



BACTERIAL SELF-HEALING IN CONCRETE: A REVIEW OF MICP MECHANISMS, MATERIALS, AND PERFORMANCE ASSESSMENT

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ABSTRACT: THE MOST POPULAR BUILDING MATERIAL IS CONCRETE, BUT CRACKING, PERMEABILITY, AND EXPOSURE TO HARSH CONDITIONS ALL COMPROMISE ITS DURABILITY. BECAUSE OF THEIR NEGATIVE EFFECTS ON THE ENVIRONMENT AND INCOMPATIBILITY WITH CURRENT CONCRETE MATRICES, TRADITIONAL REPAIR TECHNIQUES FREQUENTLY FAIL. THROUGH THE METABOLIC ACTIVITY OF BACTERIA LIKE BACILLUS SPECIES AND SPOROSARCINA PASTEURII, MICROBIALLY INDUCED CALCIUM CARBONATE PRECIPITATION (MICP) PROVIDES A BIO-BASED AND SUSTAINABLE SOLUTION THAT PERMITS SELF-HEALING CAPABILITIES. THE IMPACT OF BACTERIAL TREATMENTS ON CONCRETE'S COMPRESSIVE STRENGTH, CORROSION RESISTANCE, WATER PERMEABILITY, AND CRACK HEALING IS EXAMINED IN THIS REVIEW. IT HIGHLIGHTS THE TRADE-OFFS BETWEEN DURABILITY ADVANTAGES AND MECHANICAL PERFORMANCE BY PRESENTING COMPARATIVE STUDIES OF FREE AND ENCAPSULATED BACTERIAL SYSTEMS. ENCAPSULATION METHODS, BACTERIAL VIABILITY IN CHALLENGING CONCRETE CONDITIONS, AND THE FUNCTION OF DIFFERENT CARRIERS SUCH AS SILICA GEL, POLYURETHANE, AND EXPANDED PERLITE ARE ALL HIGHLIGHTED. EVALUATION METHODS FOR DETERMINING MICROSTRUCTURAL ALTERATIONS AND HEALING EFFECTIVENESS ARE COVERED IN DETAIL, INCLUDING SEM, EDS, XRD, ULTRASONIC PULSE TRANSMISSION, AND LINEAR POLARIZATION RESISTANCE (LPR). ALL THINGS CONSIDERED, MICP-BASED SELF-HEALING TECHNOLOGIES OFFER A VIABLE STRATEGY FOR EXTENDING THE DURABILITY AND ROBUSTNESS OF CONCRETE INFRASTRUCTURE.

Index Terms – Bacteria, MICP, SEM, XRD, EDS, LPR

I. INTRODUCTION

Concrete is the most commonly used building material in the world, but because of its permeability, cracking, and environmental degradation, its durability is still a major concern. Due to environmental concerns and their incompatibility with existing concrete, traditional repair methods frequently fall short. New developments in microbiologically induced calcium carbonate precipitation (MICP) present a viable environmentally friendly way to increase the durability of concrete and allow for self-healing cracks. In order to fill pores and cracks, decrease permeability, and boost compressive strength, MICP uses particular bacteria, such as *Bacillus* species and *Sporosarcina pasteurii*, to precipitate calcium carbonate (Achal et al.,

2013a; Achal et al., 2013b). According to studies, bacterial treatments can greatly increase the mechanical qualities and crack-repair ability of concrete while decreasing water absorption and chloride permeability (Achal et al., 2013a; Chahal et al., 2012; Nosouhian et al., 2014). By supporting effective bacterial activity and calcite precipitation comparable to traditional media, the use of industrial by-products such as lactose mother liquor (LML) and corn steep liquor (CSL) as alternative, affordable bacterial growth media has advanced the sustainability of MICP applications (Achal et al., 2013b; Achal et al., 2013c). To ensure extended self-healing capacity and enhanced strength recovery, encapsulation techniques, such as silica gel and polyurethane carriers, have been developed to protect bacterial viability in the harsh alkaline environment of concrete (Wang et al., 2014; Van Tittelboom et al., 2010). Furthermore, it has been demonstrated that adding bacterial surface treatments to concrete mixes lengthens the structural service life by lowering concrete permeability, chloride ingress, and sulfate attack effects (Nosouhian et al., 2014; Pacheco-Torgal & Labrincha, 2013). In order to track microcracking and evaluate the healing process in concrete that has been treated with bacteria, non-destructive evaluation techniques like ultrasonic testing have also been investigated (Ahn et al., 2015; Pal Kaur et al., 2017). By utilizing natural biomineralization processes to increase durability while reducing environmental impact, these microbiological strategies are in line with the growing demand for sustainable building materials (Siddique & Chahal, 2017; Ivanov & Chu, 2008). Despite all of these advances, there are still issues with maximizing calcite precipitation and self-healing effectiveness in field settings by optimizing bacterial strains, nutrient sources, and delivery systems. To move these promising laboratory-scale methods to real-world, large-scale applications in infrastructure maintenance and repair, ongoing interdisciplinary research combining microbiology, materials science, and structural engineering is essential (De Muynck et al., 2010; Jonkers et al., 2010). In this paper, different approaches to self-healing are explained. Subsequently, the advantages and disadvantages of different types of healing agents and encapsulation techniques are discussed. This is followed by a discussion about the different trigger mechanisms which can be applied to activate self-healing. To conclude, the properties regained due to self-healing and the techniques used to quantify self-healing are considered.

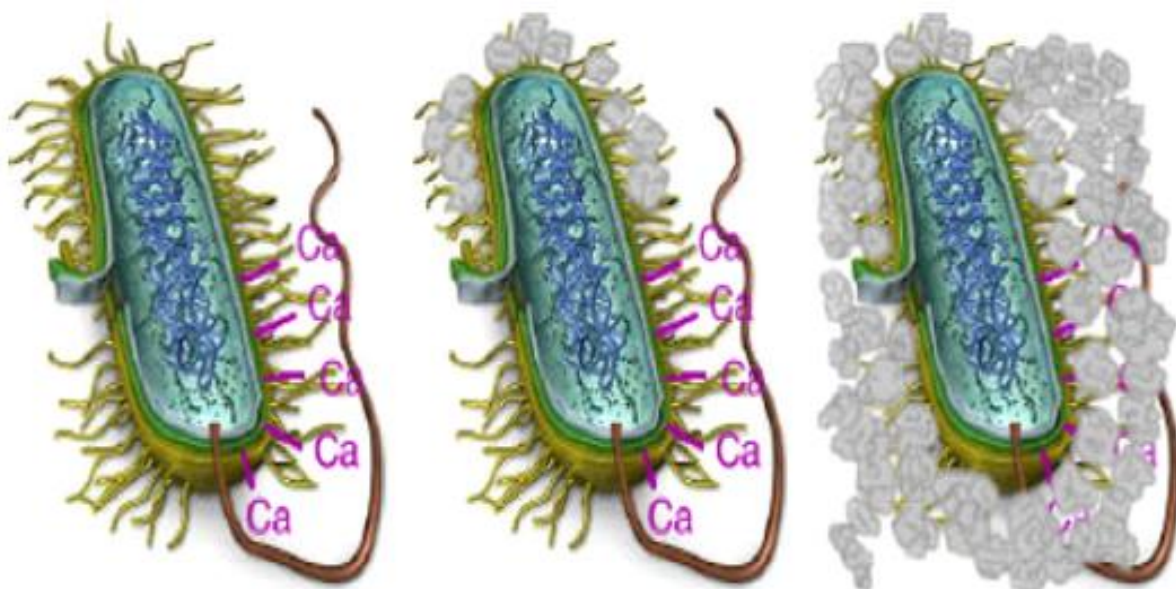


Fig.1 Calcium carbonate formation on cell wall of bacteria (Wikipedia).

1.0 GROWTH AND PH PROFILE

Over the course of 30 hours, the growth profile of *Sporosarcina pasteurii* in a variety of media, such as Low-Cost Media with Lactic Mother Liquor (LML), Nutrient Broth (NB), and Yeast Extract (YE), showed that the bacterium could efficiently use nutrients in all formulations, including LML. Among the tested media, there were no discernible variations in growth (measured in cfu/mL) (Joshi et al., 2021). A significant rise in pH was observed during this time, rising to pH

11.0 after 30 hours of incubation, a pattern that held true for all media kinds. Microbial urease activity, which produces ammonia and carbonate ions and promotes the precipitation of calcium carbonate (CaCO_3), is closely linked to this pH increase (Dhami et al., 2013). Furthermore, complex biological polymers like lipids and polysaccharides may promote bacterial growth through the action of extracellular hydrolytic enzymes, even though there are few reports directly demonstrating the use of LML by *S. pasteurii* (De Muynck et al., 2010). Furthermore, it was discovered that growth in corn steep liquor (CSL) medium was on par with, and occasionally better than, that in NB and YE media. The presence of external medium carbon/nitrogen sources, amino acids (like isoleucine, arginine, and cystine), and vitamins (like inositol and choline) is probably the cause of this, as these substances are known to greatly increase the growth of bacteria (Achal et al., 2009; Hammes et al., 2003).

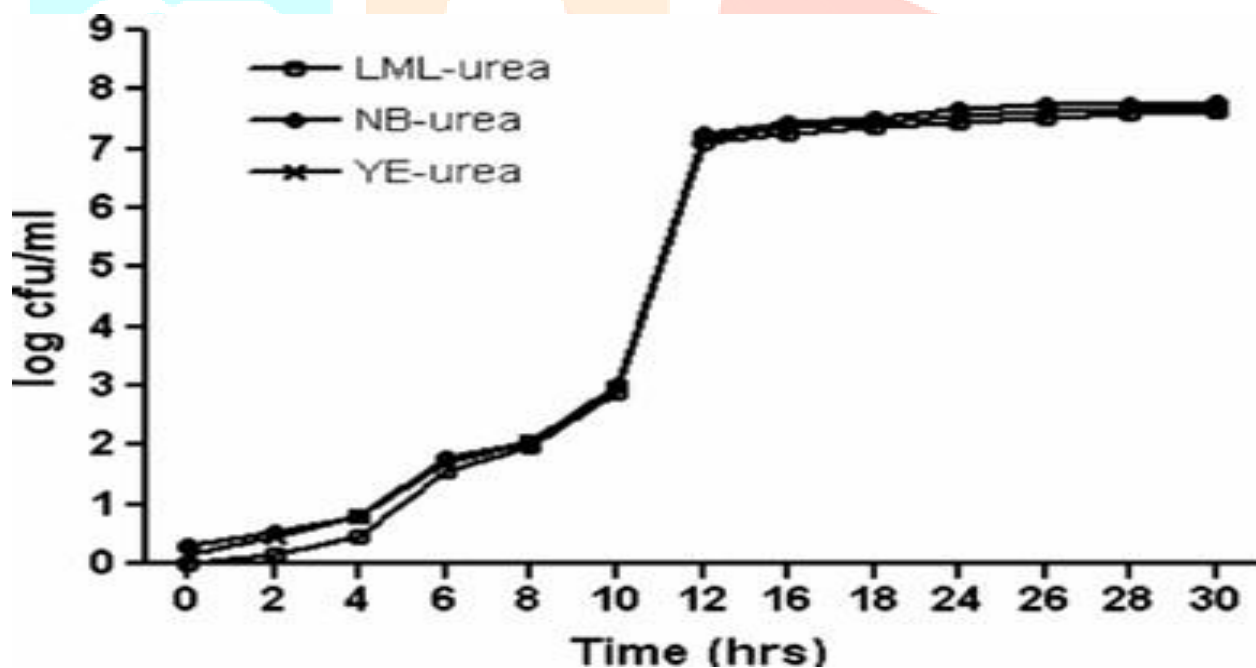


Fig. 2: Growth profile of *S. pasteurii* in LML, nutrient and yeast extract media supplemented with urea (Achal, V. et.al., 2013)

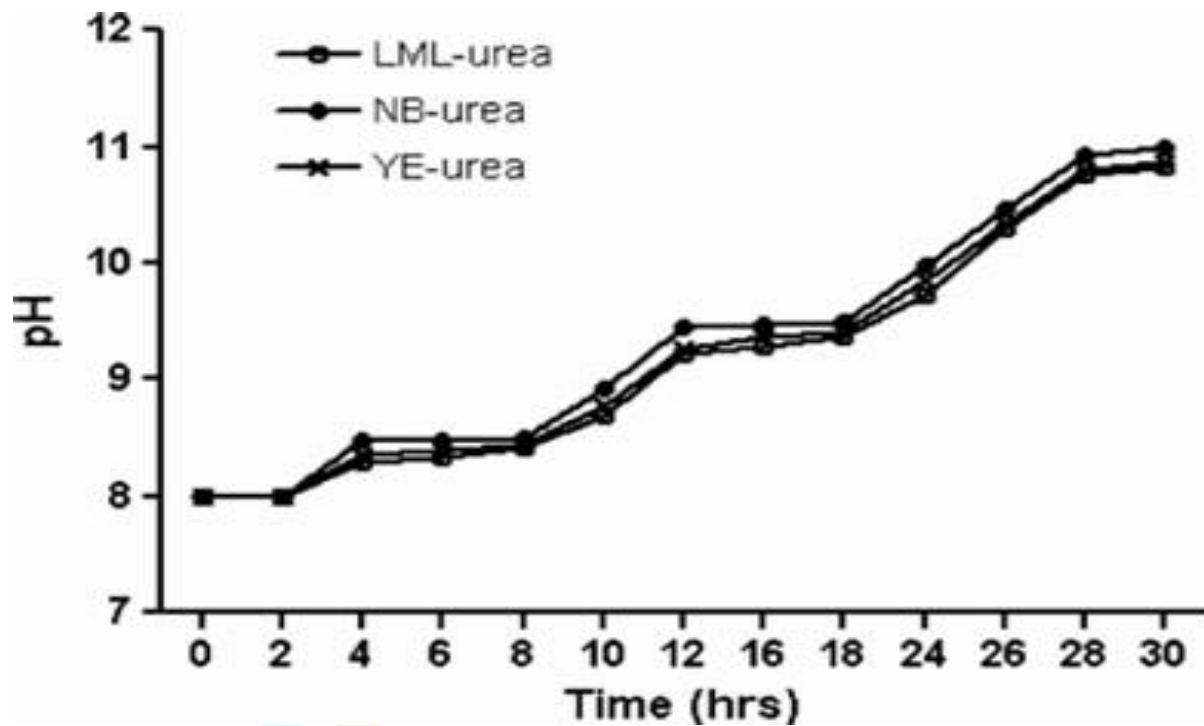


Fig. 3: pH profile of *S. pasteurii* in LML, nutrient and Yeast extract media supplemented with urea (Achal, V. et.al., 2013).

2.0 COMPARATIVE ANALYSIS OF FREE AND MICROENCAPSULATED BACTERIA IN MORTAR

The use of bacterial agents in cementitious systems for self-healing purposes has advanced significantly in recent years. Despite the range of methods studied, the use of free bacteria and microencapsulated bacterial spores remains a crucial part of current research. This section offers a case study that evaluates and compares the viability, durability, and overall material performance of the two bacterial delivery systems, drawing on the experimental work of Zhang et al. (2017) and Wang et al. (2014).

2.1 Viability and Activation of Bacterial Spores

The ureolytic activity of *Sporosarcina pasteurii* spores following encapsulation in polymeric microcapsules was examined by Zhang et al. (2017). Only a small amount of urea (~3 g/L) was broken down in 24 hours after intact microcapsules were added to a nutrient medium, and this amount barely increased over the course of three days. On the other hand, by the third day, the urea had completely degraded due to broken capsules. This behavior demonstrated that the spores were still viable and dormant inside the capsules, and that they needed to burst open the capsule in order to get nutrients and start their metabolism. In contrast, over the course of 24 weeks, free bacteria investigated by Wang et al. (2014) demonstrated consistent ureolytic activity. The significance of environmental conditions for metabolic efficiency was further highlighted by the explanation that the slight increase in activity between weeks 4 and 6 was due to pH optimization (adjusted to 7.0). These results highlight the long-term viability of both free and encapsulated bacterial systems, but encapsulation offers controlled activation, which could be crucial in actual crack-healing situations.

2.2. Survivability During Mortar Processing Zhang et al. (2017) showed in the same study that microcapsules did not break down while mortar was being mixed. The encapsulated system's mechanical resilience was demonstrated by microscopic analysis, which revealed that the capsules stayed distributed and stuck to the cement and aggregate surfaces without breaking. This is a significant benefit over free bacteria, which might be more prone to dying as a result of the extremely abrasive and alkaline environment during mixing.

2.3 TRIGGERED RELEASE UPON CRACKING

The autonomous release of healing agents upon crack formation is a critical function of self-healing systems. Zhang et al. (2017) verified through microstructural observations that microcapsules successfully ruptured at fracture surfaces, leaving visible capsule remnants embedded in the matrix. Bacterial spores could be released locally because the capsule size (2–5 μm) was appropriate for interacting with microcracks. Free bacteria must endure the initial curing process and continue to be active or dormant within the cement matrix, making such triggered activation impractical. Although this may work (Wang et al., 2014), targeted activation and long-term control are limited by the absence of protective encapsulation.

2.4 IMPACT ON MECHANICAL PROPERTIES

Both systems have an impact on mortar's mechanical strength. Tensile and compressive strength were statistically significantly reduced by microencapsulation, especially at dosages greater than 3% (Zhang et al., 2017). For capsule contents ranging from 1% to 5%, the compressive strength decreased by 15% to 34%, respectively. The maximum strength loss in samples with 5% bacteria-loaded capsules was 47% when nutrients were also added. Although the effect was not as great as in encapsulated systems, Wang et al. (2014) also observed a slight decrease in strength for mixes containing free bacteria. These findings imply a trade-off between mechanical integrity and healing potential, with microcapsules making a larger contribution to matrix discontinuities and porosity.

2.5 WATER ABSORPTION AND DURABILITY

Significantly less water was absorbed by encapsulated systems, indicating increased long-term durability. After 72 hours, capillary water absorption was decreased by 14% in nutrient-only specimens, 42% in specimens with pure microcapsules, and 48% in specimens with bacteria-loaded capsules, according to Zhang et al. (2017). A major advantage of microencapsulation is its ability to limit permeability and moisture ingress, as demonstrated by vacuum saturation tests, which verified 20–30% decreases in water uptake. Although free bacteria have the ability to heal, they might not provide the same durability boost because they don't have an encapsulating matrix to serve as a physical barrier.

2.6 SUMMARY

While microencapsulated spores and free bacteria both show long-term viability and the ability to heal themselves in mortar, encapsulated systems provide better survivability during mixing, controlled activation that triggers cracks, and significantly increased durability due to reduced water absorption and customized pore structure, although at the expense of mechanical strength at higher dosages (Wang et al., 2014; Zhang et al., 2017) as shown in table 1.

3.0 BACTERIAL ACTIVITY AND SURVIVABILITY IN MICP APPLICATION

A promising environmentally friendly method for enhancing the resilience and self-healing potential of cementitious materials is microbial-induced carbonate precipitation, or MICP. The ability of bacteria to survive and function metabolically in the dense, alkaline matrix of concrete and mortar is essential to MICP's success.

3.1 SURVIVABILITY OF BACTERIA IN FLY ASH- AMENDED MORTAR AND CONCRETE

A promising environmentally friendly method for enhancing the resilience and self-healing potential of cementitious material is microbial-induced carbonate precipitation, or MICP. The ability of bacteria to survive and function metabolically in the dense, alkaline matrix of concrete in mortar and concrete

specimens amended with fly ash was examined by Achal, et.al. They showed that an initial bacterial inoculum of 5×10^7 cfu/ml gradually loses viable cell counts using serial dilution techniques. But 40% fly ash concrete maintained up to $\sim 8.3 \times 10^6$ cfu/ml viable bacteria at 3 days, which is significantly higher than unaltered controls ($\sim 10^4$ cfu/ml range). This indicates that the fly ash amendment significantly improved bacterial survival. Increased porosity from the addition of fly ash is thought to be responsible for this enhanced survivability, as it probably promotes better aeration and microbial growth (Achal, et.al).

3.2 BACTERIAL ACTIVITY OF IMMOBILIZED BACTERIA IN SILICA GEL AND POLYURETHANE (PU)

Wang et al. (2012) investigated bacterial ureolytic activity in addition to survivability studies after immobilizing *Bacillus sphaericus* cells in protective matrices like polyurethane (PU) and silica gel (SG). While immobilized cells demonstrated delayed but sustained enzymatic function, free bacteria demonstrated rapid urease activity, according to conductivity monitoring of urea hydrolysis. Compared to PU-immobilized cells (30%), SG-immobilized bacteria maintained roughly 50% of their free-cell activity. Significantly, both immobilization systems showed reversible inhibition brought on by ammonium buildup, indicating that they could be used as carriers for MICP applications in cementitious environments for an extended period of time (Wang et al., 2012).

3.3 MICP EFFICIENCY ON RCA

Qiu et al. investigated how calcium content and bacterial concentration affected MICP efficiency on recycled concrete aggregate (RCA). Although the specific carbonate precipitation rate per cell decreased because of the limited RCA surface area, increasing the bacterial concentrations (10^6 to 10^8 cells/mL) slightly improved CaCO_3 precipitation (25% improvement). MICP was also strongly impacted by calcium ion concentration, with ideal CaCl_2 levels being approximately 15 g/L. Beyond this point, bacterial ureolytic activity was inhibited by oversaturation and excessive CaCO_3 precipitation, which limited additional increases in MICP efficiency.

4.0 EFFECT OF BACTERIA ON VARIOUS PARAMETER

4.1 Compressive strength

Microbial-induced calcium carbonate precipitation (MICP) has been shown in numerous studies to have the ability to increase cementitious materials' compressive strength. By blocking pores with CaCO_3 deposition, calcite-precipitating bacteria like *Bacillus* sp. or *Sporosarcina pasteurii* enhance matrix densification when added to mortar and concrete. In contrast to controls, *S. pasteurii* grown in different media (LML-urea, NB-urea, and YE-urea) demonstrated a 13–20% improvement in 28-day compressive strength, achieving strengths of 26.3–27.9 MPa, while the control specimen was 23.2 MPa [Ghosh et al., 2005; Achal et al., 2009]. Even more noticeable gains were made by *Bacillus* sp. CT-5, which increased strength by 36% (up to 31 MPa) [Achal et al., 2009a]. Significant strength increases were observed in other studies that included bacterial inoculation and silica fume. For instance, concrete containing 10^5 cells/mL *S. pasteurii* and 10% silica fume reached 38.2 MPa after 28 days, which is 36% higher than the 28 MPa control [Achal et al., 2011]. Strength rose to 44 MPa at 91 days. Bacterial treatment also improved lightweight aggregate concrete (LWAC). Microbial calcite filling finer

pores following the hydration phase was the main cause of the 17.4% increase in compressive strength at 28 days and the 26.4% increase at 150 days [Jonkers, et.al.,2010]. It's interesting to note that a study comparing bio- based agents with standard mixes found that mixes containing calcium lactate-based agents showed higher strength even with lower cement content, suggesting that nutrient sources can improve bacterial performance [Jonkers et al., 2010]. Strength gains were typically only seen after 28 days across all studies, which corresponds to the time needed for bacteria to acclimate to the alkaline cement environment. Microbial growth was restricted during the first three to seven days of curing, which led to very slight variations in strength when compared to controls. Comparative results are shown in table 2 which shows the different results of compressive strength of bacterial concrete embedded with different material which can help in further research work in future and also this study helps in comparing of various materials as well as in different environments which may help the structure for enhancing its compressive strength.

4.2 WATER PERMEABILITY

The durability and service life of concrete structures are significantly impacted by water permeability. High permeability permits the entry of hostile substances, which causes reinforcement corrosion, freeze-thaw damage, and general structural deterioration. Through the autonomous sealing of cracks, bio-based self-healing systems- especially those that employ microbially induced calcium carbonate precipitation (MICP)-have shown in table 3 encouraging results in reducing water infiltration. Because of its biocompatibility and capacity to buffer pH variations, silica gel (SG) has been extensively researched as a bacterial carrier. Through the precipitation of CaCO_3 within microcracks, SG-enabled systems have been able to reduce water permeability by up to three orders of magnitude when compared to untreated cracked concrete when combined with *Bacillus* species (Van Tittelboom et al., 2010). Among the tested systems, polyurethane (PU) foam, which is known for being naturally hydrophobic, showed the lowest final permeability values. The limited bacterial viability within the PU matrix led to a slight improvement over PU alone, even though the addition of bacteria further decreased permeability through CaCO_3 infill in PU pores, the water permeability performance of sol-gel systems that included bacteria and non-chloride calcium sources (such as $\text{Ca}(\text{NO}_3)_2$ or $\text{Ca}(\text{CH}_3\text{COO})_2$) was on par with epoxy treatments. The significance of encapsulation for bacterial survival is highlighted by the fact that systems employing CaCl_2 and lacking a protective carrier were unable to promote healing because of bacterial inactivation in high-pH environments (De Muynck et al., 2006).

4.3 EVALUATION OF MICROSTRUCTURE VIA SEM AND EDS IN MICP-ENHANCED CONCRETE

Clarifying the mechanisms and effects of microbially induced calcium carbonate precipitation (MICP) in self- healing concrete systems has been made possible by microstructural characterization using energy-dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM). Insights into how microbial activity improves concrete durability and crack healing are provided by these instruments, which offer direct visual and compositional proof of calcite formation, distribution, and morphology. Without bacterial treatment, control concrete specimens usually have weak, porous microstructures with

unfilled cracks and no crystalline precipitates. SEM images of such control samples revealed no discernible calcium carbonate (CaCO_3) formations, and the voids remained open, suggesting a lower matrix integrity and limited capacity for self-healing (Achal et al., 2009). Specimens treated with MICP, however, demonstrated notable advancements. Rod-shaped bacterial imprints were embedded within the crystals, and SEM images showed dense calcite deposition at the crack surfaces, especially around the sand grains. These imprints, which are morphologically consistent with *Bacillus* species, imply that bacteria are efficient mineralization nucleation sites. The well-formed, sharp-edged crystals that were seen demonstrated successful structural integration and a full crystallization process (Achal et al., 2009). The amount of calcite and visible bacterial remnants gradually decreased, according to additional investigation into the interior of the cracks. The lower oxygen availability deeper within the crack, which limits the activity of facultative anaerobes like *Bacillus pasteurii*, was blamed for this decrease in deposition. According to Achal et al. (2009), MICP efficiency and calcite formation seem to be depth-dependent, with more extensive healing taking place closer to the surface where environmental conditions are more favorable. Research using recycled concrete aggregates (RCA) revealed complementary results. Due in large part to the residue of adhered mortar, Nosouhian et al. (2015, 2016) showed that untreated RCA had porous, irregular surfaces with a high silica content. SEM pictures following MICP treatment revealed calcium-rich precipitates covering the RCA surfaces. Calcium carbonate formation was indicated by EDS analyses, which verified a notable decrease in silicon and an increase in calcium content. Furthermore, the precipitated crystals' morphology changed depending on the surroundings. Larger, rhombohedral calcite crystals were more likely to form in the P4 treatment condition due to slower precipitation, while smaller, spherical vaterite crystals were more likely to form in the O3 condition due to faster MICP. These findings corroborate previous research showing that MICP polymorphs are extremely sensitive to microbial activity kinetics and saturation levels (Nosouhian et al., 2016). The positive effects of MICP were further supported by a long-term SEM analysis of concrete specimens that had been cured for 150 days. In comparison to the control group, specimens that contained bacteria—either in the aggregates or the mixing water—showed noticeably denser microstructures. The treated samples showed enhanced matrix integrity as calcite filled the voids that were noticeable in the control specimens. Intriguingly, carbonation of calcium hydroxide, a naturally occurring hydration product of cement, caused minor calcite crystals to form in even control specimens. However, this process was much slower and produced much less calcite deposition than the biologically mediated pathway (Nosouhian et al., 2015; Achal et al., 2011). EDS spectra continuously revealed calcium, carbon, and oxygen dominant peaks in MICP-treated areas, confirming the matrix's biochemical change and the microbial activity's deposition of calcium carbonate. This demonstrates the vital role that bacteria play as biocatalysts in improving the microstructure of concrete, in addition to supporting mechanical observations like enhanced durability and compressive strength (Achal et al., 2011). In conclusion, studies using SEM and EDS offer strong proof that MICP drastically changes the microstructure of concrete. By starting and promoting calcium carbonate deposition, bacteria improve

the material's resistance to harsh environments, reduce porosity, and improve crack healing. These results support MICP as a viable strategy for resilient and sustainable concrete infrastructure.

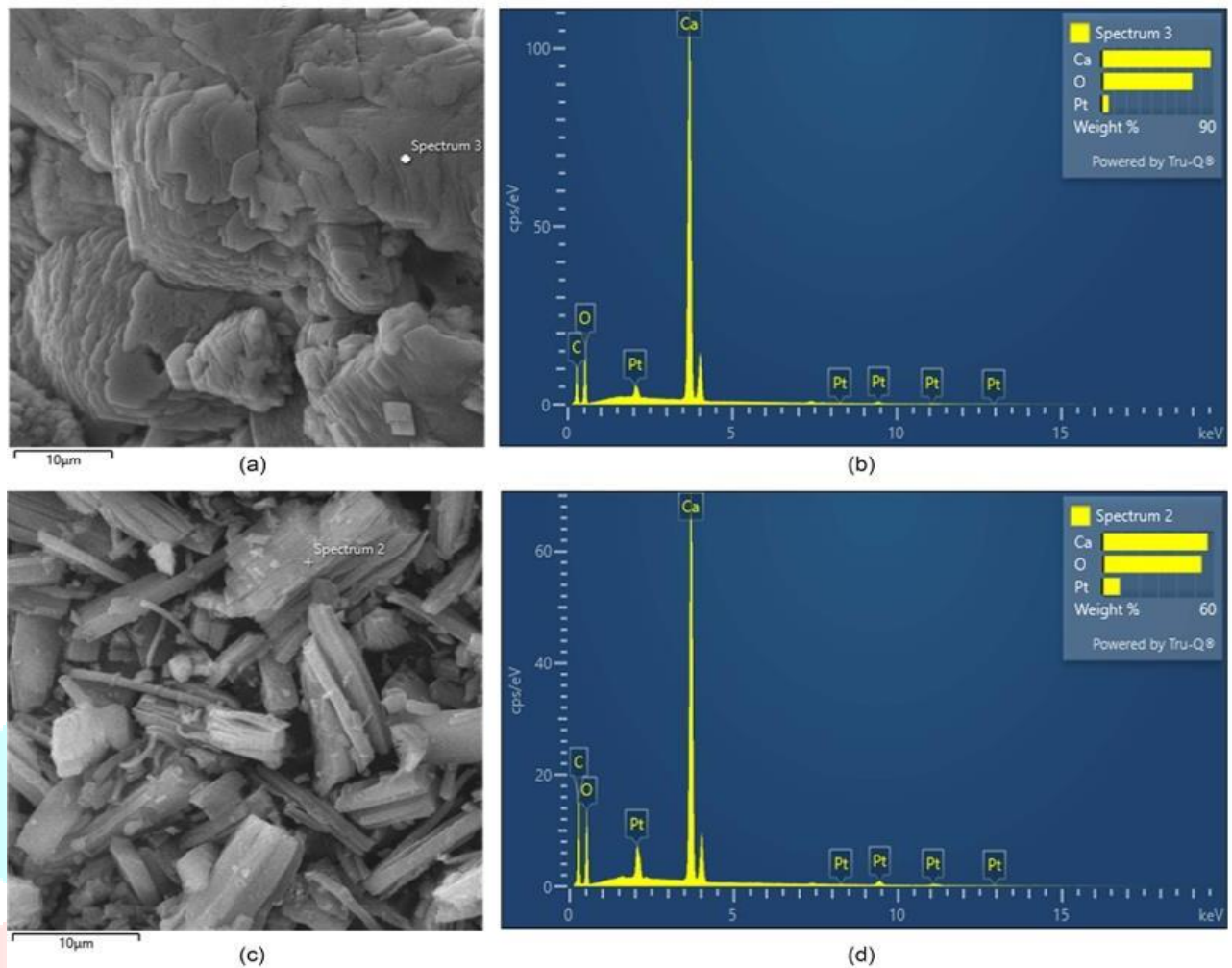


Fig 4: SEM micrographs and EDS of the precipitates after healing treatment: (a and b) DHC specimen; and (c and d) DHA specimen. (Nosouhian, F. et.al., 2015)

Parameter	Free Bacteria	Microencapsulated Spores
Viability (long-term)	High (24 weeks)	High (activated upon rupture)
Survivability in Mixing	Moderate (risk of alkaline damage)	High(encapsulated protection)
Activation Control	Passive(environment-dependent)	Controlled (rupture-triggered)
Mechanical Strength Impact	Mild to moderate	Significant at >3% dosage
Effect on Hydration	Slight interference	Dosage-dependent delay in hydration
Water Absorption	Minimal improvement	Significant reduction (up to 48%)
Pore Structure	Slight refinement post-healing	Altered bimodal distribution + nano porosity
Self-Healing Efficiency (potential)	Proven in lab studies	Enhanced by targeted release

Table 1: Comparative Analysis of Free and Microencapsulated Bacteria in Mortar (Wang et al., 2014; Zhang et. al., 2017)

4.4 CARBONATION RESISTANCE OF MSHC WITH EXPANDED PERLITE-BASED CARRIERS

Expanded perlite (EP) is a useful carrier in microbial self-healing concrete (MSHC) because of its porous structure and compatibility with microbial agents. However, whether the EP is coated or not has a major impact on how well EP-based microbial self-healing agents (EPMSAs) work. Zhang et al. (2023) examined MSHC specimens with uncoated and MKPC-coated EPMSAs exposed to carbonation. The results showed that uncoated EPMSA performed better in a number of parameters. Strong resistance to CO₂ ingress was demonstrated by the carbonation depth, which was only 1–2.2 mm after 28 days. Due to efficient microbial-induced calcite precipitation (MICP), which densified the pore structure, the uncoated system also attained a high compressive strength of 63.8 MPa. Cracks up to 0.81 mm in width were successfully repaired even though carbonation suppressed bacterial activity. Long-term durability was further improved by this system's exceptional resistance to chloride penetration. According to these results, uncoated EPMSA is a more sensible and efficient choice for MSHC applications in marine or carbonation-prone environments.

4.5 ULTRASONIC PULSE TRANSMISSION ASSESSMENT OF CRACK HEALING EFFICIENCY

Measurements of ultrasonic pulse transmission made both before and after crack treatment provide a quantitative way to assess how well different repair techniques work. Transmission time reductions close to cracks were adjusted by deducting decreases seen at measurement points further away from the cracks in order to differentiate the effects of crack healing from continuous hydration in concrete specimens (De Belie et al., 2012). Epoxy and bacterial spores (BS) embedded in sol-gel with calcium chloride (CaCl₂) showed the greatest reductions in transmission time for 10 mm cracks, suggesting superior crack closure. Potentially as a result of bacterial activity and immersion in urea-calcium solutions filling the pores in the concrete, other treatments involving BS with sol-gel and CaCl₂ or CaCl₂ alone also demonstrated reductions. While untreated controls showed longer transmission times, probably as a result of heterogeneous hydration effects, sol-gel treatment alone produced only modest improvements (De Belie et al., 2012). Cross-sectional analysis confirmed that epoxy treatment was the most effective method for completely filling 20 mm deep cracks. Because of their inability to fully penetrate the depths of the cracks, BS-based treatments in combination with CaCl₂, calcium nitrate, or calcium acetate were less successful. Since grout mainly coated the surface without filling in cracks, ultrasonic waves were able to avoid the cracks and maintain longer transmission times. Grout and sol-gel treatments showed only modest improvements. The lack of natural crack healing was confirmed by the longer transmission times observed in untreated samples (De Belie et al., 2012). These results are supported by similar ultrasonic-based assessments in more recent research, which emphasizes the dependability of ultrasonic methods for long-term surveillance of concrete structures that have been bacterially repaired (Pal Kaur et al., 2023).

4.6 XRD CHARACTERIZATION OF CALCITE FORMATION IN BACTERIA-ENHANCED CONCRETE

An effective method for verifying mineralogical alterations brought on by microbial activity in self-healing concrete is X-ray diffraction (XRD) analysis. In a study examining the impact of *Sporosarcina pasteurii* on concrete modified with 10% silica fume, samples treated with an optimal bacterial concentration (10^5 cells/mL) showed more diffraction peaks corresponding to calcite in their XRD spectra than control specimens (Camara et al., 2019). More calcite peaks indicate increased calcium carbonate precipitation, which helps to densify and refine the pores in the concrete matrix. This mineralogical evidence confirms *S. pasteurii*'s feasibility for commercial crack remediation applications by demonstrating how well it promotes microbial-induced calcite precipitation (MICP).

4.7 RAPID CHLORIDE PERMEABILITY TEST (RCPT)

One important technique for assessing concrete's resistance to chloride-induced corrosion is the Rapid Chloride Permeability Test (RCPT). Bacterial integration considerably improves chloride resistance, according to comparative studies on lightweight aggregate concrete (LWAC) treated by microbial-induced calcium carbonate precipitation (MICP). Specimens treated with bacteria, either in aggregates or mix water, demonstrated significant improvements in permeability compared to those cured with urea- CaCl_2 solution alone. Incorporating bacteria into aggregates and water resulted in the highest resistance, lowering chloride penetration by up to 67% when compared to control specimens. Bacterial calcite deposition, which densifies the concrete matrix and decreases pore connectivity, is responsible for this enhanced performance. Such biogenic mineralization is consistent with research by Dhama et al. (2013), who showed that certain bacterial strains could enhance the microstructure of concrete by inducing the formation of calcium carbonate. These findings lend credence to MICP as a viable strategy for improving the durability of concrete in environments high in chloride.

4.8 ULTRASONIC EVALUATION OF GROUT TREATMENT IN CORROSION-INDUCED CRACKS

When grout injection is used to repair corrosion-induced cracks in reinforced concrete, ultrasonic testing efficiently tracks the process. Prior to treatment, corrosion cracks with broad, non-contacting faces demonstrated a considerable attenuation of ultrasonic signals, necessitating a gain increase from 40 dB to 60 dB in order to detect minimal transmission of pulses, mainly through the reinforcing steel. With waveforms that closely resembled those of uncracked specimens, a significant improvement in ultrasonic pulse transmission was seen after grout treatment, suggesting that the grout had successfully penetrated and filled large cracks. The much narrower tensile cracks, on the other hand, showed only slight changes in wave velocity and attenuation following treatment, indicating little grout infiltration. The study emphasizes that wave velocity changes are not as sensitive as signal attenuation as a measure of crack healing. Effective void filling and crack healing are confirmed by the decrease in attenuation following treatment. Thus, this ultrasonic method offers a trustworthy, non-destructive way to differentiate between concrete cracks that have healed and those that have not (Neville, 1995). Fig 5 showing presents the ultrasonic signals before cracking (uncracked), after cracking (cracked) and after grout treatment (treated) for the corrosion cracked specimen

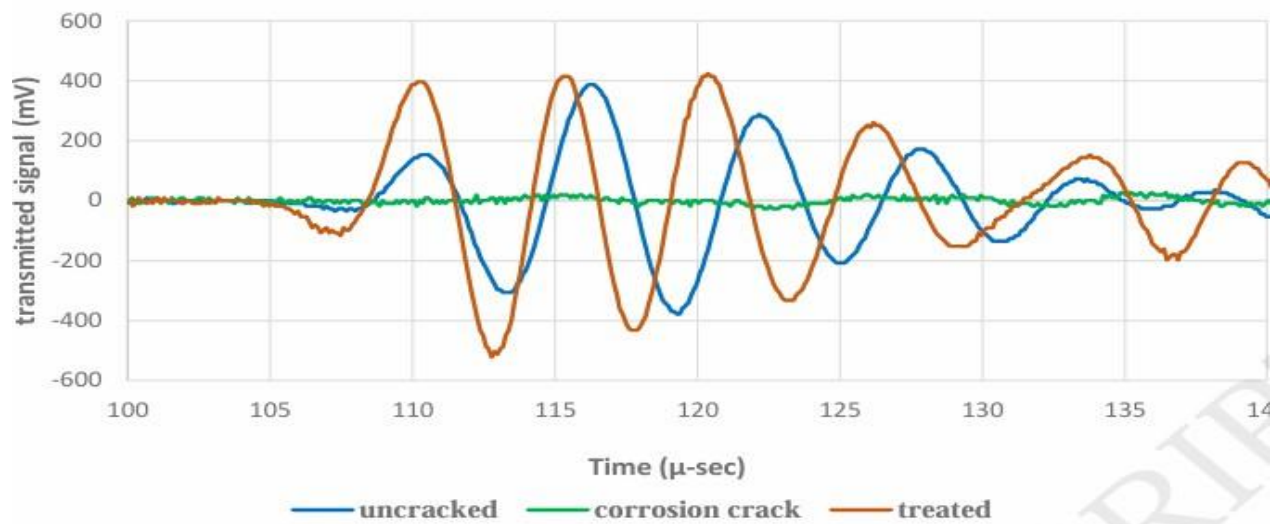


Fig 5: Ultrasonic transmission through corrosion cracked specimen: before cracking (uncracked), after cracking (corrosion crack) and after treatment (treated) (Neville, A. 1995.)

4.9 LPR-BASED CORROSION MONITORING IN REINFORCED CONCRETE

Linear polarization resistance (LPR) measurements were used by Nosouhian and Mostofinejad (2016) to track the corrosion development of reinforced concrete specimens over time. The corrosion current density (I_{corr}) and potential (E_{corr}) were determined by Tafel extrapolation, which shed light on the electrochemical behavior of intact, damaged, and healed specimens. Undamaged (UD) specimens showed low and stable I_{corr} (124-137 μA) and moderately negative E_{corr} values (-268 mV to -419 mV), indicating minimal corrosion. On the other hand, damaged (D) specimens showed aggressive corrosion as a result of crack-induced chloride ingress, with I_{corr} rising sharply to approximately 600 μA by day 14 and E_{corr} falling to -625 mV. The behavior of the healed specimens (DHA and DHC) was intermediate; the initial I_{corr} of 200 μA increased over time, more slowly in DHA and more quickly in DHC, reaching 400 μA by day 22. In comparison to D samples, E_{corr} decreased from -400 mV to -600 mV, indicating continued but lessened corrosion. For a more thorough evaluation of rebar integrity, the study made clear that the electrolytes of healing agents may have an impact on LPR accuracy, requiring the use of supplementary techniques like guided wave testing and post-exposure destructive analysis.

5.0 CONCLUSION

It has been shown that adding microbial-induced calcium carbonate precipitation (MICP) to cementitious systems can significantly increase compressive strength, decrease permeability, and improve crack sealing. Although both free and encapsulated bacterial systems exhibit potential, encapsulated bacteria offer better activation control, increased durability under harsh exposure, and improved survivability during mixing. Higher capsule dosages result in a trade-off in mechanical performance, but the durability benefits—particularly in terms of corrosion and water resistance—are significant. The calcite formation and matrix densification are confirmed by microstructural analyses using SEM and EDS, which corroborate the observed enhancements in mechanical and transport properties. The efficiency of bacterial healing in concrete is further confirmed by complementary non-destructive and electrochemical techniques like LPR and ultrasonic testing. All of these results highlight

the importance of MICP in resolving the issues with traditional repair methods and advancing the development of longer-lasting, more sustainable concrete structures.

6.0 FUTURE SCOPE

More research is required in a few crucial areas if microbial-induced calcium carbonate precipitation (MICP) is to move from successful lab-scale use to practical implementation. Optimizing bacterial viability in a variety of environmental settings is necessary for field-level implementation. Research into economical carriers and nutrients (such as using industrial by-products) will improve sustainability, while developments in strain engineering may increase bacterial efficiency. Non-destructive technologies, such as embedded sensors, should be used to track long-term performance. Standardizing performance benchmarks and design guidelines is also essential for wider industry adoption. Concrete's functionality could be further improved by integrating MICP with smart materials. To fully realize MICP's potential in long-lasting, environmentally friendly infrastructure, interdisciplinary cooperation will be necessary.

7.0 REFERENCES

1. Achal, V., Mukherjee, A., & Reddy, M. S. (2009). Effect of calcium sources on microbially induced calcium carbonate precipitation by *Sporosarcina pasteurii*. *Journal of Industrial Microbiology & Biotechnology*, 6(3), 377–382. <https://doi.org/10.1007/s10295-008-0494-9>
2. Achal, V., A. Mukerjee, and M. S. Reddy. 2013. "Biogenic treatment improves the durability and remediates the cracks of concrete structures." *Constr. Build. Mater.* 48(Jun):1–5. <https://doi.org/10.1016/j.conbuildmat.2013.06.061>.
3. Achal, V., X. Pan, and N. Ozyurt. 2011. "Improved strength and durability of fly ash-amended concrete by microbial calcite precipitation." *Ecol. Eng.* 37 (4): 554–559. <https://doi.org/10.1016/j.ecoleng.2010.11.009>.
4. Ahn, E., M. Shin, J. S. Popovics, and R. L. Weaver. 2019. "Effectiveness of diffuse ultrasound for evaluation of micro-cracking damage in concrete." *Cem. Concr. Res.* 124 (Oct):105862. <https://doi.org/10.1016/j.cemconres.2019.105862>.
5. Ahn, T. H., and T. Kishi. 2010. "Crack self-healing behavior of cementitious composites incorporating various mineral admixtures." *J. Adv. Concr. Technol.* 8 (2): 171–186. <https://doi.org/10.3151/jact.8.171>.
6. Azarsa, P., and R. Gupta. 2017. "Electrical resistivity of concrete for durability evaluation: A review." *Adv. Mater. Sci. Eng.* 2017(1):1–30. <https://doi.org/10.1155/2017/8453095>.
7. Camara, L. A., M. Wons, I. C. A. Esteves, and R. A. Medeiros-Junior. 2019. "Monitoring the self-healing of concrete from the ultrasonic pulse velocity." *J. Compos. Sci.* 3 (1): 16. <https://doi.org/10.3390/jcs3010016>.
8. Chahal, N., R. Siddique, and A. Rajor. 2012a. "Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of concrete incorporating silica fume." *Constr. Build. Mater.* 37: 645–651. <https://doi.org/10.1016/j.conbuildmat.2012.07.029>.
9. Chahal, N., R. Siddique, and A. Rajor. 2012b. "Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete." *Constr. Build. Mater.* 28 (1): 351–356. <https://doi.org/10.1016/j.conbuildmat.2011.07.042>.

10. De Belie, N., De Muynck, W., De Corte, W., & Van Tittelboom, K. (2012). Crack Repair and Healing in Concrete: Evaluation by Ultrasonic Measurements. *Construction and Building Materials*,36,690–698. <https://doi.org/10.1016/j.conbuildmat.2012.06.054>
11. De Muynck, W., K. Cox, N. De Belie, and W. Verstraete. 2008. “Bacterial carbonate precipitation as an alternative surface treatment for concrete.” *Constr. Build. Mater.* 22 (5): 875–885. <https://doi.org/10.1016/j.conbuildmat.2006.12.011>.
12. De Muynck, W., N. De Belie, and W. Verstraete. 2010. “Microbial carbonate precipitation in construction materials: A review.” *Ecol. Eng.* 36 (2):118–136. <https://doi.org/10.1016/j.ecoleng.2009.02.006>.
13. Dhami, N. K., Reddy, M. S., & Mukherjee, A. (2013). Biomineralization of calcium carbonate polymorphs by the bacterial strains isolated from calcareous sites. *Journal of Microbiology and Biotechnology*,23(5),707–714. <https://doi.org/10.4014/jmb.1212.12087>.
14. Dick, J., W. De Windt, B. De Graef, H. Saveyn, P. Van der Meeren, N. De Belie, and W. Verstraete. 2006. “Bio-deposition of a calcium carbonate layer on degraded limestone by *Bacillus* species.” *Int. Biodeterior. Bio degrad.* 17(4): 357–367. <https://doi.org/10.1007/s10532-005-9006-x>.
15. Grabiec, A., J. Klama, D. Zawal, and D. Krupa. 2012. “Modification of recycled concrete aggregate by calcium carbonate biodeposition.” *Constr. Build. Mater.*34:145–150. <https://doi.org/10.1016/j.conbuildmat.2012.02.027>.
16. Hammes, F., Boon, N., De Villiers, J., Verstraete, W., & Siciliano, S. D. (2003). Strain-specific ureolytic microbial calcium carbonate precipitation. *Applied and Environmental Microbiology*, 69(8), 4901–4909. <https://doi.org/10.1128/AEM.69.8.4901-4909.2003>
17. Hosseini Balam, N., D. Mostofinejad, and M. Eftekhari. 2017b. “Use of carbonate precipitating bacteria to reduce water absorption of aggregates.” *Constr. Build. Mater.*141:565–577. <https://doi.org/10.1016/j.conbuildmat.2017.03.042>.
18. Ivanov, V., and J. Chu. 2008. “Applications of microorganism to geotechnical engineering for bioclogging and biocementation of soil in situ.” *Rev. Environ. Sci. Biotechnol.* 7 (2): 139–153. <https://doi.org/10.1016/10.1007/s1117-007-9126-3>.
19. Jonkers, H. M., A. Thijssen, G. Muyzer, O. Copuroglu, and E. Schlangen. 2010. “Application of bacteria as self-healing agent for the development of sustainable concrete.” *Ecol. Eng.*36(2):230–235. <https://doi.org/10.1016/j.ecoleng.2008.12.036>.
20. Joshi, S., Goyal, N., & Kaur, J. (2021). Evaluation of *Sporosarcina pasteurii* growth and CaCO_3 precipitation in low-cost media using lactic mother liquor. *Environmental Technology & Innovation*, 23,101755. <https://doi.org/10.1016/j.eti.2021.101755>.
21. Martinez, R. E., O. Pourret, and Y. Takahashi. 2014. “Modeling of rare earth element sorption to the Gram-positive *Bacillus subtilis* bacteria surface.” *J. Colloid. Interface Sci.* 413: 106–111. <https://doi.org/10.1016/j.jcis.2013.09.037>.
22. McCarter, W. J., M. C. Forde, and H. W. Whittington. 1982. “Resistivity characteristics of concrete.” *Proc. Inst. Civ. Eng.* 73 (1): 223–224. <https://doi.org/10.1680/iicep.1982.1993>.
23. Neville, A. 1995. “Chloride attack of reinforced concrete: An overview.” *Mater. Struct.*28(2):63–70. <https://doi.org/10.1007/BF02473172>.
24. Nosouhian, F., and D. Mostofinejad. 2016. “Reducing permeability of concrete by bacterial mediation on surface using treatment gel.” *ACIMater.J.*113(3):287–293. <https://doi.org/10.14359/51688701>.

25. Nosouhian, F., D. Mostofinejad, and H. Hasheminejad. 2015. "Influence of biodeposition treatment on concrete durability in a sulphate environment." *Bio. Eng.* 133: 141–152. <https://doi.org/10.1016/j.biosystemseng.2015.03.008>.
26. Nosouhian, F., D. Mostofinejad, and H. Hasheminejad. 2016. "Concrete durability improvement in a sulfate environment using bacteria." *J. Mater. Civ. Eng.* 28 (1): 04015064. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001337](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001337).
27. Pacheco-Torgal, F., and J. A. Labrincha. 2013. "Biotech cementitious materials: Some aspects of an innovative approach for concrete with enhanced durability." *Constr. Build. Mater.* 40: 1136–1141. <https://doi.org/10.1016/j.conbuildmat.2012.09.080>.
28. Pal Kaur, N., J. Kumar Shah, S. Majhi, and A. Mukherjee. 2019. "Healing and simultaneous ultrasonic monitoring of cracks in concrete." *Mater. Today Commun.* 18 (Mar): 87–99. <https://doi.org/10.1016/j.mtcomm.2018.10.022>.
29. Pal Kaur, N., Y. Wang, K. Dhami, and A. Mukherjee. 2023. "Long-term corrosion monitoring of bacterially healed concrete using electrochemical and ultrasonic techniques." *J. Mater. Civ. Eng.* 35 (7):04023195. <https://doi.org/10.1061/JMCEE7.MTENG-14160>.
30. Ramachandran, S. K., V. Ramakrishnan, and S. S. Bang. 2001. "Remediation of concrete using micro-organisms." *ACI Mater.* 98(1):3–9. <https://doi.org/10.14359/10154>.
31. Van Tittelboom, K. V., N. De Belie, W. De Muynck, and W. Verstraete. 2010. "Use of bacteria to repair cracks in concrete." *Cem. Concr. Res.* 40(1):157–166. <https://doi.org/10.1016/j.cemconres.2009.08.025>.
32. Van Tittelboom, K., and N. De Belie. 2013. "Self-healing in cementitious materials-A review." *Materials* 6(6):2182–2217. <https://doi.org/10.3390/ma6062182>.
33. Wang, J. Y., H. Soens, W. Verstraete, and N. De Belie. 2014. "Self-healing concrete by use of microencapsulated bacterial spores." *Cem. Concr. Res.* 56:139–152. <https://doi.org/10.1016/j.cemconres.2013.11.009>.
34. Wang, L., Z. Ren, H. Wang, X. Liang, S. Liu, J. Ren, Y. He, and M. Zhang. 2022. "Microstructure-property relationships in cement mortar with surface treatment of microbial induced carbonate precipitation." *Composites, Part B* 239 (Jun): 109986. <https://doi.org/10.1016/j.compositesb.2022.109986>.
35. Wang, J., K. V. Tittelboom, N. De Belie, and W. Verstraete. 2012. "Use of silica gel or polyurethane immobilized bacteria for self-healing concrete." *Constr. Build. Mater.* 26 (1):532–540. <https://doi.org/10.1016/j.conbuildmat.2011.06.054>.
36. Wiktor, V., and H. M. Jonkers. 2011. "Quantification of crack-healing in novel bacteria-based self-healing concrete." *Cem. Concr. Compos.* 33 (7): 763–770. <https://doi.org/10.1016/j.cemconcomp.2011.03.012>.
37. Zhang, D., Lv, Y., & Yang, Z. (2017). Bio-microcapsule based self-healing cementitious composites: Bacteria viability, compatibility, and effectiveness. *Cement and Concrete Composites*, 82, 150–160. <https://doi.org/10.1016/j.cemconcomp.2017.05.001>
38. Zhang, H., Wang, S., Liu, Y., Chen, X., & Yang, Z. (2023). Influence of coated and uncoated expanded perlite-based microbial agents on performance of microbial self-healing concrete under carbonation conditions. *Construction and Building Materials*, 369, 130634. <https://doi.org/10.1016/j.conbuildmat.2023.130634>