

Self-Healing Reinforced Concrete: A Review of Development and
Sustainable Applications

<http://www.doi.org/10.62341/istj-vol39-1-ra62>

Received	2026/09/10	تم استلام الورقة العلمية في
Accepted	2026/09/29	تم قبول الورقة العلمية في
Published	2026/09/30	تم نشر الورقة العلمية في

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Abstract

Concrete remains the most widely used construction material worldwide due to its structural performance, availability, and cost efficiency. However, reinforced concrete structures are inherently vulnerable to cracking caused by shrinkage, thermal stresses, mechanical loading, and environmental exposure. These cracks allow the ingress of water, oxygen, and aggressive agents, which accelerate reinforcement corrosion and significantly reduce structural durability and service life. In recent years, self-healing concrete has emerged as a promising strategy for mitigating crack-related deterioration by enabling the autonomous repair of microcracks without external intervention. This review paper

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critically examines the development and performance of self-healing reinforced concrete (SHRC) as an innovative approach for enhancing durability and sustainability in modern infrastructure. Particular emphasis is placed on microbial-based healing techniques, including bacterial systems such as *Bacillus* species, and their comparative performance against chemical and encapsulation-based healing mechanisms. Furthermore, the study evaluates the reliability of different self-healing approaches under diverse environmental conditions and assesses their long-term economic feasibility by considering lifecycle performance and maintenance reduction. The findings highlight the potential of SHRC to extend infrastructure lifespan while reducing environmental impacts associated with conventional repair and cement-intensive construction practices.

Keywords: Self-Healing Concrete, Reinforced Concrete, Microbial-Induced Calcite Precipitation (MICP), Encapsulation Mechanisms, Durability, Life-Cycle Assessment.

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الخرسانة المسلحة ذاتية الشفاء : مراجعة للتطور والتطبيقات المستدامة

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الملخص

تظل الخرسانة أكثر مواد البناء استخداماً في جميع أنحاء العالم نظراً لأدائها الإنشائي، وتوافرها، وكفاءتها من حيث التكلفة. ومع ذلك، فإن الهياكل الخرسانية المسلحة عرضة بطبيعتها للتصدع الناتج عن الانكماش، والإجهادات الحرارية، والتحميل الميكانيكي، والتعرض البيئي. تسمح هذه الشقوق بتسرب الماء والأكسجين والعوامل العدوانية، مما يسرع من تآكل حديد التسليح ويقلل بشكل كبير من متانة الهيكل وعمره الافتراضي. في السنوات الأخيرة، برزت الخرسانة ذاتية الشفاء كاستراتيجية واحدة للتخفيف من التدهور المرتبط بالشقوق من خلال تمكين الإصلاح الذاتي للشقوق الدقيقة دون تدخل خارجي. تستعرض هذه الورقة البحثية بشكل نقدي تطور وأداء الخرسانة المسلحة ذاتية الشفاء (SHRC) كنهج مبتكر لتعزيز المتانة والاستدامة في البنية التحتية الحديثة. ويتم التركيز بشكل خاص على تقنيات الشفاء القائمة على الميكروبات، بما في ذلك الأنظمة البكتيرية مثل أنواع الباسيلوس (*Bacillus*)، ومقارنتها بآليات التئام الكيمائية والقائمة على التغليف. علاوة على ذلك، تقيم الدراسة موثوقية مناهج الشفاء الذاتي المختلفة في ظل ظروف بيئية متنوعة، وتقدر جدواها الاقتصادية طويلة الأجل من خلال مراعاة أداء دورة الحياة وخفض تكاليف الصيانة. تسلط النتائج الضوء على إمكانات الخرسانة المسلحة ذاتية الشفاء في

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إطالة العمر الافتراضي للبنية التحتية مع الحد من الآثار البيئية المرتبطة بعمليات الإصلاح التقليدية وممارسات البناء كثيفة الاستهلاك للأسمدة
الكلمات المفتاحية: الخرسانة ذاتية الشفاء، الخرسانة المسلحة، الترسيب الكلسي المحثوث ميكروبياً (MICP)، آليات التغليف، المتانة، تقييم دورة الحياة.

1. Introduction

Concrete remains the dominant structural material globally owing to its superior compressive performance, material accessibility, and cost-effectiveness (Mehta & Monteiro, 2014). Nevertheless, reinforced concrete (RC) elements suffer from an intrinsic susceptibility to microcracking induced by early-age thermal gradients, plastic/drying shrinkage, cyclic fatigue loading, and aggressive environmental exposure (Scrivener et al., 2018; De Belie et al., 2018). These interconnected microcrack networks act as rapid diffusion pathways for water, dissolved oxygen, sulfates, and chloride ions (Tuutti, 1982). Consequently, aggressive agent ingress triggers the depassivation and accelerated corrosion of internal steel reinforcement, leading to expansive spalling and severe structural capacity degradation (Tuutti, 1982; Emmons, 1993).

Traditional structural maintenance reliant on surface sealing, manual epoxy injection, or partial structural replacement incurs massive economic burdens and presents severe logistical execution challenges in submerged, subterranean, or high-density urban infrastructure (Emmons, 1993; Hasan et al., 2026). To overcome these challenges, Self-Healing Reinforced Concrete (SHRC) has gained substantial attention as an autonomous remediation strategy capable of sealing cracks independently without human intervention (Hasan et al., 2026; Jonkers & Mors, 2021).

Among autonomous healing strategies, Microbial-Induced Calcite Precipitation (MICP)—predominantly employing spore-forming alkaliphilic *Bacillus* species—and dynamic chemical encapsulation (utilizing polymeric or sodium silicate cores within tubular/spherical shells) represent the two primary competing engineering approaches (Jonkers & Mors, 2021; Wang et al., 2022; Van Tittelboom & De Belie, 2022). While chemical encapsulation

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facilitates rapid, localized sealants upon mechanical rupture, biological mechanisms offer multi-cyclic, long-term regenerative capabilities (Wang et al., 2022; Seifan & Berenjian, 2023).

Self-healing concrete is designed to autonomously repair internal micro-cracks, thereby enhancing structural durability and reducing maintenance requirements. The performance of self-healing mechanisms strongly depends on the baseline quality and physical properties of the concrete matrix components. As reported by Albady et al. (2025), assessing constituent materials—specifically high-strength cement and aggregates—is crucial for establishing a stable matrix capable of supporting autonomous healing reactions. Therefore, controlling aggregate abrasion resistance and cement hydration behavior provides a suitable microenvironment for encapsulation techniques.

2. Objective

The principal objective of this review is to deliver a critical, state-of-the-art comparative evaluation of Self-Healing Reinforced Concrete (SHRC) systems for structural engineering applications. Specific sub-objectives comprise:

1. Systematic Comparative Analysis: To rigorously compare microbial-based (MICP) self-healing mechanisms with chemical/encapsulation routes regarding crack width closure limits, depth of healing, dynamic reaction kinetics, and inherent operational drawbacks (Jonkers & Mors, 2021; Wang et al., 2022; Van Tittelboom & De Belie, 2022; Seifan & Berenjian, 2023; Souradeep & Dai, 2021).

2. Environmental Reliability Mapping: To assess operational stability across hostile environments, including freeze-thaw regimes, hyper-arid cycles, marine chloride exposure, and variable pH conditions (Ferrara et al., 2023; Snoeck & De Belie, 2021).

3. Life-Cycle Costing and Carbon Quantification: To evaluate long-term economic feasibility (CAPEX vs. OPEX) and quantify carbon footprint reductions achievable through structural life extension (Habert et al., 2020; Van den Heede et al., 2022; Soutsos & Kanavaris, 2021).

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3 .Methods

This study employs a systematic review framework based on the updated PRISMA guidelines (Page et al., 2021):

- Comprehensive Literature Retrieval: Bibliographic databases (Scopus, Web of Science, Google Scholar) were queried for high-impact peer-reviewed literature published predominantly between 2021 and 2026 using keywords: self-healing concrete, bacterial MICP, encapsulation methods, crack closure efficiency, and life-cycle assessment.

- Performance Data Extraction: Comparative performance indicators were categorized according to max healable crack width (mm), regain of compressive strength (%), regain of water permeability resistance (%), and dynamic healing longevity.

- Synthesis and Critical Evaluation: Extracted experimental data were systematically synthesized to establish quantitative comparative benchmarks between microbial and chemical encapsulation mechanisms.

Detailed PRISMA Screening & Flow Implementation

To ensure methodological rigor, the selection process followed four distinct phases:

- 1 .Identification: A total of 342 records were identified from Scopus, Web of Science, and Google Scholar using targeted search queries.
- 2 .Screening: After removing 110 duplicate entries, 232 titles and abstracts were screened for domain relevance, eliminating 147 articles that focused on unreinforced paste or lacked quantitative self-healing indicators.
- 3 .Eligibility: 85 full-text articles were evaluated against strict eligibility criteria, prioritizing studies assessing crack sealing kinetics, mechanical recovery, and lifecycle costs.
- 4 .Inclusion: 20 key studies meeting all inclusion criteria were incorporated into the final synthesis and critical comparative analysis

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4 .Results and Discussion

4.1 Mechanism Comparison: Microbial (MICP) vs. Chemical Encapsulation

Table 1. Comprehensive Comparison between Microbial (MICP) and Chemical Encapsulation Self-Healing Mechanisms

Feature / Parameter	Microbial-Based Healing (MICP)	Chemical Encapsulation Healing
Active Healing Agent Precursor Matrix	Bacterial spores (e.g., <i>Bacillus pseudoformal</i>) +Nutrient Organic calcium lactate / Nitrate source	Polyurethanes, Epoxy resins, Cyanoacrylates, Sodium silicate Polymeric or inorganic shell (glass, ceramic, polymeric)
Healing Reaction Mechanism	Enzymatic hydrolysis of urea / organic substrate producing CaCO_3 (Calcite) precipitation via bacterial metabolism	Mechanical shell rupture releasing liquid monomer/core; physical/chemical polymerization upon exposure to matrix
Maximum Healable Crack Width	High capacity: 0.3 mm to 0.8 mm (up to 1.0 mm with SAPs)	Moderate capacity: 0.1 mm to 0.4 mm
Healing Kinetics & Rate	Slow to Moderate: Requires 14 to 28 days for full calcite crystallization	Fast to Instantaneous: Minutes to a few hours dep on polymer curing agent ending
Permeability & Sealing Depth	Deep, continuous crack bridging throughout depth via dense micro-crystalline CaCO_3 precipitation	Shallow to medium depth; potential core clogging or uneven distribution along the crack line
Strength Regain (%)	Moderate regain (10% - 25% recovery in compressive/flexural) capacity via matrix densification	High localized strength recovery (up to 40% - 70%) for structural adhesives like epoxy
Longevity & Cyclic Capability	Excellent Multi-cyclic Capacity: Spores remain viable/dormant for decades; reactivates	Single-use Limit: Once capsule ruptures and releases core, the localized area loses

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	upon subsequent water ingress	future self-healing potential
Major Drawbacks & Limitations	• Requires continuous ingress of H₂O and O₂ for metabolism . • Bacterial viability loss in high pH (>12.5) concrete . • Potential compressive strength reduction if unprotected. • Higher initial raw substrate material cost	• High shell breakage rate during concrete mixing. • Reduced long-term bond strength at resin-concrete interface • Thermal degradation during exothermic cement hydration • Chemical incompatibility / toxic polymerization byproducts

Experimental data synthesize a profound operational divergence between microbial systems and chemical encapsulation methods. Table 1 provides a comprehensive, multi-criteria comparison detailing the primary mechanisms, healing performance, and fundamental drawbacks of each technology based on recent state-of-the-art literature (Jonkers & Mors, 2021; Wang et al., 2022; Van Tittelboom & De Belie, 2022; Seifan & Berenjia, 2023; Souradeep & Dai, 2021; Khaliq & Ehsan, 2023; Vijay & Murmu, 2024; Al-Tabbaa et al., 2025).

4.2 Environmental Reliability and Sustainability Performance

Recent assessments show that while chemical encapsulation yields immediate structural bond restoration, its susceptibility to thermal degradation during early-age exothermic cement hydration (>60°C) limits its shell survivability during mixing (Souradeep & Dai, 2021; Snoeck & De Belie, 2021). Conversely, biological systems utilizing protective carriers (e.g., Expanded Clay, Biochar, Light Weight Aggregates) exhibit over 85% spore survivability during heavy mixing (Wang et al., 2022; Khaliq & Ehsan, 2023). Furthermore, lifecycle assessments (LCA) demonstrate that SHRC systems reduce 30-year operational repair frequencies by 50–70%, directly translating to an 18–25% reduction in net infrastructure carbon

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footprint despite a 15–30% initial material cost premium (Habert et al., 2020; Van den Heede et al., 2022; Soutsos & Kanavaris, 2021). Comprehensive Lifecycle Cost Analysis (CAPEX, OPEX, & Payback Period)

The economic viability of SHRC systems was evaluated through standard Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) frameworks:

- Initial Material Premium (CAPEX): Incorporating self-healing admixtures increases initial concrete production costs by approximately \$25 to \$40 per cubic meter (a 15% to 30% CAPEX increase over standard C30/37 concrete).
- Operational Maintenance Savings (OPEX): By preventing early-age macro-cracking and reinforcement depassivation, major repair cycles over a 50-year service lifecycle are reduced by 50% to 70%.
- Payback Period: Financial modeling demonstrates that the initial CAPEX premium is fully recovered within a payback period of 7 to 10 years in marine and aggressive subterranean exposures, beyond which net operational savings accumulate significantly.

5. Discussion

The comparative findings highlight a distinct functional trade-off in modern self-healing reinforced concrete design. Chemical encapsulation excels in rapid, high-strength structural repair suitable for sudden impact or dynamic loading cracks (Van Tittelboom & De Belie, 2022; Souradeep & Dai, 2021). However, its "one-time release" nature limits its applicability for durable infrastructure subjected to continuous fatigue cracking.

Critical Evaluation of Biological Limitations & Real-World Extrapolation

•Lab vs. Field Extrapolation: A primary reason for MICP performance discrepancies between lab studies and real-world sites is environmental oxygen starvation in submerged/underground structures and moisture deficits in hyper-arid regions. Lab specimens cured under continuous water immersion achieve optimal 0.8 mm sealing, whereas field elements under seasonal wetting-drying cycles experience delayed crystallization kinetics.

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•Impact of Concrete High Alkalinity ($\text{pH} > 12.5$): Unprotected bacterial cells undergo severe osmotic shock and cell wall lysis in fresh cementitious pore solutions. Encapsulation inside protective carriers (e.g., biochar or expanded clay) is essential to shield spores from mechanical crushing during mixing and chemical degradation until cracking occurs.

•Sealing Efficiency vs. Mechanical Recovery: A crucial distinction exists between permeability restoration (sealing) and mechanical load recovery. MICP achieves superior watertightness (up to 95% permeability reduction) via dense crystalline CaCO_3 bridging, but provides modest flexural/compressive strength regain (10-25%). Conversely, chemical adhesives like epoxy restore up to 70% structural integrity but lack long-term cyclic sealing capacity once the initial core is depleted.

From an economic perspective, civil engineering procurement must pivot from initial Capital Expenditure (CAPEX) evaluation toward Life-Cycle Cost (LCC) and Operational Expenditure (OPEX) modeling. Incorporating SHRC extends structural service lives beyond 100 years, significantly mitigating maintenance costs and aligning with global carbon neutrality mandates (Habert et al., 2020; Van den Heede et al., 2022; Soutsos & Kanavaris, 2021; Al-Tabbaa et al., 2025).

6. Research Gaps and Future Perspectives

Despite significant technological advancements in autonomous healing, several critical research gaps must be resolved to accelerate industrial adoption:

1. Long-Term Multi-Cycle Durability in Extreme Environments: Current empirical studies are predominantly limited to 28-to-90-day lab testing. Extended multi-decade field performance under coupled mechanical fatigue and severe freeze-thaw/chloride ingress cycles remains unverified.

2. Commercial Scalability & Cost Optimization of Bio-Carriers: Mass production of bio-carriers (such as expanded shale or specialized biochars) requires cost reduction to lower initial concrete premiums below 10%.

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3. Most Commercially Viable Technologies: Hybrid microbial systems incorporating Superabsorbent Polymers (SAP) combined with protective biochar carriers represent the most promising route for commercialization, as SAP provides both internal curing reservoirs and accelerated initial swelling sealants.
4. Standardized NDT Evaluation Protocols: Universal non-destructive testing (NDT) protocols, such as ultrasonic pulse velocity and electrical resistivity mapping, are needed to monitor internal healing kinetics in real-time within active field structures.

7. Conclusion

This review paper provides a critical, updated assessment of Self-Healing Reinforced Concrete (SHRC) systems. The main conclusions are:

1. Microbial systems (MICP) outperform chemical encapsulation in long-term durability, multi-cyclic healing capability, and maximum crack sealing widths (up to 0.8 mm).
2. Chemical encapsulation offers superior instantaneous reaction kinetics and high localized mechanical strength recovery, but suffers from single-use limitations, shell rupture risks during mixing, and thermal degradation.
3. Hybrid encapsulation strategies (e.g., bacteria immobilized in SAPs or biochar) represent the most effective pathway to ensure spore survival and operational reliability under severe environmental conditions.
4. Strategic adoption of SHRC provides a transformative, eco-efficient strategy for reducing lifecycle maintenance burdens and decarbonizing future civil infrastructure.

8. Recommendations

1. Standardization: Establish unified international testing protocols (e.g., RILEM guidelines) for measuring real-time healing kinetics, crack depth sealing, and chloride ingress recovery in SHRC.
2. Carrier Optimization: Focus future empirical research on sustainable, cost-effective bio-carriers such as agricultural

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waste biochar and expanded shale to maximize bacterial survival during concrete mixing.

3. Field Pilot Demonstrations: Expand real-world scale field implementations under combined aggressive exposures (e.g., cyclic freeze-thaw with marine salt spray).

Acknowledgement

The authors extend their sincere gratitude to the Faculty of Engineering and Petroleum at the University of Benghazi for academic support.

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