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DEVELOPMENT OF ENCAPSULATION TECHNOLOGY TO ENHANCE THE PERFORMANCE OF MICROBIAL SELF-HEALING CONCRETE

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Abstract

Microbial self-healing concrete offers an innovative solution to address the problem of cracks in modern infrastructure, but its field application is hindered by the viability of bacteria within the harsh concrete matrix. This systematic literature review aims to explore the development of encapsulation technology as a strategy to enhance the performance of microbial self-healing concrete. The methodology includes a comprehensive search of major academic databases using a combination of specific keywords, and article selection based on strict inclusion and exclusion criteria. Analysis found that a diverse range of encapsulation technologies have been adopted, including the use of sodium silicate-coated Recycled Coarse Aggregate (RCA), fly ash, cement shell microencapsulation, biopolymer encapsulation, pH-sensitive hydrogels, and modified manufactured aggregates. These technologies significantly enhance bacterial viability and the effectiveness of the self-healing process, resulting in more efficient crack closure and improved mechanical properties and durability of the concrete. Nevertheless, significant challenges still include the long-term viability of bacteria, limitations in the scale of field application, and the high cost of encapsulation production. This research concludes that the development of essential encapsulation technology is crucial in advancing microbial self-healing concrete applications toward more durable and environmentally friendly construction solutions.

Keywords: Self-healing concrete, Microbes, Encapsulation, Bacterial viability, Calcium carbonate precipitation, Systematic review.

1. Introduction

Concrete, as the most widely used construction material, is highly susceptible to cracking, which can reduce structural integrity, accelerate deterioration, and increase maintenance costs (Sidhu et.al., 2023, Wong et.al, 2024; Amer et.al, 2020). In addition, cracks facilitate the ingress of aggressive agents, leading to the corrosion of steel reinforcement (J. Xu, Tang, Wang, et.al, 2020; Ling & Qian, 2017). To address these challenges, self-healing concrete, which possesses the ability to autonomously repair cracks, has emerged as a promising and innovative solution (Sidhu et.al, 2023; Su et.al, 2021).

This systematic review aims to provide a comprehensive assessment of the development of encapsulation technologies in the field of microbial self-healing concrete. Specifically, the study seeks to identify the various types of encapsulation technologies, evaluate their effects on microbial viability and the self-healing performance of concrete, including crack-closing efficiency and strength recovery, and examine existing challenges as well as future research directions. It is

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anticipated that this review will offer valuable insights and practical guidance for future studies and real-world applications in the field of sustainable construction materials.

2. Literature Review

This literature review identifies various innovations in microorganism encapsulation technologies for self-healing concrete, which are designed to protect biological agents within the harsh concrete environment and activate them when cracks occur. Overall, these studies demonstrate significant efforts to develop intelligent and sustainable encapsulation solutions to enhance the self-healing capacity of concrete. In general, the selection of encapsulation technology largely depends on the type of bacteria used, the desired conditions within the concrete environment, and the release efficiency of the self-healing agents. The primary objective is to ensure optimal protection and timely activation of the microorganisms, enabling them to effectively perform their healing function within the concrete matrix over an extended service life.

Encapsulation technology plays a crucial role in overcoming the limitations of microbial viability in the harsh concrete environment, thereby significantly improving the effectiveness of self-healing. Its main impact can be seen in the enhanced survival and activity of bacteria, which have been shown to perform better than direct mixing methods, as reported by (Zheng et.al, 2020) and (Dinarvand & Rashno, 2022).

3. Methodology

This study employed the Systematic Literature Review (SLR) method to examine encapsulation technologies for microbial self-healing concrete, with a particular focus on the sustainability and performance of the system. The review was conducted in accordance with the PRISMA 2020 guidelines, as illustrated in Figure 1, to provide a comprehensive overview of the application of this technology in the context of sustainable development.

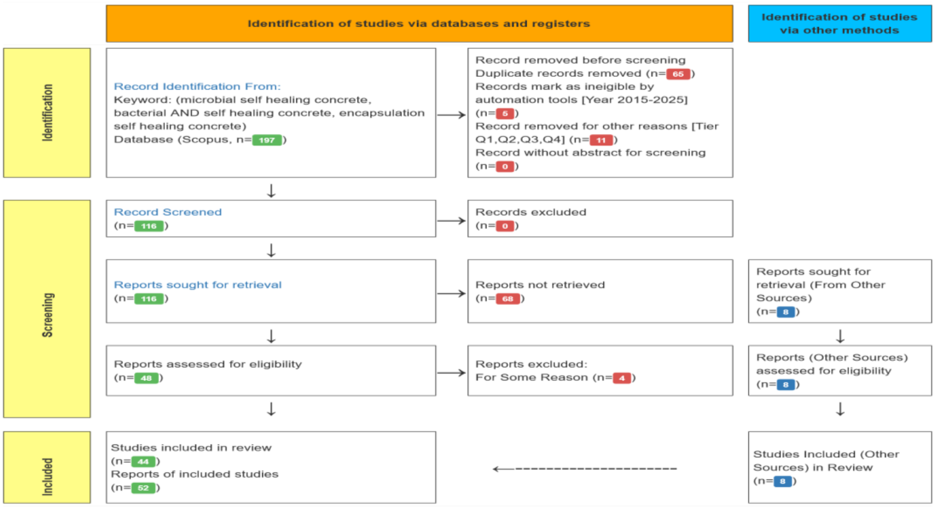

Figure 1. PRISMA Flow Diagram

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The literature review was conducted using the Systematic Literature Review (SLR) approach through a structured process, beginning with article searches in selected databases, followed by data screening and eligibility assessment of the studies. Each identified record was screened based on clearly defined criteria to ensure that only relevant studies were included. Accordingly, every stage of the process was documented in detail, from identification to the final inclusion of studies in the review.

The SLR approach minimizes bias in the selection of reviewed literature, as each study is assessed objectively using predefined criteria. As a result, it provides a comprehensive literature review that is methodologically rigorous and scientifically reliable.

4. Hasil dan Pembahasan

4.1 PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis)

The process began with the identification of relevant studies through searches in the Scopus database, using highly specific keywords such as “microbial self-healing concrete,” “bacterial AND self-healing concrete,” and “encapsulation self-healing concrete.” This search yielded 197 articles published between 2015 and 2025. An initial screening process was then conducted by removing duplicate records and articles that did not meet the inclusion criteria, including those excluded by automation tools (n = 65), as well as articles without abstracts for further assessment (n = 11). Subsequently, 116 screened articles were subjected to further evaluation through abstract assessment and additional screening procedures. Of these 116 articles, 68 reports could not be accessed or retrieved from relevant sources, while 8 additional articles were identified through other sources and included in the evaluation process. These reports were then further assessed based on topic relevance and methodological quality, with particular emphasis on encapsulation technologies supporting microbial self-healing concrete. Following the screening process, a total of 44 studies were included in the final review, comprising journal articles published between 2015 and 2025.

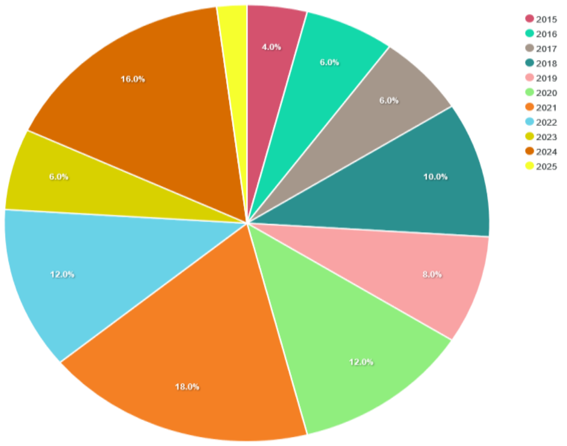

Figure 2. Classification Graph Based on Year of Publication

The classification graph in Figure 2 illustrates the distribution of publications by year of publication. The year 2021 was identified as the most productive year, with a total contribution of 18

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publications. Overall, this distribution indicates an increasing trend in research activity and scientific publications in the related field, particularly over the last five years.

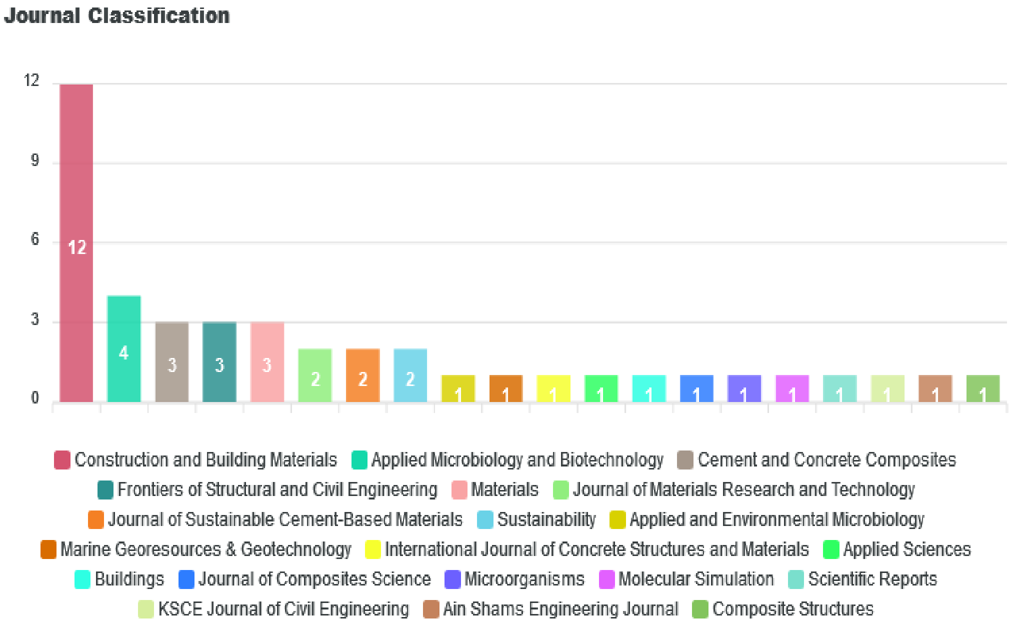

Figure 3. Bar Chart Based on Journal Classification

The first bar chart in Figure 3 presents the distribution of publications based on journal classification. The majority of articles were published in the journal Construction and Building Materials, indicating that the primary research focus lies in building materials and construction. This was followed by several other journals, reflecting the interdisciplinary nature of the field, particularly the integration of civil engineering and biotechnology. This distribution suggests that publications are not confined to a single discipline, but rather involve multiple scientific domains. The diversity of journals also reflects the broad range of research topics pursued by scholars in this area.

Further analysis, as shown in Figure 4, indicates that the majority of studies were conducted in countries such as China, India, and Belgium, as reflected in the geographical distribution of the studies. These reports were subsequently analyzed to categorize findings based on encapsulation techniques, concrete performance, and sustainability in real-world applications. Through this analysis, the SLR provides a clear overview of the application of encapsulation technology in microbial self-healing concrete, highlighting its potential to enhance sustainability in the construction industry, particularly through the development of more durable and environmentally friendly materials.

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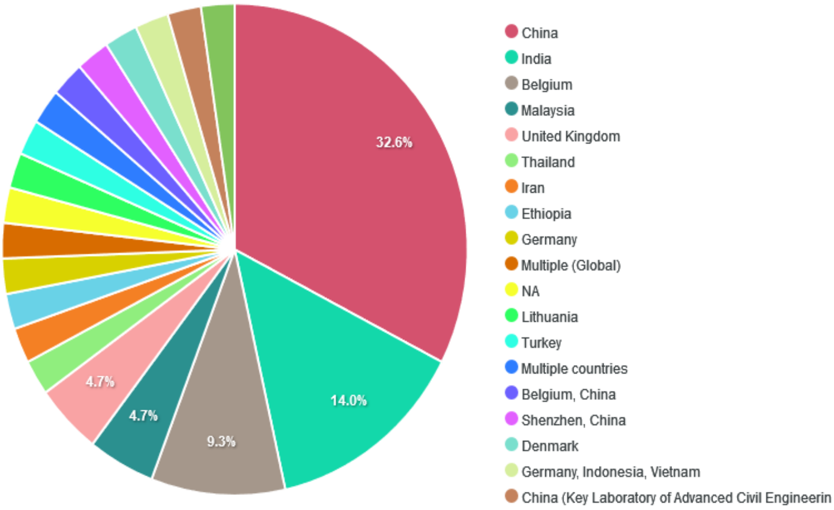

Figure 4. Bar Chart by Journal Classification

3.2 Application of Encapsulation Technology and Various Encapsulation Media for Microorganisms in Concrete

In the development of microbial-based self-healing concrete, encapsulation technology plays a crucial role in protecting bacteria from the harsh conditions of concrete, such as high alkalinity and limited nutrient availability, while also controlling the release of healing agents (Wong et.al, 2024; Kim et.al, 2021; Lee & Park, 2018).

Based on the findings presented in Table 1, which classifies encapsulation applications, various strategies have been developed to incorporate healing agents into concrete, primarily bacteria. The main categories demonstrate a diversification of methods, ranging from waste-inspired materials to synthetic compounds. This diversity reflects multidisciplinary efforts to address the challenges of bacterial viability and the controlled release of healing agents in self-healing concrete.

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Table 1. Classification of Encapsulation Applications

Application Category	Encapsulation Media	Author(s) (Year)
Recycled Aggregate / Porous Aggregate-Based	LWA, RCA/RFA, FAA, Silica gel, Diatomaceous earth, Ca-alginate beads, Expanded clay/perlite, Ceramsite, Recycled brick, Biochar	(Vedrtnam et.al, 2025b); (Zanjad et.al, 2024); (J. Xu et.al, 2024); (Mohan Rao Pannem et.al, 2024); (Kim et.al, 2021); (Wong et.al, 2024);(Huang et.al, 2022); (Ivaškė et.al, 2023); (J. Zhu et.al, 2022); (Liu et.al, 2021); (Huang et.al, 2022); (J. Xu et.al, 2018); (Dinarvand & Rashno, 2022); (J. Xu, Tang, & Wang, 2020);(Lee & Park, 2018); (Alghamri et.al, 2016)
Polymer / Hydrogel Microencapsulation	PU microcapsules, Alginate beads, Hydrogel kitosan, Mikrokapsul melamine, Kapsul kaca, PMMA capsules, SAP, Resin/epoxy/healing agents	(Vedrtnam et.al, 2025b); (Zanjad et.al, 2024); (Kim et.al, 2021); (Pungrasmi et.al, 2019); (Dai et.al, 2022); (Hanna, 2022);(Huang et.al, 2022); (X. Zhu et.al, 2021); (Dinarvand & Rashno, 2022); (Mauludin et.al, 2020); (Nielsen et.al, 2020); (Debnath & Sen, 2024); (Lee & Park, 2018); (Mauludin et.al, 2018)
Cement / Mineral-Based	Cement-shell, Metakaolin, Limestone powder, Fly ash, Slag, Sulfo-aluminate cement, Mortar metakaolin, Na_2SiO_3 coatings, Partikel karet berlapis semen	(Vedrtnam et.al, 2025b); (J. Xu et.al, 2024); (Kim et.al, 2021); (Wong et.al, 2024); (Sidhu et.al, 2023); (Liu et.al, 2021); (Qian, Zhang, et.al, 2021); (H. Xu et.al, 2019)
Without Encapsulation (Direct Method) and Micropores	Bubuk spora Bacillus, Pencampuran langsung, In-situ encapsulation, Urea + $Ca(NO_3)_2$, Spora + Ca-laktat, Substrat organik	(Mohammed et.al, 2024);(Qian, Zhang, et.al, 2021); (Amer Algaifi et.al, 2020); (X. Zhang & Qian, 2020); (J. Xu, Tang, & Wang, 2020); (Chithambar Ganesh et.al, 2019); (Ling & Qian, 2017); (Da Silva et.al, 2015)
Others	Mikrovoid alami, CERUP (spora kering + garam)	(Feng et.al, 2021); (Da Silva et.al, 2015)

Table 2. Classification Based on Capsule Size

Size Category	Capsule/Carrier Size	Author(s) (Year)
Micro	100–500 µm; 100–300 µm; 220 nm; 200–300 µm; 50–100 µm; 65–120 µm; 0.5 mm; 1–10 µm; 600–800 µm; 20–40 µm; 5–200 µm; <500 µm	(Wong et.al, 2024); (Dai et.al, 2022); (Hanna, 2022); (Luhar et.al, 2022); (Huang et.al, 2022); (Feng et.al, 2021); (Su et.al, 2021); (Dinarvand & Rashno, 2022); (Nielsen et.al, 2020);(Pungrasmi et.al, 2019);(Lee & Park, 2018); (J. L. Zhang et.al, 2016); (Erşan et.al, 2015);(Da Silva et.al, 2015)
Macro	0.075–5 mm; 10–20 mm; 1–2 mm; 0.2–2 mm; 0.5–2 mm; 2–5 mm; 2.36–4.75 mm; 3.2–4.0 mm; 2–3 mm; 1.7–7.2 mm; 0.2–0.4 mm & 1–3 mm; Ø 3 mm p 50 mm; Ø luar 11.4 mm p 50 mm; 4–8 mm	(J. Xu et.al, 2024);(Mohan Rao Pannem et.al, 2024); (Kim et.al, 2021); (Wong et.al, 2024); (Debnath & Sen, 2024);(Zanjad et.al, 2024); (J. Zhu et.al, 2022); (Liu et.al, 2021); (Huang et.al, 2022); (Liu et.al, 2021); (Qian, Zhang, et.al, 2021);(X. Zhu et.al, 2021); (Dinarvand & Rashno, 2022); (Erşan et.al, 2015); (Mauludin et.al, 2020); Xu et.al (2020); (X. Zhang & Qian, 2020); (H. Xu et.al, 2019); (Mauludin et.al, 2018); (Gilabert, Van Tittelboom, Van Stappen, et.al, 2017); (Qureshi et.al, 2016); (Alghamri et.al, 2016)
Unspecified / Very Small	No Specific Size; Powdered Spores; Without Synthetic Capsules	(Vedrtnam et.al, 2025b); (Zanjad et.al, 2024); (Kim et.al, 2021);(Mohammed et.al, 2024); (Sidhu et.al, 2023);(X. Zhu et.al, 2021); (Qian, Zhang, et.al, 2021); (Qian, Zheng, et.al, 2021); (Amer Algaifi et.al, 2020); (Chithambar Ganesh et.al, 2019); (Ling & Qian, 2017); (Da Silva et.al, 2015)

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Based on the capsule size classification presented in Table 2, encapsulation methods in self-healing concrete vary widely in dimension, reflecting efforts to adapt to the specific requirements and conditions of concrete systems. Micro-sized capsules, generally ranging from 100–500 µm to the nanometer scale of approximately 220 nm, are frequently reported in studies involving polymer microcapsules, silica gel, or diatomaceous earth (Wong et.al, 2024; Dai et.al, 2022; Luhar et.al, 2022).

The chart in Figure 5 illustrates the distribution of bacterial use in self-healing concrete research based on the compiled data. Bacillus subtilis and Sporosarcina pasteurii were the most dominant species, each accounting for 21% of the total studies. These findings confirm that ureolytic bacteria remain the primary focus of research, although non-bacterial alternatives have also received attention in the development of self-healing concrete technologies.

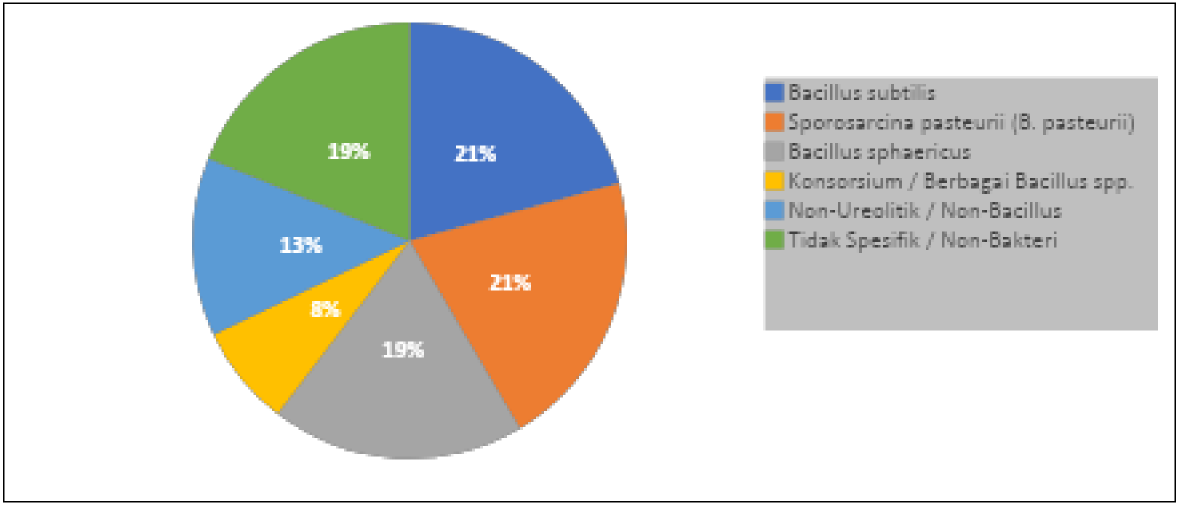

Figure 5. Distribution of Bacterial Use in Self-Healing Concrete

3.3 Effect of Encapsulation Technology on Microbial Viability and the Self-Healing Performance of Concrete

In Table 3, the category “Biological (MICP) – Encapsulation” highlights the use of various materials as carriers, ranging from zeolite, hydrogel, ceramsite, and lightweight aggregates (LWA) to microcapsules, all of which have been shown to protect microorganisms from the harsh concrete environment. These findings demonstrate that encapsulation consistently improves microbial viability. The success of encapsulation not only preserves microbial viability but also significantly enhances the effectiveness of crack repair in concrete.

In contrast, the table clearly distinguishes its effectiveness from the direct mixing approach, in which microorganisms are incorporated directly into the concrete matrix. The category “Biological (MICP) – Direct Mixing” indicates a rapid decline in microbial viability and limited crack-healing

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performance, as reported by Tesfaye A. Mohammed et.al (2024) and Kaur et.al (2022), who used Bacillus subtilis without protective carriers. Even when using spray-dried spores or nutrient solutions, as reported in the studies by (X. Zhang & Qian, 2022) and (Amer Algaifi et.al, 2020), the healing effect remained limited to small cracks of up to 0.5 mm or 0.3 mm.

Table 3. Comparison of Encapsulation Technologies Based on Approach, Material Type, and Crack-Healing Performance

Classification	Approach	Study (Author(s) & Year)	Type of Microorganism	Type of Material	Viability Efficiency	Crack-Healing Effectiveness
Biological (MICP) – Encapsulation	Zeolite, hydrogel, ceramsite, LWA, microcapsules	(Javeed et.al, 2024)	*B. subtilis, B. aerius, B. odysseyi, S. pasteurii*	Conventional Concrete + Carrier (Zeolite, Hydrogel, LWA)	Carrier Enhances Viability	Cracks ≤1 mm healed, compressive strength increased
	Fly Ash Aggregates (FAA)	(Mohan Rao Pannem et.al, 2024)	*B. subtilis*	OPC Concrete + Fly Ash Aggregate	Porous FAA Stores Bacteria	Healing ≤0.25 mm, compressive strength increased
	RCA + sodium silicate	(J. Xu et.al, 2024)	*S. pasteurii*	RCA + Sodium Silicate Coating	Nutrients and Spores Protected	~90% Healing of 0.3–0.4 mm cracks
	Hydrogel, LWA, polymer coating, diatomaceous silica	(Vedrtnam et.al, 2025b); (J. Xu, Tang, Wang, et.al, 2020); (Duan et.al, 2023)	*B. sphaericus, S. pasteurii*	Concrete + Natural Fibers	Fibers Enhance Bacterial Retention	75% Effectiveness for Cracks <0.6 mm
	Cement Microcapsules with Self-Oxygen Supply	(Ahmad et.al, 2024)	*B. subtilis*	Cement Microcapsules with Oxygen Supply	High viability; spores protected from high pH and controlled O_2 release	In the BPN group (B6 + nutrients + CaO_2), complete healing (≈100%) was achieved, whereas the other groups showed only partial healing (20–60%).
	Microencapsulation in Sodium Alginate	(Ivaškė et.al, 2023); (Pungrasmi et.al, 2019)	*B. subtilis, B. sphaericus*	Alginate beads	Good Viability	Healing of Cracks <0.5 mm
	Bacterial Spores in Metakaolin	(Sidhu et.al, 2023)	*B. paramycoides (spora)*	Metakaolin + Corn Steep Liquor (CSL)	Stable for 180 Days	Complete Healing in 28–50 Days
	EPS (Extracellular tances)	(Debnath & Sen, 2024)	*Paenibacillus alkaliterrae*	EPS dari *Cellulomonas flavigena*, CaO_2	Only 0.2% Spore Leakage	High $CaCO_3$ Content, Improved Crack Resistance
	LWA with PU, Silicate, or MgO Coating	(Kim et.al, 2021)	*Bacillus sp.*	PU-, Silicate-,	Adequate Viability	Healing ≤0.3 mm

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	Protective Media: Diatomaceous Earth, GAC	(Erşan et.al, 2015)	*B. subtilis*	or MgO-Coated LWA Diatomaceous Earth, GAC	Good Viability	Healing ≤0.4 mm
Biological (MICP) – Direct Mixing	Direct Culture/Spores without Encapsulation	(Mohammed et.al, 2024); (Feng et.al, 2021);(Amer Algaifi et.al, 2020);(Chithambar Ganesh et.al, 2019);(Ling & Qian, 2017)	*B. subtilis*	Conventional Concrete	Viability Rapidly Declined	Minor Healing, Low Effectiveness
	Spray-Dried Spores Directly Mixed	(X. Zhang & Qian, 2022); (Qian, Zheng, et.al, 2021);	*S. pasteurii*	OPC Concrete	Moderate Stability	Healing ≤0.5 mm
	Urea + $Ca(NO_3)_2$ Solution Mixed In	(Amer Algaifi et.al, 2020)	*B. subtilis*	Urea–$Ca(NO_3)_2$ Solution	Urea–$Ca(NO_3)_2$ Solution	Healing ≤0.3 mm
	Calcium Lactate Solution Added to Mixing Water	(Vijay & Murmu, 2019)	*B. subtilis*	Concrete + Calcium Lactate	Moderate Viability	Healing of Small Cracks
	Mixed Spores (Non-Axenic) Powder	(Da Silva et.al, 2015)	*Campuran Bacillus spp.*	Mixed Spore Powder	Low	Healing ≤0.25 mm
Biological (MICP) – Nutrient-Focused	Nutrient-Rich Liquid Media (Lactate, Nitrate, Ca^{2+})	(J. L. Zhang et.al, 2016)	*B. subtilis*	Concrete + Nutrients (Lactate/Nitrate/Ca^{2+})	Viability Increased	Healing ≤0.4 mm
	SAP (Superabsorbent Polymer) with Growth Medium	(Nielsen et.al, 2020)	*B. subtilis*	SAP Rehydrated with Nutrients	SAP Maintains Moisture	Healing ≤0.3 mm
Chemical (Non-Biological)	Poliuretan, sodium silicate, MgO/CaO/bentonite	(Gilabert, Van Tittelboom, Tsangouri, et.al, 2017); (Alghamri et.al, 2016); (Qureshi et.al, 2016)	–	Glass Capsules, LWA, Reactive Minerals	–	Healing ≤0.5 mm (Non-Biological)
Computational / Simulation	XFEM, DFT, ML, Numerical Simulation	(Hanna, 2022); (J. Zhu et.al, 2022); (Mauludin et.al, 2020); (Huang et.al, 2022); (Mauludin et.al, 2018)	–	–	–	Simulation Only, Not Experimental
Review	Literature review	(Zanjad et.al, 2024); (Wong et.al, 2024); (Luhar et.al, 2022); (Dinarvand & Rashno, 2022)	–	–	–	Method Evaluation, Without Experimental Data

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3.4 Current Limitations of Encapsulation Technology in Enhancing the Performance of Microbial Self-Healing Concrete

There are several significant limitations that need to be addressed from technical, economic, and environmental perspectives. From a technical standpoint, the primary challenge lies in ensuring the long-term survival of bacteria as well as the stability of the encapsulation materials themselves within the highly aggressive concrete environment (Wong et.al, 2024; Lee & Park, 2018). Concrete exhibits very high alkalinity, particularly Alkali-Activated Slag (AAS), where the pH may exceed 12, in addition to limited oxygen availability and extreme mechanical stresses during mixing and compaction (Lee & Park, 2018; Zanjad et.al, 2024; Mohan Rao Pannem et.al, 2024).

The uniform distribution of capsules within the concrete matrix also remains a technical challenge. If capsules are not homogeneously dispersed, crack-healing efficiency may be compromised because not all damaged zones can be reached by the healing agents (Mauludin et.al, 2020; Hanna, 2022). Another limitation concerns the size of cracks that can be effectively healed. Most studies report high effectiveness for microcracks (less than 0.5 mm), whereas the healing of larger cracks remains challenging (Wong et.al, 2024; Mohan Rao Pannem et.al, 2024; J. Xu et.al, 2024). Healing efficiency also varies depending on bacterial species, dosage, carrier type, and environmental conditions such as temperature and ion concentration (Javeed et.al, 2024; J. Xu, Tang, Wang, et.al, 2020). A study by (Amer Algaifi et.al, 2020) further revealed that bacterial healing performance decreases with increasing pH and insufficient oxygen availability.

From an economic perspective, one of the major constraints is the high cost associated with the production and implementation of encapsulation materials (Wong et.al, 2024). The use of materials such as biopolymers (Kim et.al, 2021) or pH-sensitive hydrogels (X. Zhu et.al, 2021), as well as techniques such as freeze-drying (Pungrasmi et.al, 2019), often requires substantially higher costs than conventional materials or methods. Although (Da Silva et.al, 2015) developed a more efficient and low-cost method for producing non-axenic ureolytic spores (CERUP) to reduce bacterial production costs, the initial capital investment for industrial-scale implementation remains high.

From an environmental perspective, some encapsulation materials, such as synthetic polymers or glass capsules as reported by (Qureshi et.al, 2016), may not be fully biodegradable, and their production processes may generate additional environmental burdens (Gilabert, Van Tittelboom, Tsangouri, et.al, 2017; Qureshi et.al, 2016). Although the use of industrial waste materials such as fly ash and recycled concrete aggregate (RCA) offers significant sustainability benefits (Mohan Rao Pannem et.al, 2024; J. Xu et.al, 2024), their large-scale application still requires further investigation regarding cumulative environmental impacts and long-term supply sustainability (Mohan Rao Pannem et.al, 2024).

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3.5 Future Prospects and Research Directions of Encapsulation Technology in Microbial Self-Healing Concrete

Future research directions for encapsulation technology in microbial self-healing concrete are focused on four major areas aimed at improving optimization, efficiency, and scalability. First, the development of more resilient microorganisms, together with cost-effective and environmentally friendly encapsulation strategies, is crucial, as emphasized by (Lee & Park, 2018), including the exploration of affordable production methods such as freeze-drying (Pungrasmi et.al, 2019).

Second, the validation and optimization of large-scale field applications are essential, particularly by replicating the successful outcomes of case studies such as those reported by (X. Zhang & Qian, 2020), as well as integrating smart sensors for real-time monitoring (Qian, Zhang, et.al, 2021).

Third, the integration of sustainable alternative materials such as recycled concrete aggregate (RCA) (X. Zhang & Qian, 2022; J. Zhu et.al, 2022), fly ash (Mohan Rao Pannem et.al, 2024), and corn steep liquor (Sidhu et.al, 2023; Wong et.al, 2024) is expected to reduce both costs and environmental impacts, including the development of low-carbon concrete formulations (Medeiros & Di Sarno, 2022).

Finally, multi-parameter approaches and the application of machine learning techniques (Javeed et.al, 2024; Huang et.al, 2022) will be key to optimizing material design and predicting performance, thereby advancing this technology as an effective and sustainable solution for future infrastructure systems.

4. Conclusion

Encapsulation technology plays a crucial role in enhancing the performance of microbial self-healing concrete, particularly in maintaining bacterial viability within harsh concrete environments. Various encapsulation methods, such as porous aggregates, polymer-based microencapsulation, and cement-based materials, have proven effective in protecting microorganisms and improving crack-healing efficiency. Compared to direct mixing methods, encapsulation significantly results in higher crack-healing performance and improved mechanical properties of concrete. Microorganisms such as Bacillus subtilis and Sporosarcina pasteurii are the most commonly used due to their ability to precipitate calcium carbonate. However, several challenges remain, including long-term bacterial survival, uniform distribution of capsules, and limitations in healing larger cracks. From an economic perspective, the relatively high production cost of encapsulation materials hinders large-scale implementation. Additionally, some synthetic encapsulation materials raise environmental concerns due to their lack of biodegradability and potential ecological impact. Therefore, future research should focus on developing more efficient, cost-effective, and environmentally friendly encapsulation strategies, as well as integrating intelligent technologies to support broader and more sustainable applications.

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5. References

Ahmad, M. A., Zhang, J., Bing, L., Tan, P., & Deng, X. (2024). Unlocking the efficacy of cement-shell encapsulation for microbial self-healing process of concrete cracks. *Journal of Materials Research and Technology*, *32*, 2733–2742. https://doi.org/10.1016/j.jmrt.2024.08.133

Alghamri, R., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Impregnation and encapsulation of lightweight aggregates for self-healing concrete. *Construction and Building Materials*, *124*, 910–921. https://doi.org/10.1016/j.conbuildmat.2016.07.143.

Amer Algaifi, H., Abu Bakar, S., Rahman Mohd. Sam, A., Ismail, M., Razin Zainal Abidin, A., Shahir, S., & Ali Hamood Altowayti, W. (2020). Insight into the role of microbial calcium carbonate and the factors involved in self-healing concrete. *Construction and Building Materials*, *254*. https://doi.org/10.1016/j.conbuildmat.2020.119258.

Chithambar Ganesh, A., Muthukannan, M., Malathy, R., & Ramesh Babu, C. (2019). An Experimental Study on Effects of Bacterial Strain Combination in Fibre Concrete and Self-Healing Efficiency. *KSCE Journal of Civil Engineering*, *23*(10), 4368–4377. https://doi.org/10.1007/s12205-019-1661-2.

Da Silva, F. B., De Belie, N., Boon, N., & Verstraete, W. (2015). Production of non-axenic ureolytic spores for self-healing concrete applications. *Construction and Building Materials*, *93*, 1034–1041. https://doi.org/10.1016/j.conbuildmat.2015.05.049

Dai, Z., Tsangouri, E., Van Tittelboom, K., Zhu, X., & Gilabert, F. A. (2022). Understanding fracture mechanisms via validated virtual tests of encapsulation-based self-healing concrete beams. *Materials and Design*, *213*. https://doi.org/10.1016/j.matdes.2021.110299

Debnath, A., & Sen, R. (2024). Construction nanobiotechnology approach for performance enhancement of microbially induced biomineralization (MIB) using a biopolymer encapsulated spore-based system. *Applied and Environmental Microbiology*, *90*(9). https://doi.org/10.1128/aem.01407-24.

Dinarvand, P., & Rashno, A. (2022). Review of the potential application of bacteria in self-healing and the improving properties of concrete/mortar. In *Journal of Sustainable Cement-Based Materials* (Vol. 11, Issue 4, pp. 250–271). Taylor and Francis Ltd. https://doi.org/10.1080/21650373.2021.1936268.

Duan, Z., Lv, Z., Xiao, J., Liu, C., & Nong, X. (2023). Study on the Performance of Recycled Coarse and Fine Aggregates as Microbial Carriers Applied to Self-Healing Concrete. *Materials*, *16*(6). https://doi.org/10.3390/ma16062371.

Erşan, Y. Ç., Da Silva, F. B., Boon, N., Verstraete, W., & De Belie, N. (2015). Screening of bacteria and concrete compatible protection materials. *Construction and Building Materials*, *88*, 196–203. https://doi.org/10.1016/j.conbuildmat.2015.04.027.

Feng, J., Chen, B., Sun, W., & Wang, Y. (2021). Microbial induced calcium carbonate precipitation study using Bacillus subtilis with application to self-healing concrete preparation and characterization. *Construction and Building Materials*, *280*. https://doi.org/10.1016/j.conbuildmat.2021.122460.

Gilabert, F. A., Van Tittelboom, K., Tsangouri, E., Van Hemelrijck, D., De Belie, N., & Van Paepegem, W. (2017). Determination of strength and debonding energy of a glass-concrete interface for encapsulation-based self-healing concrete. *Cement and Concrete Composites*, *79*, 76–93. https://doi.org/10.1016/j.cemconcomp.2017.01.011.

Gilabert, F. A., Van Tittelboom, K., Van Stappen, J., Cnudde, V., De Belie, N., & Van Paepegem, W. (2017). Integral procedure to assess crack filling and mechanical contribution of polymer-based healing agent in encapsulation-based self-healing concrete. *Cement and Concrete Composites*, *77*,

Received October 09, 2025, Revised April 15, 2026, Accepted for publication April 20, 2026

68–80. https://doi.org/10.1016/j.cemconcomp.2016.12.001.

Hanna, J. (2022). Computational Modelling for the Effects of Capsular Clustering on Fracture of Encapsulation-Based Self-Healing Concrete Using XFEM and Cohesive Surface Technique. *Applied Sciences (Switzerland)*, *12*(10). https://doi.org/10.3390/app12105112.

Huang, X., Sresakoolchai, J., Qin, X., Ho, Y. F., & Kaewunruen, S. (2022). Self-Healing Performance Assessment of Bacterial-Based Concrete Using Machine Learning Approaches. *Materials*, *15*(13). https://doi.org/10.3390/ma15134436.

Ivaškė, A., Gribniak, V., Jakubovskis, R., & Urbonavičius, J. (2023). Bacterial Viability in Self-Healing Concrete: A Case Study of Non-Ureolytic Bacillus Species. *Microorganisms*, *11*(10). https://doi.org/10.3390/microorganisms11102402.

Javeed, Y., Goh, Y., Mo, K. H., Yap, S. P., & Leo, B. F. (2024). Microbial self-healing in concrete: A comprehensive exploration of bacterial viability, implementation techniques, and mechanical properties. *Journal of Materials Research and Technology*, *29*, 2376–2395. https://doi.org/10.1016/j.jmrt.2024.01.261.

Kim, H., Son, H. M., Seo, J., & Lee, H. K. (2021). Recent advances in microbial viability and self-healing performance in bacterial-based cementitious materials: A review. *Construction and Building Materials*, *274*, 122094. https://doi.org/10.1016/j.conbuildmat.2020.122094.

Lee, Y. S., & Park, W. (2018). Current challenges and future directions for bacterial self-healing concrete. In *Applied Microbiology and Biotechnology* (Vol. 102, Issue 7, pp. 3059–3070). Springer Verlag. https://doi.org/10.1007/s00253-018-8830-y.

Ling, H., & Qian, C. (2017). Effects of self-healing cracks in bacterial concrete on the transmission of chloride during electromigration. *Construction and Building Materials*, *144*, 406–411. https://doi.org/10.1016/j.conbuildmat.2017.02.160.

Liu, C., Zhang, R., Liu, H., Xu, X., & Lv, Z. (2021). Experimental and analytical study on the flexural rigidity of microbial self-healing concrete based on recycled coarse aggregate (RCA). *Construction and Building Materials*, *285*. https://doi.org/10.1016/j.conbuildmat.2021.122941.

Luhar, S., Luhar, I., & Shaikh, F. U. A. (2022). A Review on the Performance Evaluation of Autonomous Self-Healing Bacterial Concrete: Mechanisms, Strength, Durability, and Microstructural Properties. In *Journal of Composites Science* (Vol. 6, Issue 1). MDPI. https://doi.org/10.3390/jcs6010023.

Mauludin, L. M., Oucif, C., & Rabczuk, T. (2020). The effects of mismatch fracture properties in encapsulation-based self-healing concrete using cohesive-zone model. *Frontiers of Structural and Civil Engineering*, *14*(3), 792–801. https://doi.org/10.1007/s11709-020-0629-0.

Mauludin, L. M., Zhuang, X., & Rabczuk, T. (2018). Computational modeling of fracture in encapsulation-based self-healing concrete using cohesive elements. *Composite Structures*, *196*, 63–75. https://doi.org/10.1016/j.compstruct.2018.04.066.

Medeiros, J. M. P., & Di Sarno, L. (2022). Low Carbon Bacterial Self-Healing Concrete. *Buildings*, *12*(12). https://doi.org/10.3390/buildings12122226.

Mohammed, T. A., Kasie, Y. M., Assefa, E., Getu, Y. M., & Tufa, D. H. (2024). Enhancing Structural Resilience: Microbial-Based Self-Healing in High-Strength Concrete. *International Journal of Concrete Structures and Materials*, *18*(1). https://doi.org/10.1186/s40069-024-00661-4.

Mohan Rao Pannem, R., Bashaveni, B., & Kalaiselvan, S. (2024). The effect of fly ash aggregates on the self-healing capacity of bacterial concrete. *Ain Shams Engineering Journal*, *15*(1). https://doi.org/10.1016/j.asej.2023.102261.

Nielsen, S. D., Koren, K., Löbmann, K., Hinge, M., Scoma, A., Kjeldsen, K. U., & Røy, H. (2020).

Received October 09, 2025, Revised April 15, 2026, Accepted for publication April 20, 2026

Constraints on CaCO3 precipitation in superabsorbent polymer by aerobic bacteria. *Applied Microbiology and Biotechnology*, *104*(1), 365–375. https://doi.org/10.1007/s00253-019-10215-4.

Pang, B., Zhou, Z., Hou, P., Du, P., Zhang, L., & Xu, H. (2016). Autogenous and engineered healing mechanisms of carbonated steel slag aggregate in concrete. *Construction and Building Materials*, *107*, 191–202. https://doi.org/10.1016/j.conbuildmat.2015.12.191.

Pungrasmi, W., Intarasoontron, J., Jongvivatsakul, P., & Likitlersuang, S. (2019). Evaluation of Microencapsulation Techniques for MICP Bacterial Spores Applied in Self-Healing Concrete. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-49002-6.

Qian, C., Zhang, Y., & Xie, Y. (2021). Effect of ion concentration in crack zone on healing degree of microbial self-healing concrete. *Construction and Building Materials*, *286*. https://doi.org/10.1016/j.conbuildmat.2021.122969.

Qian, C., Zheng, T., Zhang, X., & Su, Y. (2021). Application of microbial self-healing concrete: Case study. *Construction and Building Materials*, *290*. https://doi.org/10.1016/j.conbuildmat.2021.123226.

Qureshi, T. S., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Encapsulation of expansive powder minerals within a concentric glass capsule system for self-healing concrete. *Construction and Building Materials*, *121*, 629–643. https://doi.org/10.1016/j.conbuildmat.2016.06.030.

Sidhu, N., Goyal, S., & Reddy, M. S. (2023). Self-healing by biocomposite containing metakaolin immobilized bacterial spores in concrete using low-cost corn steep liquor media. *Journal of Sustainable Cement-Based Materials*, *12*(11), 1430–1446. https://doi.org/10.1080/21650373.2023.2224805

Su, Y., Li, F., He, Z., & Qian, C. (2021). Artificial aggregates could be a potential way to realize microbial self-healing concrete: An example based on modified ceramsite. *Journal of Building Engineering*, *35*. https://doi.org/10.1016/j.jobe.2020.102082.

Vedrtnam, A., Kalauni, K., & Palou, M. T. (2025a). Finite element simulation of bacterial self-healing in concrete using microstructural transport and precipitation modeling. *Scientific Reports*, *15*(1), 1–22. https://doi.org/10.1038/s41598-025-99844-6.

Vedrtnam, A., Kalauni, K., & Palou, M. T. (2025b). Ranking Bacteria for Carbon Capture and Self-Healing in Concrete: Performance, Encapsulation, and Sustainability. In *Sustainability (Switzerland)* (Vol. 17, Issue 12). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su17125353\

Vijay, K., & Murmu, M. (2019). Effect of calcium lactate on compressive strength and self-healing of cracks in microbial concrete. *Frontiers of Structural and Civil Engineering*, *13*(3), 515–525. https://doi.org/10.1007/s11709-018-0494-2

Wong, P. Y., Mal, J., Sandak, A., Luo, L., Jian, J., & Pradhan, N. (2024). Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions. In *Science of the Total Environment* (Vol. 947). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2024.174553

Xu, H., Lian, J., Gao, M., Fu, D., & Yan, Y. (2019). Self-healing concrete using rubber particles to immobilize bacterial spores. *Materials*, *12*(14). https://doi.org/10.3390/ma12142313

Xu, H., Wu, S., Li, H., Zhao, Y., & Lv, Y. (2020). Study on recycling of steel slags used as coarse and fine aggregates in induction healing asphalt concretes. *Materials*, *13*(4). https://doi.org/10.3390/ma13040889

Xu, J., Tang, Y., & Wang, X. (2020). A correlation study on optimum conditions of microbial precipitation and prerequisites for self-healing concrete. *Process Biochemistry*, *94*, 266–272. https://doi.org/10.1016/j.procbio.2020.04.028

Received October 09, 2025, Revised April 15, 2026, Accepted for publication April 20, 2026

Xu, J., Tang, Y., Wang, X., Wang, Z., & Yao, W. (2020). Application of ureolysis-based microbial CaCO3 precipitation in self-healing of concrete and inhibition of reinforcement corrosion. *Construction and Building Materials*, *265*. https://doi.org/10.1016/j.conbuildmat.2020.120364

Xu, J., Wang, X., & Wang, B. (2018). Biochemical process of ureolysis-based microbial CaCO3 precipitation and its application in self-healing concrete. *Applied Microbiology and Biotechnology*, *102*(7), 3121–3132. https://doi.org/10.1007/s00253-018-8779-x

Xu, J., Wang, X., Yao, W., Kulminskaya, A. A., & Shah, S. P. (2024). Microbial-inspired self-healing of concrete cracks by sodium silicate-coated recycled concrete aggregates served as bacterial carrier. *Frontiers of Structural and Civil Engineering*, *18*(1), 14–29. https://doi.org/10.1007/s11709-023-0993-7

Zanjad, N., Pawar, S., & Nayak, C. (2024). Self-Healing Molecular Biology for Microbial Concrete: A Review. *Macromolecular Symposia*, *413*(1). https://doi.org/10.1002/masy.202300001

Zhang, J. L., Wu, R. S., Li, Y. M., Zhong, J. Y., Deng, X., Liu, B., Han, N. X., & Xing, F. (2016). Screening of bacteria for self-healing of concrete cracks and optimization of the microbial calcium precipitation process. *Applied Microbiology and Biotechnology*, *100*(15), 6661–6670. https://doi.org/10.1007/s00253-016-7382-2

Zhang, X., & Qian, C. (2020). WITHDRAWN: Engineering Application of Microbial Self-healing Concrete in Lock Channel Wall. *Case Studies in Construction Materials*, e00398. https://doi.org/10.1016/j.cscm.2020.e00398

Zhang, X., & Qian, C. (2022). Engineering application of microbial self-healing concrete in lock channel wall. *Marine Georesources and Geotechnology*, *40*(1), 96–103. https://doi.org/10.1080/1064119X.2021.1871690

Zheng, T., Su, Y., Zhang, X., Zhou, H., & Qian, C. (2020). Effect and Mechanism of Encapsulation-Based Spores on Self-Healing Concrete at Different Curing Ages. *ACS Applied Materials and Interfaces*, *12*(47), 52415–52432. https://doi.org/10.1021/acsami.0c16343

Zhu, J., Shen, D., Xie, J., Jin, B., & Wu, S. (2022). Transformation mechanism of carbamic acid elimination and hydrolysis reaction in microbial self-healing concrete. *Molecular Simulation*, *48*(8), 719–735. https://doi.org/10.1080/08927022.2022.2049773

Zhu, X., Mignon, A., Nielsen, S. D., Zieger, S. E., Koren, K., Boon, N., & De Belie, N. (2021). Viability determination of Bacillus sphaericus after encapsulation in hydrogel for self-healing concrete via microcalorimetry and in situ oxygen concentration measurements. *Cement and Concrete Composites*, *119*. https://doi.org/10.1016/j.cemconcomp.2021.104006

Received October 09, 2025, Revised April 15, 2026, Accepted for publication April 20, 2026