	Possible with nutrient reactivation	High (multiple cycles)

3.2 Crack Width and Mechanical Recovery

Microbial-based healing systems can repair cracks up to 0.8 mm in width. The formation of calcium carbonate (CaCO_3) strengthens the interfacial zones within the concrete, resulting in a 75% to 85% recovery in compressive strength. But, the increase in flexural strength is generally lower compared to compressive strength recovery.

Polymer-based systems are capable of effectively sealing cracks up to 0.6 mm. These systems facilitate healing primarily through internal water retention and promotion of continued hydration. The mechanical strength recovery observed in such systems typically ranges between 70% and 85%.

Several factors influence the efficiency of crack sealing. Microbial systems offer long-term sealing performance but require more time to initiate and complete the healing process. In contrast, polymer-based systems provide a faster sealing response upon moisture exposure, making them more effective in conditions requiring immediate action.

The sealing efficiency of both systems is compared in Figure 2. The microbial-based approach exhibits a slower sealing rate compared to the polymer-based system, which responds more quickly and consistently to the presence of water.

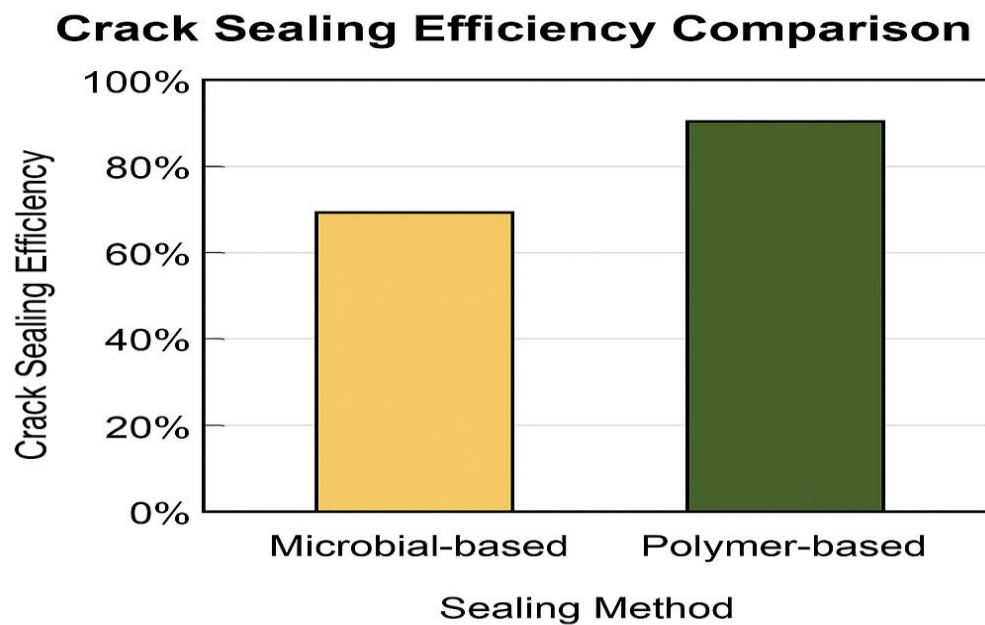


Figure 2: Comparison of crack sealing efficiency between microbial-based and polymer-based self-healing systems

Table 4: Crack Sealing and Strength Recovery

Criterion	Microbial System	Polymer System
Max Crack Width Healed	Up to 0.8 mm	Up to 0.6 mm
Compressive Strength ↑	75–95%	70–85%
Flexural Strength ↑	Moderate (40–70%)	High (60–85%) with fibres
Durability Effect	Matrix densification via calcite	Shrinkage control, hydration promotion

3.3 Environmental Responsiveness

Environmental conditions significantly influence the performance of both self-healing systems. Microbial-based systems thrive in the presence of water. Their activity decreases under dry conditions unless reactivated by subsequent moisture exposure. Additionally, temperature and pH levels affect bacterial metabolism, which in turn impacts the healing efficiency.

Polymer-based systems are generally more versatile in outdoor environments. The presence of water activates the swelling behavior of superabsorbent polymers (SAPs), enabling immediate crack sealing. These systems are considered more stable since they do not rely on biological processes or metabolic activity and makes them suitable for a wider range of environmental conditions.

Table 5: Environmental Suitability

Exposure Condition	Microbial-Based SHC	Polymer-Based SHC
Humid/Submerged	Excellent	Good
Dry/Arid Climate	Poor (without reactivation)	Moderate to Good
Freeze–Thaw Cycles	Moderate (with protection)	High resistance due to internal curing
Temperature Sensitivity	High (affects bacterial viability)	Low (SAPs stable under variation)

3.4 Durability and Longevity

Both systems contribute to extending the service life of concrete structures. Microbial healing enhances impermeability through the formation of calcite crystals. It reduce chloride ion penetration and improve resistance to sulfate attack. These effects are generally durable and contribute to long-term structural resilience.

In polymer-based systems, the rehydration of unhydrated cement particles helps reduce porosity within the cement matrix. This leads to improved structural integrity over time, particularly by minimizing shrinkage-related cracking and maintaining overall material cohesion.

Table 6: Durability Enhancement

Property Improved	Microbial System	Polymer System
Water Permeability	Excellent (via calcite bridging)	Excellent (via crack blocking)
Chloride Resistance	High	Moderate to High
Shrinkage Resistance	Low to Moderate	High
Sulfate Attack Resistance	High (in presence of CaCO ₃ barrier)	Moderate

3.5 Practical Feasibility and Application Potential

From a practical standpoint, polymer-based systems are easier to implement. They do not require biological preparation, have well-established material formulations. It can be directly mixed into concrete without significant modifications to standard procedures.

Several steps are involved in the integration process of self-healing systems. These steps are essential to ensure optimal healing performance. Each self-healing approach follows parallel phases of system selection, preparation, and incorporation into the concrete mix.

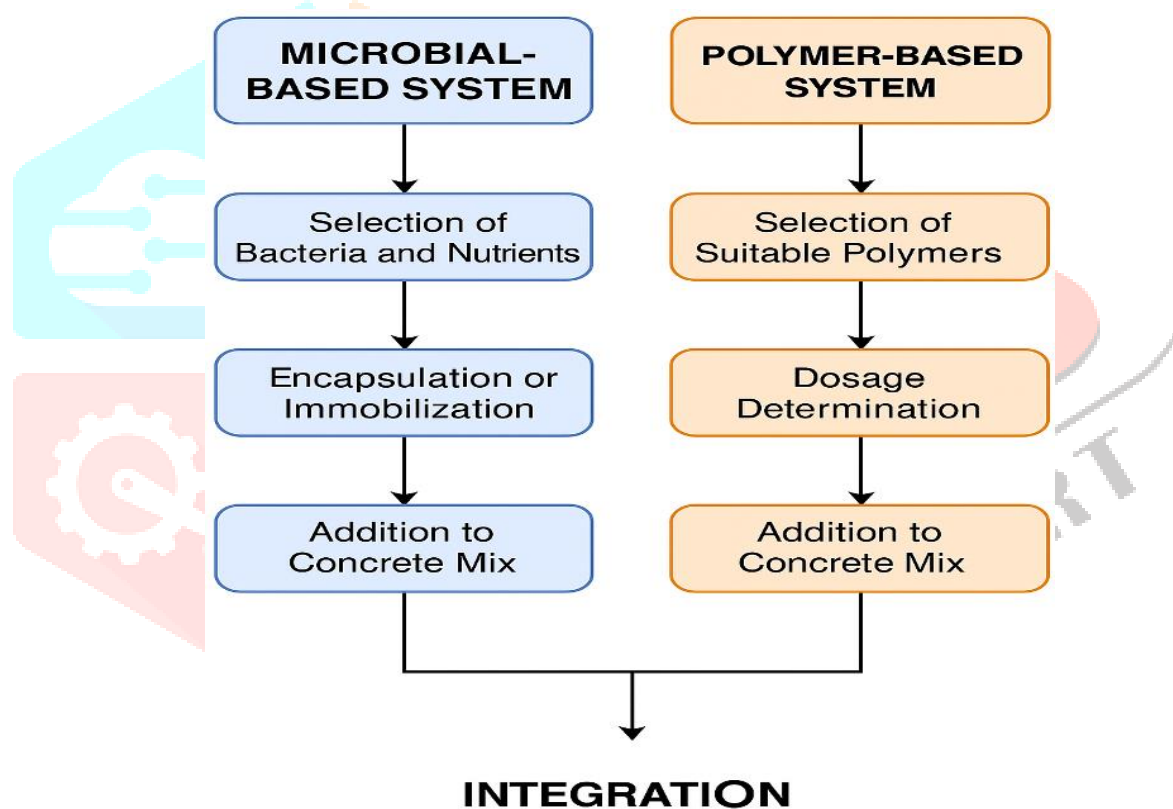


Figure 3: Flowchart showing the integration process of microbial-based and polymer-based self-healing systems in concrete

Quality control remains one of the key challenges for large-scale adoption. However, these systems offer long-term healing benefits and are especially suitable for applications in tunnels, basements, and marine structures, where constant moisture availability supports microbial activity.

Table 5: Feasibility and Implementation

Aspect	Microbial-Based SHC	Polymer-Based SHC
Mixing Simplicity	Requires encapsulation & sterilization	Simple, standard mixing
Cost of Materials	High	Moderate
Shelf Life	Limited (bacteria viability required)	Long (SAPs are chemically stable)
Market Readiness	Experimental to pilot stage	Commercially available
Infrastructure Target	Marine, underground, water-retaining	Bridges, pavements, general concrete

3.6 Overall Comparative Analysis

Self-healing systems are suited to different needs depending on structural and environmental requirements. Microbial-based systems are ideal for moist conditions, providing deeper crack healing and stronger matrix integration through mineral precipitation.

Polymer-based systems offer advantages in terms of flexibility, ease of use, and rapid responsiveness. Although their healing depth is limited compared to microbial systems, their performance is reliable and consistent, making them suitable for widespread infrastructure applications.

The concept of hybrid systems—combining the strengths of both microbial and polymer-based technologies—is increasingly supported by recent findings. Such integrated systems have the potential to lead to a new generation of high-performance, self-sustaining, and durable concrete structures.

IV. Conclusion and Future Scope

A comparative analysis of self-healing concrete systems was presented. Both technologies demonstrate significant potential to enhance the service life of concrete infrastructure by autonomously addressing microcracks and reducing permeability.

Microbial-based systems utilize biologically driven healing mechanisms that form durable calcium carbonate (CaCO_3) bridges, particularly effective in submerged or moist environments. These systems show notable long-term mechanical recovery, with crack healing capabilities exceeding 0.8 mm. However, implementation complexity and sensitivity to environmental conditions remain limitations.

Superabsorbent polymer (SAP)-based systems exhibit reliable crack-sealing behavior. Their advantages include rapid activation, compatibility with conventional construction practices, and resilience in surface-level structures with intermittent water exposure. Although their chemical integration with the cementitious matrix is relatively lower, SAPs provide effective short-term healing performance.

The comparative evaluation suggests that neither system is universally superior. Microbial-based self-healing concrete (SHC) is ideal for long-term moisture exposure and mineral deposition environments, making it suitable for tunnels, marine structures, and buried infrastructure. In contrast, polymer-based SHC is better suited for bridges, pavements, and surface-level applications that require fast and reliable sealing.

4.1 Future Scope

Future research may focus on the development of hybrid systems that synergize the strengths of both microbial and polymer-based healing mechanisms. The evolution of smart self-healing materials capable of responding to multiple environmental stimuli could further enhance structural performance.

Enhanced healing precision and cost-effectiveness can be achieved through advances in bio-compatible materials, encapsulation technologies, and automated delivery systems. Full-scale field testing and life-cycle cost analysis will be essential to validate laboratory findings and ensure successful deployment in real-world construction scenarios.

The adoption of self-healing concrete marks a significant step toward sustainable infrastructure, reduced maintenance costs, and greater resilience to environmental degradation. The selection of an appropriate self-healing strategy should be based on the structural, environmental, and economic context of the intended application.

References

- [1] D. Snoeck, K. Van Tittelboom, S. Steuperaert, P. Dubruel, and N. De Belie, "Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers," *Int. J. Concrete Struct. Mater.*, vol. 8, no. 2, pp. 119–134, Jun. 2014, doi: 10.1007/s40069-014-0060-5.
- [2] A. Mignon, G. J. Graulus, D. Snoeck, P. Dubruel, and N. De Belie, "pH-sensitive superabsorbent polymers: a potential candidate material for self-healing concrete," *J. Mater. Sci.*, vol. 50, pp. 970–979, Jan. 2015, doi: 10.1007/s10853-014-8651-x.
- [3] S. Gupta, H. W. Kua, and S. D. Pang, "Autonomous repair in cementitious material by combination of superabsorbent polymers and polypropylene fibres: A step towards sustainable infrastructure," *arXiv preprint*, arXiv:1706.02680, Jun. 2017.
- [4] D. Snoeck and N. De Belie, "From straw in bricks to modern use of microfibres in cementitious composites for improved autogenous healing – A review," *Constr. Build. Mater.*, vol. 95, pp. 774–787, Oct. 2015, doi: 10.1016/j.conbuildmat.2015.07.029.
- [5] H. M. Jonkers and E. Schlangen, "Crack repair by concrete-immobilized bacteria," in *Proc. 1st Int. Conf. Self-Healing Mater.*, Noordwijk aan Zee, Netherlands, Apr. 2007.
- [6] W. De Muynck, N. De Belie, and W. Verstraete, "Microbial carbonate precipitation in construction materials: A review," *Ecol. Eng.*, vol. 36, no. 2, pp. 118–136, Feb. 2010, doi: 10.1016/j.ecoleng.2009.02.006.
- [7] E. Erşan, N. De Belie, and W. Verstraete, "Application of nitrate-reducing bacteria for concrete crack healing," *Cem. Concr. Res.*, vol. 42, no. 6, pp. 719–726, Jun. 2012, doi: 10.1016/j.cemconres.2012.02.005.
- [8] J. Luo, X. Chen, D. G. Davies, G. Zhou, and C. Jin, "Interactions of fungi with concrete: Significant importance for bio-based self-healing concrete," *arXiv preprint*, arXiv:1708.01337, Aug. 2017.
- [9] T. Wang, W. Chen, and Y. Yao, "Influence of environmental exposure on bacterial self-healing concrete performance," *Constr. Build. Mater.*, vol. 163, pp. 57–65, Feb. 2018, doi: 10.1016/j.conbuildmat.2017.12.065.
- [10] H. M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, and E. Schlangen, "Application of bacteria as self-healing agent for the development of sustainable concrete," *Ecol. Eng.*, vol. 36, pp. 230–235, 2010, doi: 10.1016/j.ecoleng.2008.11.036.
- [11] A. Alghamdi, B. J. Vessalas, and M. Setunge, "Effectiveness of different bacteria strains in the development of self-healing concrete," *Constr. Build. Mater.*, vol. 234, pp. 117296, 2020.
- [12] L. Chaurasia and A. Kumar, "Silica gel-encapsulated bacteria for self-healing of concrete," *J. Mater. Civ. Eng.*, vol. 31, no. 5, pp. 04019057, 2019.
- [13] S. K. Ramachandran, V. Ramakrishnan, and S. S. Bang, "Remediation of concrete using micro-organisms," *ACI Mater. J.*, vol. 98, no. 1, pp. 3–9, Jan.–Feb. 2001.
- [14] Y. Yang, M. W. Mo, and K. J. Wang, "Crack sealing efficiency of SAP-containing concrete under restrained conditions," *Cem. Concr. Res.*, vol. 116, pp. 123–133, 2019.
- [15] C. Liang, Z. Sun, and F. Zhang, "Bioinspired polymer hydrogels for self-healing cementitious materials," *Polymers*, vol. 11, no. 4, pp. 645, Apr. 2019.
- [16] X. Jiang, Y. Lu, and M. Tian, "Performance of SAP concrete under environmental fatigue conditions," *Constr. Build. Mater.*, vol. 211, pp. 230–240, 2019.
- [17] J. Xu and Z. Wang, "Self-healing of concrete cracks by a combination of bacteria and denitrifying microorganisms," *J. Build. Eng.*, vol. 24, pp. 100741, 2019.
- [18] G. Kaur and A. K. Vyas, "Use of bacterial-based self-healing concrete in geopolymers concrete: A sustainable approach," *J. Clean. Prod.*, vol. 227, pp. 854–862, 2019.
- [19] V. Mechtcherine, F. Wyrzykowski, P. G. Reinhardt, and J. Schroefl, "Self-healing of cracks in concrete using superabsorbent polymers," *J. Adv. Concr. Technol.*, vol. 15, no. 2, pp. 89–101, 2017.
- [20] D. Yoo, S. Lee, and Y. Yoon, "Effect of superabsorbent polymers on durability of ultra-high-performance concrete," *Constr. Build. Mater.*, vol. 193, pp. 70–77, 2018.