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Healing the Infrastructure: Bio concrete as a Sustainable Frontier for the Circular Economy A Review

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Abstract

The best thing about concrete is that it's the backbone of modern infra, but it can crack because of environmental or mechanical pressure. These cracks threaten the longevity and integrity of the building by allowing water and corrosive fluids to penetrate. The objective of this study is to examine how Microbiologically Induced Carbonate Precipitation (MICP) aims at production of "self-healing" bio concrete as an environmentally friendly solution. We study the incorporation of nutrient precursors, namely calcium lactate and alkaliphilic microorganisms (predominantly from *Bacillus species*) into the concrete matrix. The methods described in this article provide protective encapsulation for bacterial spores during the high-pH mixing process. These include hydrogels, bio-based polymers, melamine-based microcapsules, and nano-encapsulation. Bio-concrete can even be able to improve about 95% tensile strength by comparing to the autogenous healing method in repairing of crack ranges from 0.5mm -1.0mm, according to a recent study. In addition, MICP use is proven in increasing compressive strength and water impermeability for up to 40%, gaining the infrastructure with a service life of 50 years to over 100 years. Even though bio concrete utilization and industrial by-products for bacterial activation is a revolutionary step toward concepts of the circular economy, still the issues with bacteria activation dependency, precursor price and homogeneity exist. For wide application to engineering, future studies should transfer focus on genetic modifications of highly alkaliphilic bacteria and low-cost feeding substrates.

Introduction

Concrete is a necessary and flexible construction material that can be considered in various applications. Durability is an important consideration in selecting building materials as it has a direct impact on economy, serviceability and maintenance. Issues like cracking, spalling, scaling and discoloration shorten the life of conventional concrete. These problems are often related to issues with mixing (too much water), placement (poor compacting, over-trowelling), curing (lack of moisture) and environmental conditions (freeze-thaw, acid/sulfate attack, shrinkage). As good as concrete can be, it is also prone to a great deal of breaking which permits corrosive elements into the structure. One of the leading causes of concrete deterioration and loss in resilience is known as fractures. Cracks can be formed in both the flexible and cemented phase. In the hardened state, cracking occurs due to weathering, drying shrinkage, thermal stress, design errors and detailing mistakes, chemical reaction (e.g., expansive chemical reactions), sustained load and external load [1]. Plastic Shrinkage Cracks: It is either Form work movement or plastic settlement, plastic shrinkage due to the rapid loss of water from top surfaces of concrete. Chemical, water and air intrusion weaken the structure of the building. One such concrete that heals itself is known as self-healing concrete. One of the key components in self-healing concrete is including bacteria, typically one that comes from the *Bacillus* or *Sporosarcina* species, along with a calcium-based healing agent such as calcium lactate or calcium carbonate. The microorganisms embedded in self-healing concrete do not grow until the concrete ruptures. When moisture or water seep into the cracks, the bacteria get reactivated. Once the calcium lactate or carbonate are broken down, limestone (calcium carbonate) is produced as a byproduct of the bacteria's metabolism. This limestone performs essential functions in the concrete by sealing the gaps [2]. And, rather than just fixing damage, bio concrete can extend the usable life of infrastructure from fifty years to more than a hundred, reducing global demand for newly produced cement. They should be the focus of future studies based on super alkaliphilic bacterial genetic engineering and cheap source of nutrition.

Bacteria that produce spores, like *Bacillus* species, can be continuously mixed into concrete with a food source (e.g., calcium lactate) within expanded protective or defensive capsules to keep them inactive. Crack conformation and activation when a crack forms, oxygen and water can infiltrate the concrete matrix. When the water expands the carrier or makes the capsules burst, so germs and nutrients will be released. When latent bacterial spores are wetted and given nutrients, these spores germinate into active bacteria. biomineralization. However, the activated bacteria turn calcium lactate (decomposed organic matter) into calcium carbonate ($CaCO_3$), mostly limestone, through a process called microbiologically induced calcite precipitation (MICP). Sealing Cracks This $CaCO_3$ precipitation seals the crack, and prevents damage from fresh water intrusion. This way of stone-mending preserves the fullness and integrity of the concrete while mending fissures that are generally broader than 0.5 mm. This project used bio concrete as a building skin in the effort to maintain wild bee habitat for increased urban biodiversity. The study showed 40% higher strength of bio cement compared with common concrete and high-water impermeability. We propose a transdisciplinary project that integrates ecological, design and biological research to facilitate sustainability. Future studies should focus mainly on super alkaliphilic bacterial genetic engineering and low-cost nutrition sources. The intention here was to also showcase how the combination of design, biology and eco system engineering has a large potential for sustainable environment projects as well, this coincides with the writing in this study your application of bio cement [3].

History and evolution of bio concrete

The healing process was first discovered by French Academy of Science in 1836. According to a detailed and extensive review of the literature, Lauer and Slate (1956) suggested that, as a part of this self-healing mechanism [4]. Calcium hydroxide—the product from hydrated cement—could be transformed into calcium carbonate upon exposure to the atmosphere. As early as in 1973 Malinskii, was the first person to investigate an application of polymeric materials for crack healing. By observing various parameters like temperature dependence, delamination and the time taken for relaxations to occur on polyvinyl acetate (a polymer), his study detected crack healing. Several researchers have since then, tried to use various healing agents focusing on repair of cracks in cement-based materials [5]. Polymer is acknowledged to be a good candidate for self-healing concrete. For the filling and healing of cracks in polymeric materials, mechanical interaction must occur between the polymeric material and crack surfaces [6]. However, due to weak adhesive interaction between the polymer and the fracture surface, the polymer used to fill in the fissures often does not fully recover mechanical properties [7]. On the other side, water could be supplied by Super Absorbent Polymers (SAPs) to the cementitious matrix and thereby triggering an autogenous self-healing process [8]. [9] Ivanov and Polyakov observed in 1974 the effectiveness of hydraulic concrete due to its self-healing properties. Gray invented that self-healing concrete back in 1984 [11]. The autogenous healing capacity of the interface area between steel fibres and cement mortar matrix under water curing conditions is superior to that of fractured concrete or plain mortar [10]. Jacobsen et al. 2017, propose to prepare self-healing cement. The effect of silica fume additions on the hardness and strength of previously air-entrained versus non-air -entrained concrete. The main areas in which future research needs to be focused are super alkaliphilic bacterial genetic engineering and low-cost nutrition sources.

Mechanism of bio concrete formation

Bio-concrete involves adding a nutrition source (e.g. calcium lactate or urea) and dormant, crack-healing bacteria (e.g. *Bacillus* species) to concrete. When cracks develop and water enters, the bacteria kick in. To fill and seal the cracks while prolonging the life of the concrete, they eat the nutrients, precipitating insoluble calcium carbonate or limestone by biomineralization. To address these challenges, microbial-induced carbonate precipitation (MICP) takes a form of eco-bio-concrete crack healing technology (Figure 1)

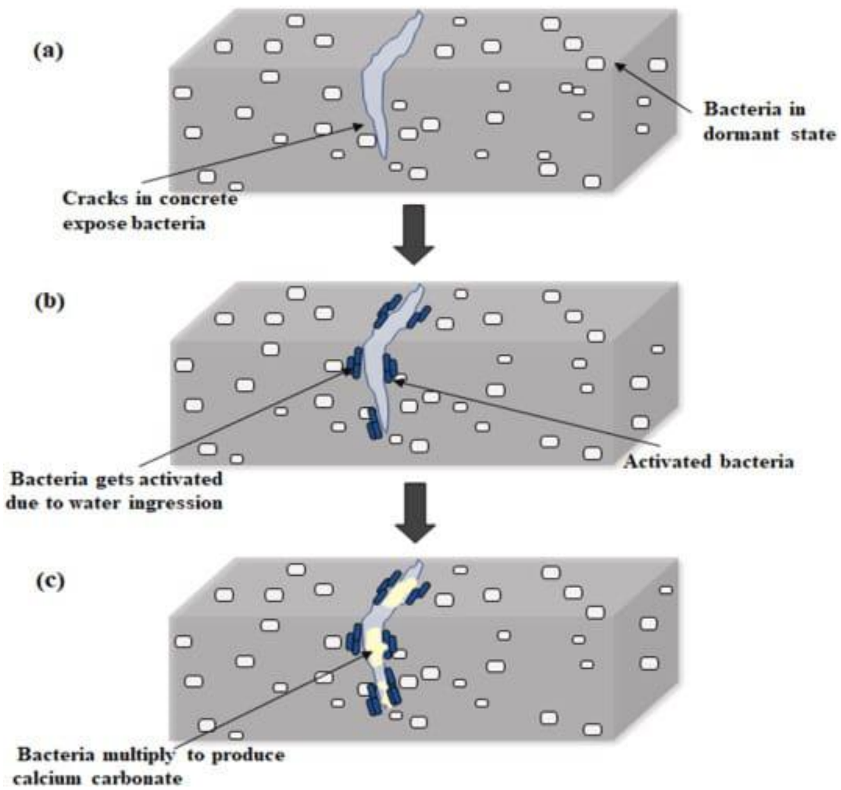

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Fig. 1 Biobased Self-Healing Concrete Leads the Way for Construction Materials

MICP employs urease-producing bacteria such as Bacillus megaterium and *Sporosarcina pasteurii* to catalyze urea hydrolysis, resulting in the precipitation of calcium carbonate ($CaCO_3$) within the fractures [12,13,14]. Besides the structural restoration, this biomineralization process also has self-healing capacity that considerably reduces a need for continuous maintenance [15,16]. Furthermore, MICP improves throughput and sustainability by using industrial by products such as fly ash and slag, consistent with the circular economy [17,18,19,20]. Researches indicate that MICP effectively seals cracks with width up to 2.0 mm, thus plays a major role in improving elastic property and water impermeability of concrete self-healing bio concrete mechanism as shown in Figure. 2 [21, 22, 23]. In addition, supplementing the microbial growth medium with industrial wastes such as fly ash and slag is consistent with the principles of circular economy that promotes sustainability and efficiency of resource utilization. MICP bacteria can develop within concrete and form calcite upon activation with water, as they may be encapsulated in components including polyurethanes or lightweight aggregates [24,25]. By reducing dependency on synthetic chemicals generally incorporated into conventional repair materials, this technology not only enhances the concrete but also provides a sustainable alternative for repairing [26].

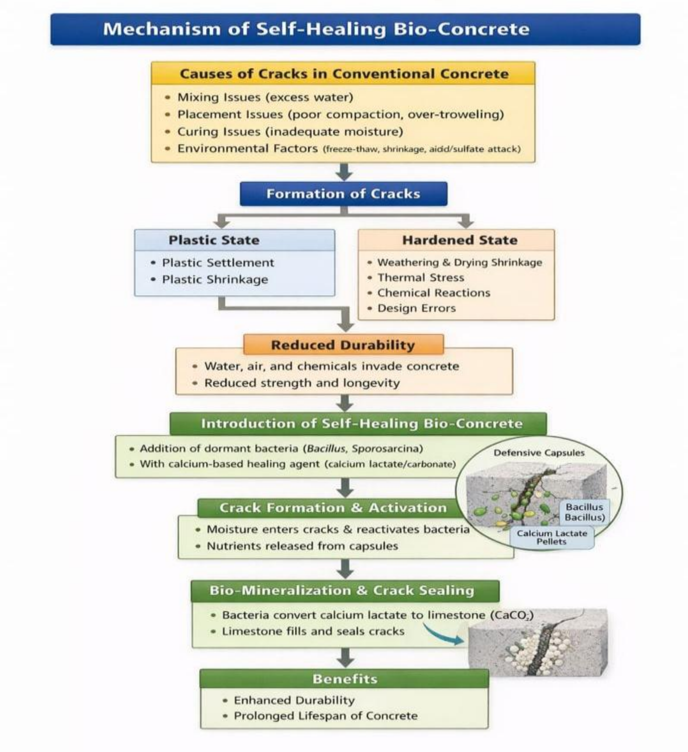

Fig. 2 Mechanism of self-healing bio concrete

Microorganisms used

One of the successful methods for cracks repair is bacteria based healing (figure 3). The high pH that is present in concrete can put the bacteria into a dormant state, and allows them to survive for more than two centuries depending on the type of bacterium [27]. The healing of cracks is done with the help of bacteria which when added into these cracks, can also help form a layer of calcium carbonate [28]. Ureolytic bacteria are commonly associated with self-healing of defect in concrete and postulated to be better suited for repairing cracks than non-ureolytic bacteria due to the fact that they do not proliferate at high pH [29]. *B. halodurans*, *B. licheniformis*, and *B. thuringiensis* when non-ureolytic bacteria can only heal cracks of maximum 0.45 mm wide with a recovery strength of up to 65%, the ureolytic bacterium *S. pasteurii,* along with *B. subtilis*, *B. sphaericus* and *B.megaterium* are reported for healing up to 0.85–0.97 mm wide cracks [30]. Depending on their ability to grow at various pH ranges, the bacteria used in self-healing concrete fall into three categories:

- Acidophile (pH 1–5.5)
- Neutrophile (pH 5.5–8.5)
- Alkaliphile (pH 7.5–12)

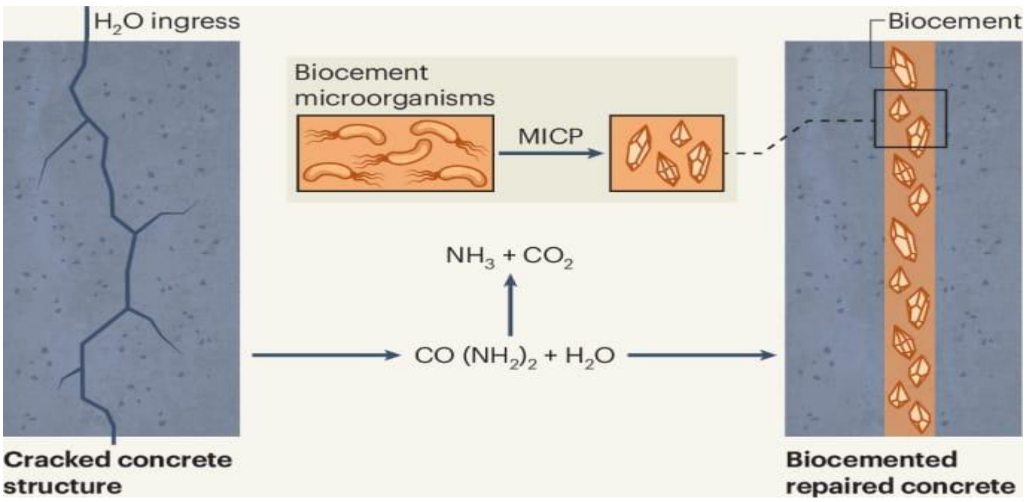

Fig. 3 Microorganisms and their role in self-healing

The most frequently utilized bacteria used in the self-healing for concrete are gram-positive alkaliphile bacteria such as Bacillus strain. Thermophilic and alkaliphilic bacteria can proliferate in environments with relatively high temperatures and pH [31,32]. *B. sphaericus* is a pressure endospore producer in an extreme environment, and *Bacillus subtilis* produces urease activity at pH 9 [33,34]. This led to success with *Bacillus cereus*, *Bacillus sphaericus*, *Sporosarcina pasteurii* and *Bacillus subtilis* in concrete mixtures. Under the right conditions, cement-based materials can self-heal. This is called autogenous healing. Thus, this occurs when water is present within the fissures and that they are much smaller than 100 µm [35]. These natural remedy may not help cracks, however. And microbial self-healing, on the one hand, from previous studies were determined as power to fix cracks found that equivalent of up to 1 mm [36,37]. To completely understand the workings of bacteria based self-healing in concrete, process needs to be understood. The process by which bacteria produce calcium carbonate, a key element in healing, is as follows:

Methods of Encapsulation

1) Melamine-based micro capsulation

Wang et al. encapsulated *Bacillus sphaericus* spores in a melamine-based microcapsule system (2014b) again with some inert material for protecting the spores. Inside was a dry microcapsule containing about 109 bacterial cells. The Efficiencies of crack healing were calculated using ratio of the healed crack to initial crack area. The largest repaired crack size was 970 µm through water curing, whereas the highest healing rate (80%) was achieved using wet-dry curing [38]. In a previous study by Wang et al., diatomaceous earth (DE) was used to transport *Bacillus sphaericus* on (2012a). This species was formulated to react with simply broken-down urea inside the cementitious matrix to generate calcium carbonate. Closed FL cracks (either partial or total) with an open width of 0.15 to 0.17 mm were observed [38].

2) AM Hydrogel Encapsulated B. sphaericus Spores.

The AM polymer chain crosslinks to form a hydrogel network that captures bacterial cells. This outcome was achieved by using both UV light and an initiator called Irgacure R 2959 during the polymerization process. The AM solution (0.5 g AM in 10 mL water) was mixed evenly first, and then the trigger solution (5 g/L, 5 mL) was added [39]. 100 µm. One gram of AM-HS powder theoretically contained approximately 4.4 × 10^9 spores [39].

It was stirred for 10 additional minutes, and then allowed to cool for five minutes. They're photolabile, meaning they don't tolerate exposure to light. So the concoction was covered with foil wrap. They put the blend into a box made of two glasses. A 1 mm thick rubber spacer is located between the plates. The glass plates were held together and then treated with ultraviolet light for an hour. The liquids formed a gel-like coating under UV radiation when contained in the box. An AM hydrogel sample could also be obtained. Then, after the AM solution was well-mixed (0.5 g AM + 9 mL water), the starting solution (5 g/L, 5 mL) was added. The solution was mixed again for an additional 10 minutes. Add 1 mL of B. sphaericus spore suspension and mix for 10 min. Then it spent five minutes gas-free. The methods were the same as those used for making conventional AM hydrogel sheet. The study included AM hydrogels, named AM-HS and AM-H, containing bacterial spores or not. For the experiments, AM-H and AM-HS sheets were freeze-dried and ground into dry powder (20–100 µm). According to its theoretical calculation, one gram of AM-HS powder corresponded to approximately 4.4×109 spores [39].

3)Encapsulation in bio-based polymers

Peat based Eg once made plastic but its no-mean little sister, polylactic acid (PLA), which is a biodegradable polymer that can be derived from natural biomass, has inspired researchers to look at cementitious materials as just the container for their popular new product. Studies have shown that PLA does not react similarly at greater levels of alkalinity. PLA has a long life; when combined with concrete, it hardly decomposes at all during the first 28 days, even at temperatures between 23°C and 50°C. PLA undergoes mass loss with the hydrolysis of ester linkages, significant degradation occurs after ninety days [40].

4)Nano encapsulation

The creation of nano capsules has been shown to help spread cementitious materials more evenly, reducing clumping and allowing for a more even finish. The tablet dispersion method advances crack-sealing by even distribution of self-healing tablets. Moreover, nano encapsulation allows the integration of multifunctional functionalities (e.g., enhanced mechanical performance and self-sensing). But there are some problems with cost and growth potential. Long-term stability of such nano capsules is one of the important areas to be further researched. SNPs, and iron oxide nanoparticles (IONPs): both types of artificial materials that encase microbes. Moreover, biopolymers including gelatine, chitosan and alginate are used. These materials were selected because of their long-term stability within a cementitious matrix, biocompatibility, and ability to release the cargo when required [41].

Applications of Bio concrete

In the Netherlands, a building was built out of self-healing concrete. They built it of bio-concrete, which has bacteria embedded in it that helps heal the concrete itself. A lifeguard station [42] by a lake, this prototype project was developed by Delft University of Technology. Utilization of the ability of bacteria to precipitate the minerals, especially carbonates in different areas by civil engineering [43]. *Bacillus pseudofirmus* spores plus organic nutrients (calcium acetate, yeast extract) were infiltrated in the aggregates under pressure before incorporated into the concrete. Next, the panels were taken outside to evaluate SHC in real construction projects. Thus, the self-ability of these individuals was greatly improved after six months [44]. As bio self-healing technology bonds properly, functions with concrete formulations and possesses longevity it is better than the current treatment strategies. It will fill in existing small cracks and prevents larger ones from forming. Inspection costs may be reduced as a consequence [45].

Limitations of self-healing bio concrete

That said, self-healing concrete is still not the most reliable as it depends on bacteria that already lives inside of the concrete. Bacteria serve as a catalyst [46], and thus, more amounts of mineral precursor chemicals are required to be added within the concrete mix to enhance the fracture repair process. Certain minerals in excess can cause slower healing process and changing the strength and setting time of concrete. (If you don’t have these minerals, small fractures won’t heal either.) You are only able to treat small fractures under 1 mm across. The size of the crack affects what type of microcapsules are used and how effectively they will encapsulate. Since crack widths vary from micro to macro [47, 48], it is essential to be able to develop only one type of the micro-capsule that can seal cracks within a given segment of widths. The direct application process can also mic some of the concrete, so that the porosity (the reactivity with medicinal ingredients) becomes reduced, in turn making bacteria less useful. This endangers the structural integrity of the bacterial concrete [49]. Given the harsh environment [46], self-healing concrete will perform worse in the long term. Moreover, the timeline for bacteria to kick in and the healing process to begin does not always match up with how soon cracks need treating a potential risk for structural safety down the line. In addition, the long-term environmental effects of adding bacteria to concrete must also be considered. This becomes very important in the context of bacteria or their metabolites released into the environment [47].

Future aspects and conclusion

Once bio concrete has been developed in the lab, it needs to be moved to several key areas before we can deploy it on a large scale: RECAP. Future experiments on nano-encapsulation and multifunctional shells are required to improve spores preservation and cementation of the precipitated $CaCO_3$ with respect to concrete matrix. Engineered for this purpose, the resulting "super-alkaliphilic" strains of bacteria would be metabolically and survivor-enhanced. This would help mend bigger fissures. Future work may focus on replacing expensive calcium lactate with nutritious precursors obtained from industrial wastes like flyash, slag or corn steep liquor to make it economical. Global building codes prohibiting “living materials” must first be developed before self-healing structures can be implemented in real-life applications.

References

1) Seifan, M., Samani, A. K., & Berenjian, A. (2016). Bioconcrete: next generation of self-healing concrete. Applied microbiology and biotechnology, 100(6), 2591-2602.

2) Onyelowe, K. C., Adam, A. F., Ulloa, N., Garcia, C., Andrade Valle, A. I., Zúñiga Rodríguez, M. G., ... & Ganasen, N. (2024). Modeling the influence of bacteria concentration on the mechanical properties of self-healing concrete (SHC) for sustainable bio-concrete structures. Scientific Reports, 14(1), 8414.

3) Lee, C., Lee, H., & Kim, O. B. (2018). Biocement fabrication and design application for a sustainable urban area. Sustainability, 10(11), 4079.

4) Lauer, K.R.; Slate, F.O. Autogenous healing of cement paste. J. Am. Concr. Inst. 1956, 52, 1083–1097. [Google Scholar] [CrossRef]

5) Davies, R.; Martins, P.; Antonios, K.; Trupti, S. Materials for Life (M4L): Combining multi-scale healing techniques in cementitious materials. In Proceedings of the Fifth International Conference on

Self-Healing Materials, Durham, NC, USA, 22–24 June 2015. [Google Scholar]

6) Joseph, C.; Jefferson, A.D.; Isaacs, B.; Lark, R.; Gardner, D. Experimental investigation of adhesive-based self-healing of cementitious materials. Mag. Concr. Res. 2010, 62, 831–843. [Google Scholar] [CrossRef]

7) Gilabert, F.A.; Van Tittelboom, K.; Van Stappen, J.; Cnudde, V.; De Belie, N.; Van Paepegem, W. Integral procedure to assess crack filling and mechanical contribution of polymer-based healing agent in encapsulation-based self-healing concrete. Cem. Concr. Compos. 2017, 77 (Suppl. C), 68–80. [Google Scholar] [CrossRef]

8) Snoeck, D.; Pel, L.; de Belie, N. Autogenous healing in cementitious materials with superabsorbent polymers quantified by means of NMR. Sci. Rep. 2020, 10, 1–6. [Google Scholar] [CrossRef]

9) Ivanov, F.M.; Polyakov, B.I. Self-healing and durability of hydraulic concrete. Hydrotech. Constr. 1974, 8, 844–849. [Google Scholar] [CrossRef]

10) Gray, R.J. Autogenous healing of fiber/materix interfacial bond in fiber-reinforced mortar. Cem. Concr. Res. 1984, 14, 315–317. [Google Scholar] [CrossRef]

11) Jacobsen, S.; Marchand, J.; Hugues, H. Sem observations of the microstructure of frost deteriorated and self-healed concretes. Cem. Concr. Res. 1995, 25, 1781–1790. [Google Scholar] [CrossRef]

12) Omoregie, A.I.; Ong, D.E.L.; Li, P.Y.; Senian, N.; Hei, N.L.; Esnault-Filet, A.; Muda, K.; Nissom, P.M. Effects of Push-Pull Injection-Suction Spacing on Sand Biocementation Treatment. Geotech. Res. 2024, 11, 28–42. [Google Scholar] [CrossRef]

13) Matsubara, H.; Yamada, T. Mathematical Modelling and Simulation of Microbial Carbonate Precipitation: The Urea Hydrolysis Reaction. Acta Geotech. 2020, 15, 29–38. [Google Scholar] [CrossRef]

14 Zhu, X.; Wang, J.; De Belie, N.; Boon, N. Complementing Urea Hydrolysis and Nitrate Reduction for Improved Microbially Induced Calcium Carbonate Precipitation. Appl. Microbiol. Biotechnol. 2019, 103, 8825–8838. [Google Scholar] [CrossRef] [PubMed]

15) Yang, W.; Ali, A.; Su, J.; Liu, J.; Wang, Z.; Zhang, L. Microbial Induced Calcium Precipitation Based Anaerobic Immobilized Biofilm Reactor for Fluoride, Calcium, and Nitrate Removal from Groundwater. Chemosphere 2022, 295,

133955. [Google Scholar] [CrossRef] [PubMed]

16) Liu, J.; Ali, A.; Su, J.; Wu, Z.; Zhang, R.; Xiong, R. Simultaneous Removal of Calcium, Fluoride, Nickel, and Nitrate Using Microbial Induced Calcium Precipitation in a Biological Immobilization Reactor. J. Hazard. Mater. 2021, 416. [Google Scholar] [CrossRef]

17) Javeed, Y.; Goh, Y.; Mo, K.H.; Yap, S.P.; Leo, B.F. Microbial Self-Healing in Concrete: A Comprehensive Exploration of Bacterial Viability, Implementation Techniques, and Mechanical Properties. J. Mater. Res. Technol. 2024, 29, 2376–2395. [Google Scholar] [CrossRef]

18) Sun, Y.; Liu, K.; Sun, D.; Jiang, N.; Xu, W.; Wang, A. Evaluation of Urea Hydrolysis for MICP Technique Applied in Recycled Aggregate: Concentration of Urea and Bacterial Spores. Constr. Build. Mater. 2024, 419, 135366. [Google Scholar] [CrossRef]

19) Xiao, X.; Tan, A.C.Y.; Unluer, C.; Yang, E.-H. Development of a Functionally Graded Bacteria Capsule for Self-Healing Concrete. Cem. Concr. Compos. 2023, 136, 104863. [Google Scholar]

20)Zhou, Y.; Elchalakani, M.; Cheng, L.; Shahin, M.A. Impact of Calcium Content and PH Value on MICP Crack Healing of Geopolymer Concrete. Cem. Concr. Compos. 2024, 146, 105410. [Google Scholar] [CrossRef]

21) Rajasekar, A.; Zhao, C.; Wu, S.; Murava, R.T.; Wilkinson, S. Synergistic Biocementation: Harnessing Comamonas and Bacillus Ureolytic Bacteria for Enhanced Sand Stabilization. World J. Microbiol. Biotechnol. 2024, 40, 229. [Google Scholar] [CrossRef]

22)Zhou, G.; Xu, Y.; Wang, Y.; Zheng, L.; Zhang, Y.; Li, L.; Sun, B.; Li, S.; Zhu, Y. Study on MICP Dust Suppression Technology in Open Pit Coal Mine: Preparation and Mechanism of Microbial Dust Suppression Material. J. Environ. Manag. 2023, 343, 118181. [Google Scholar] [CrossRef]

23) Wang, J.Y.; Soens, H.; Verstraete, W.; De Belie, N. Self-Healing Concrete by Use of Microencapsulated Bacterial Spores. Cem. Concr. Res. 2014, 56, 139–152. [Google Scholar] [CrossRef]

24) Huang, H.; Du, C.; Yi, F.; Wang, M.; Lv, Z. Enhancing Concrete Crack Healing: Revealing the Synergistic Impacts of Multicomponent Microbial Repair Systems. Case Stud. Constr. Mater. 2024, 21, e03402. [Google Scholar] [CrossRef]

25) Elmenshawy, Y.; Elmahdy, M.A.R.; Moawad, M.; Elshami, A.A.; Ahmad, S.S.E.; Nagai, K. Investigating the Bacterial Sustainable Self-Healing Capabilities of Cracks in Structural Concrete at Different Temperatures. Case Stud. Constr. Mater. 2024, 20, e03188. [Google Scholar] [CrossRef]

26) Oh, S.-E.; Kim, J.-S.; Maeng, S.K.; Oh, S.; Chung, S.-Y. Influence of Bacterial Biomineralization Conditions on the Microstructural Characteristics of Cement Mortar. J. Build. Eng. 2024, 91, 109455. [Google Scholar] [CrossRef]

27) Siddique, R., & Chahal, N. K. (2011). Effect of ureolytic bacteria on concrete properties. *Construction and building materials*, *25*(10), 3791-3801.

28) Pei R, Liu J, Wang S, Yang M. Use of bacterial cell walls to improve the

mechanical performance of concrete. Cem Concr Compos 2013;39:122–30.

29) Xu, J., & Yao, W. (2014). Multiscale mechanical quantification of self-healing concrete incorporating non-ureolytic bacteria-based healing agent. *Cement and concrete research*, *64*, 1-10.

30) Yamasamit, N., Sangkeaw, P., Jitchaijaroen, W., Thongchom, C., Keawsawasvong, S., & Kamchoom, V. (2023). Effect of Bacillus subtilis on mechanical and self-healing properties in mortar with different crack widths and curing conditions. *Scientific Reports*, *13*(1), 7844.

31) Wu M, Hu X, Zhang Q, Xue D, Zhao Y. Growth environment optimization for

inducing bacterial mineralization and its application in concrete healing.

Construct Build Mater 2019;209:631–43.

32) Tayebani B, Mostofinejad D. Penetrability, corrosion potential, and electrical

resistivity of bacterial concrete. J Mater Civ Eng 2019;31:04019002.

33) Jiang, N. J., Yoshioka, H., Yamamoto, K., & Soga, K. (2016). Ureolytic activities of a urease-producing bacterium and purified urease enzyme in the anoxic condition: Implication for subseafloor sand production control by microbially induced carbonate precipitation (MICP). *Ecological engineering*, *90*, 96-104.

34) Shanmuga Priya T, Ramesh N, Agarwal A, Bhusnur S, Chaudhary K. Strength and

durability characteristics of concrete made by micronized biomass silica and

Bacteria-Bacillus sphaericus. Construct Build Mater 2019;226:827–38. https://

doi.org/10.1016/j.conbuildmat.2019.07.172

35) Sisomphon K, Copuroglu O, Koenders EAB. Self-healing of surface cracks in mortars with expansive additive and crystalline additive. Cem Concr Compos 2012;34:566–74.

36) Bang SS, Galinat JK, Ramakrishnan V. Calcite precipitation induced by Polyurethane immobilized *Bacillus pasteurii* Enzyme microbe Technol 2001;28:404-9

37) Song Y, Chetty K, Garbe U, Wei J, Bu H, O'moore L, Li X, Yuan Z, McCarthy T, Jiang G. A novel granular sludge-based and highly corrosion-resistant bioconcrete in sewers. Sci Total Environ 2021;791:148270.

38) Cuenca, E., Tejedor, A., & Ferrara, L. (2018). A methodology to assess crack-sealing effectiveness of crystalline admixtures under repeated cracking-healing cycles. *Construction and Building Materials*, *179*, 619-632.

39) Wang, J., Mignon, A., Snoeck, D., Wiktor, V., Van Vliergerghe, S., Boon, N., & De Belie, N. (2015). Application of modified-alginate encapsulated carbonate producing bacteria in concrete: A promising strategy for crack self-healing. Frontiers in microbiology, 6, 1088.

40) Moussa, B. A., Hashem, H. M., Mahrouse, M. A., & Mahmoud, S. T. (2018). Experimental design approach in HPLC method development: application for the simultaneous determination of sacubitril and valsartan in presence of their impurities and investigation of degradation kinetics. *Chromatographia*, *81*(1), 139-156.

41) Macías-Silva MA, et al. Nanomaterials in construction industry: An overview of their properties and contributions in building house. Case Stud Chem Environ Eng. 2024 Dec;10. https://doi.org/10.1016/j.cscee.2024.100863

42) Hanna, J. (2024). Self-Healing Concrete Techniques and Technologies and Applications. Recent Progress in Materials, 6(1), 1-20.

43) Ojha, A., Kumar, A., Das, D., & Bandyopadhyay, T. K. (2025). Bio-concrete and its self-healing capacity to next-generation sustainable architecture: A comprehensive review. Exon, 2(1), 1-15.

44) Davies R, Teall O, Pilegis M, Kanellopoulos A, Sharma T, Jefferson A, Gardner D, Al-Tabbaa A, Paine K, Lark R. Large scale application of self-healing

concrete: design, construction, and testing. Front Mater. 2018;5:51

45) Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E (2010)Application of bacteria as self-healing agent for the development ofsustainable concrete. Ecol Eng 36:230–235

46) Zioupos, P., & Currey, J. D. (1994). The extent of microcracking and the morphology of microcracks in damaged bone. *Journal of materials science*, *29*(4), 978-986.

47) Yıldırım G, Khiavi AH, Yes¸ilmen S, S¸ahmaran M. Self-healing performance of aged cementitious composites. Cem Concr Compos 2018;87:172–86.

48) Kanellopoulos A, Giannaros P, Al-Tabbaa A. The effect of varying volume fraction of microcapsules on fresh, mechanical and self-healing properties of mortars. Construct Build Mater 2016;122:577–93.

49) Albuhairi D, Di Sarno L. Low-carbon self-healing concrete: state-of-the-art, challenges and opportunities. Buildings 2022;12:1196.

50) Lee, Y. S., & Park, W. (2018). Current challenges and future directionsfor bacterial self-healing concrete. Applied Microbiology and Biotechnology, 102(7), 3059–3070. https://doi.org/10.1007/s00253-018-883