frontiers | Frontiers in Built Environment

TYPE Mini Review
PUBLISHED 19 January 2023
DOI 10.3389/fbuil.2023.1095949

A review of durability improvement in concrete due to bacterial inclusions

Radha Kiranmaye Bandlamudi[1], Arkamitra Kar[1]* and Jayati Ray Dutta[2]

[1]Department of Civil Engineering, Birla Institute of Technology and Science-Pilani, Hyderabad Campus, Hyderabad, Telangana, India, [2]Department of Biological Sciences, Birla Institute of Technology and Science-Pilani, Hyderabad Campus, Hyderabad, Telangana, India

Check for updates

OPEN ACCESS

EDITED BY
Paul Awoyera,
Covenant University, Nigeria

REVIEWED BY
Hadee Mohammed Najm,
Aligarh Muslim University, India
Olusola Babalola,
Ton Duc Thang University, Vietnam

*CORRESPONDENCE
Arkamitra Kar,
arkamitra.kar@hyderabad.bits-pilani.ac.in

SPECIALTY SECTION
This article was submitted to Construction Materials,
a section of the journal
Frontiers in Built Environment

RECEIVED 11 November 2022
ACCEPTED 12 January 2023
PUBLISHED 19 January 2023

CITATION
Bandlamudi RK, Kar A and Ray Dutta J (2023), A review of durability improvement in concrete due to bacterial inclusions.
Front. Built Environ. 9:1095949.
doi: 10.3389/fbuil.2023.1095949

Since the invention of industrially produced Portland cement in the nineteenth century, concrete has been the world's most frequently used construction material. Because of the significant CO_2 emissions produced during cement manufacture and concrete maintenance and repair costs, sustainably improving concrete durability has become a topic of concern. Bacterial self-healing is a unique method that uses $CaCO_3$ precipitation to repair cracks in concrete, thereby improving the structure's durability. This review highlights the effect of bacterial treatment on concrete durability. The permeation properties, water absorption, and mechanical properties are assessed. Emphasis is laid on the selection of bacteria and bacteria nutrients. The paper overviews the morphological analysis of $CaCO_3$ precipitation by bacterial concrete. Despite the benefits of bacterial technology in concrete, numerous critical concerns remain unresolved. Further investigation on nutrients is required to develop a multi-nutrient system that will improve the efficiency of bacterial precipitation since a good combination of low-cost nutrients would reduce the total cost of bacterial concrete.

KEYWORDS

bioconcrete, durability, bacterial treatments, bioconcrete nutrients, $CaCO_3$ morphology

1 Introduction

Concrete, the most frequently used construction material in the world, accounts for almost 8% of the global CO_2 emissions through the production and usage of Portland cement. Exposing structures to physical, chemical, and biological elements has increased concrete consumption. Hence, it is vital to implement ways to reduce this while lowering investments in maintenance and repair.

Bacterial self-healing is being investigated as a solution for repairing cracks in concrete by precipitating $CaCO_3$. Concrete durability can be increased by reducing absorption, permeability, and diffusion. It is controlled by the amount of dissolved inorganic carbon and calcium ions in the pore solution, nucleation sites for crystal formation, salinity, and the suspension's temperature.

Figure 1 shows that the number of scientific publications on bacterial concrete has increased dramatically over the last two decades. It is clear that the number of articles generated increased significantly from 2015 and can be considered as promising subject under study.

Different bacteria and pathways are involved in microbial mineral precipitation. Nutrients, mainly carbon and nitrogen, are required to germinate and grow bacteria within concrete. Bacteria type and its media composition affect the precipitate's crystal morphology. These changes in crystal shape could be attributed to metabolic activity and the presence of organic matter. There are different methods of bacterial inclusions in concrete, the most popular being

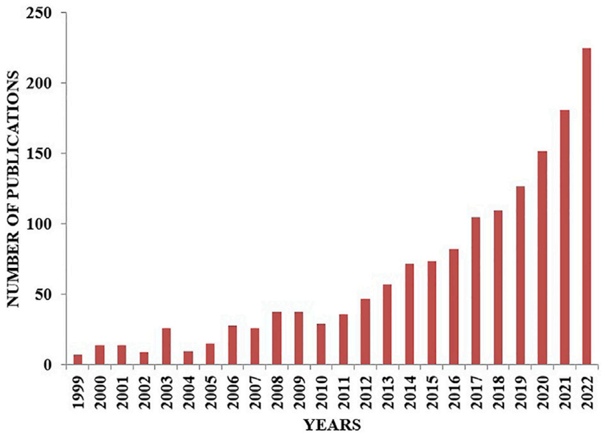

FIGURE 1
Papers published in science direct journal for phrase search "bacterial concrete" in the last two decades.

bacterial surface treatment. A layer of $CaCO_3$ crystals on the surface and a variant of the surface microstructure is observed with bacterial inclusions. However, this procedure is still experimental. Hence, this study focuses on reviewing the effect of these methods on concrete durability. The bacteria utilized to increase the durability of self-healing concrete are described in Section 2. Section 3 shows the different methods of bacterial treatment to improve the durability of concrete. The nutrient types used in bio-concrete and their effect on durability are covered in Section 4, and the morphological studies on $CaCO_3$ precipitated are explained in Section 5.

2 Types of bacteria

Microorganisms trigger chemical reactions and biological activity to cause $CaCO_3$ precipitation. Microbial cells are negatively charged colloidal particles that cause local supersaturation by inducing calcium ions in the solution environment to adsorb in the cell wall area. Calcite crystals form in the supersaturated area of the cell wall and contribute to the precipitation of calcite-type $CaCO_3$ crystals. Cyanobacteria, sulfate-reducing bacteria, denitrifying and urease-producing bacteria cause $CaCO_3$ precipitation.

Cyanobacteria are gram-negative bacteria and plants' chloroplasts due to oxygenic photosynthesis. A comparison of the $CaCO_3$ precipitation process carried out in solutions and on mortar surfaces by three cyanobacterial species is studied (Zhu et al., 2018). *Synechocystis sp PCC6803* exhibited the highest precipitation in solution and motor surfaces, followed by *Synechocystis sp PCC8806* and *Synechocystis sp. LS0519*. Comparing live and UV-treated specimens, $CaCO_3$ precipitation by *S. pevalekii* cells increased compressive strength and permeation. Also, the compressive strength of live cell specimens improved (Sidhu et al., 2022). The benefit of cyanobacteria is the need for carbon dioxide from the environment, making it cheaper.

Recent investigations were done on developing carbonate mineral compositions caused by the reduction of sulfate bacteria. The bacteria isolated from acid mine water was tested for its performance in concrete (Alshalif et al., 2016). Concrete test specimens were cured in the open air for 7, 14, and 28 days. With 5% sulfate-reducing bacteria, the maximum increase in compressive strength was 13.0%, and the maximum decrease in water penetration was 8.5%. However, this bacterium is not practical for engineering applications since it is challenging to maintain anaerobic conditions constantly in concrete. Additionally, the pungent H_2S gas is extremely harmful to the environment.

Denitrifying bacteria are dispersed in nature and are abundant in soil. They are used to treat recycled coarse aggregate and then in concrete to enhance durability (Liu et al., 2022). Compressive, split tensile strength increased by 30.3% and 19.2%, and water absorption decreased by 33%. Ersan et al. (2016) used axenic denitrifying strains of *Pseudomonas aeruginosa* and *Diaphorobacter nitroreducens* to test the viability of repairing concrete cracks. They were protected within granular activated carbon particles or expanded clay particles as microbial healing agents. It demonstrated that these strains caused concrete cracks of 400 mm in width to mend within 4 weeks and cracks of 470 mm in width to repair within 7 weeks.

Self-protecting non-axenic bio-granules called activated compact denitrifying cores were substituted for the protected axenic cultures (ACDC). ACDC bio-granules could survive in mortar, limit steel corrosion, and cause complete healing of 500 μm-wide fissures after 4 weeks of tap water treatment (Ersan et al., 2015). They were compatible with concrete up to 3% w/w cement inclusion dose. It also revealed that these bio-granules in concrete can self-heal cracks up to 400 μm wide during wet/dry cycles (Ersan, 2021). Steel rebar corrosion inhibition throughout the autonomous crack healing process was reported as an additional benefit of denitrifying microorganisms in concrete.

Urease is an abundant natural enzyme and can quickly produce $CaCO_3$ precipitation. These are Gram-positive, rod-shaped bacteria and endospores found in soil. $CaCO_3$ precipitation caused by *B.aerius* reduced water absorption and porosity of bio-concrete. Each control group of concrete samples exhibited high to moderate permeation after 28 days, but bacterial (10^5 cell/mL) samples that produced calcite displayed high to low permeability when pores were sealed with $CaCO_3$ (Siddique et al., 2016). *B.subtilis* with different cell concentrations are examined in bio-concrete (Jena et al., 2020). The study found that bacterial infusion in all cell concentrations has greater strength than the control mix.

A study by Thiyagarajan et al. (2016) reported that *B.cereus* and *B.pasteurii* could improve the performance of concrete. The results of the tests demonstrated a 38% increase in compressive strength using *B.cereus* and a 29% increase using *B.pasteurii* over the control cement mortar. Compared to the control, a lower chloride penetration was observed in *B.cereus* integrated concrete. The optimal concentration of *B.megaterium* (10^5 cells/mL) can be employed to increase mechanical and durability qualities. The chloride ion penetration and coefficient of water permeability of concrete are 26.8% and 98.7% lower, than that of control concrete (Smitha M. P et al., 2022). This section shows that bacterial inclusion in concrete improves the durability parameters and has widespread applications for self-healing. The following section discusses the methods for concrete treatment using bacterial inclusions.

3 Methods of bacterial treatment

3.1 Surface treatment

Surface treatments reinforce the protection of construction materials. De Muynck et al. (2008) applied a biodeposition treatment to the surface of the mortar specimens to compare the outcomes of permeability qualities and resistance to degradation processes with standard surface treatments. Accordingly, the surface deposition of carbonate crystals reduced water absorption, increasing the mortar's resistance to carbonation, chloride penetration, freezing, and thawing.

Nosouhian et al. (2015) studied the effect of microbial surface treatment in sulfate environments. Three distinct microbial solutions, *Sporosarcina pasteurii, B.subtilis,* and *B.sphaericus,* were surface treated on the concrete. The durability loss index calculated in the study demonstrated that surface treatment by *B.sphaericus* bacteria (6.6×10^6 cells ml^{-1}) produced the most durable concrete in a sulfate environment among all the tested biological treatments and specific cell concentrations.

In the presence of urea, $CaCO_3$ precipitation was induced on concrete with *L.sphaericus* along with $CaCl_2$ and ($Ca(CH_3COO)_2$) as nutrients. The samples treated with two rounds of *L.sphaericus* and a calcium source treatment had a thicker and even coating of calcite crystals on the surface, demonstrating that repeated treatments effectively increased $CaCO_3$ deposition (Farrugia C et al., 2019).

3.2 Self-healing material

Bacteria are introduced into cementitious composites during casting, and as cracks form, water and oxygen infiltrate *via* cracks and meet the bacteria in the crack space. Bacterial $CaCO_3$ will automatically fill the fissure. The efficiency of bio-concrete depends on the metabolic pathway of the bacteria, concentration, temperature, and pH. Bio-concrete self-healing can be achieved by directly applying bacteria inside the concrete, immobilization, and encapsulation. Ghosh et al. (2005) observed that bacteria might fill the pores in the specimen, reducing pore volumes and increasing compressive strength. This technology makes fabrication accessible, making it cheaper. However, it significantly impacts bacterial activity because cement hydration is a continual process that reduces the pore size of the cement paste and crushes the spores. Nevertheless, the major disadvantage of direct addition is the decrease in bacterial spores' viability as the cementitious composites' age increases.

Immobilization, a method of using bacteria with protective material in concrete, has been proposed to ensure the long-term effectiveness of bacteria. The efficiency of bacteria immobilized is greater than that of direct integration and depends on the efficacy of various protective materials like calcium sulfoaluminate cement, iron-oxide nanoparticles, crushed brick aggregate, etc. Khaliq and Ehsan (2016) found that bacteria immobilized in graphite nano-platelets were more successful at 3 and 7 days in healing pre-cracked specimens, while bacteria immobilized in lightweight aggregates performed better at 14 and 28 days.

Encapsulating bacteria is suggested to ensure its viability during concrete mixing, setting, and hardening. A healing chemical is released when encapsulation splits due to cracks or micro-cracks. Wang et al. (2012) investigated the use of silica gel or polyurethane as a carrier encased in a glass tube containing microorganisms. They concluded that bacteria encapsulated in silica gel were more active than polyurethane. Precracked specimens had a higher strength return and lower water permeability when repaired by bacteria encapsulated in polyurethane.

Functionally graded reactive magnesia cement-based bacteria spores (RMC-B) capsule for self-healing concrete was developed in recent times. The introduction of RMC-B capsules had no negative influence on the hydration and fresh qualities of the cement paste and increased the 28-day compressive strength of the hardened paste by 18% (Xiao X et al., 2022). In another study, microcrystalline cellulose tablets (MCC) were developed to encapsulate the bacteria (*Lysinibacillus boronitolerans* YS11 and *Bacillus miscanthi* AK13). The water permeability of specimens combined with these tablets decreased as curing time increased, with crack healing rates of up to 91.1% within 28 days (Son Y et al., 2022). Adding bacterial self-healing agents to concrete mixtures alters the microstructure of the concrete, reflected in its compressive strength. However, keeping the bacteria from crushing is critical to ensure concrete's autogenous healing ability.

3.3 Biogrout

Aside from the positive results of microbial self-healing processes in crack repair, researchers have highlighted certain constraints for commercializing this technique. One of the cost constraints is the usage of laboratory-grade nutrient supplies and transport materials for bacteria in field applications. The exterior treatment of cracks in concrete structures is another drawback. However, there is limited research in this regard. Injectable biogrout could be a potential engineering solution.

In biogrouting applications, Joshi et al. (2021) studied the strain *Bacillus sp. CT5*, looking into the effectiveness of bio-based fly ash-modified cementitious grout. Among the various altered bacterial grouts, 40% fly ash amended bacterial grout had the highest fluidity and workability. Urease based biogrout also improves the properties of soil. *Asparaginase*-based biogrout produced a UCS of 980 kPa in sand compared to 1,002 kPa for urease biogrout (Li et al., 2015).

In summary, biogrouts are cost-effective and environmentally friendly. Having rheological properties can be used to condense injection applications for concrete cracks and soil improvement. The following section covers the types of nutrients added to bacteria to enhance concrete performance.

4 Types of nutrients

Bio-concrete offers better qualities and durability than regular concrete. However, natural $CaCO_3$ production is restricted to the calcium amount in cement. Therefore, adding nutrients is required to provide extra calcium as a calcium source for bio-concrete.

In bio-concrete, calcium lactate has been used with *Enterococcus faecalis and Bacillus sp*. This study demonstrated that adding calcium lactate and bacteria can improve the strength and durability of concrete. (Irwan et al., 2016). Oyster shell-derived calcium ions are used for $CaCO_3$ precipitation by *AK13* (Hong et al., 2021). The study demonstrated that these ions, in combination with soybean meal solution, boosted bacterial survival and $CaCO_3$ precipitation within mortar cracks. Xiang et al. (2022) tested $CaCl_2$, calcium acetate, and $Ca(NO_3)_2$ on bio-cement. Calcium acetate was the best source of bio-cement compared to the other two nutrients. The ammonia emission dropped by 54.2% and 51.4% compared to $CaCl_2$ and $Ca(NO_3)_2$. Erşan and Akin (2018) established an optimal nutrient content range for

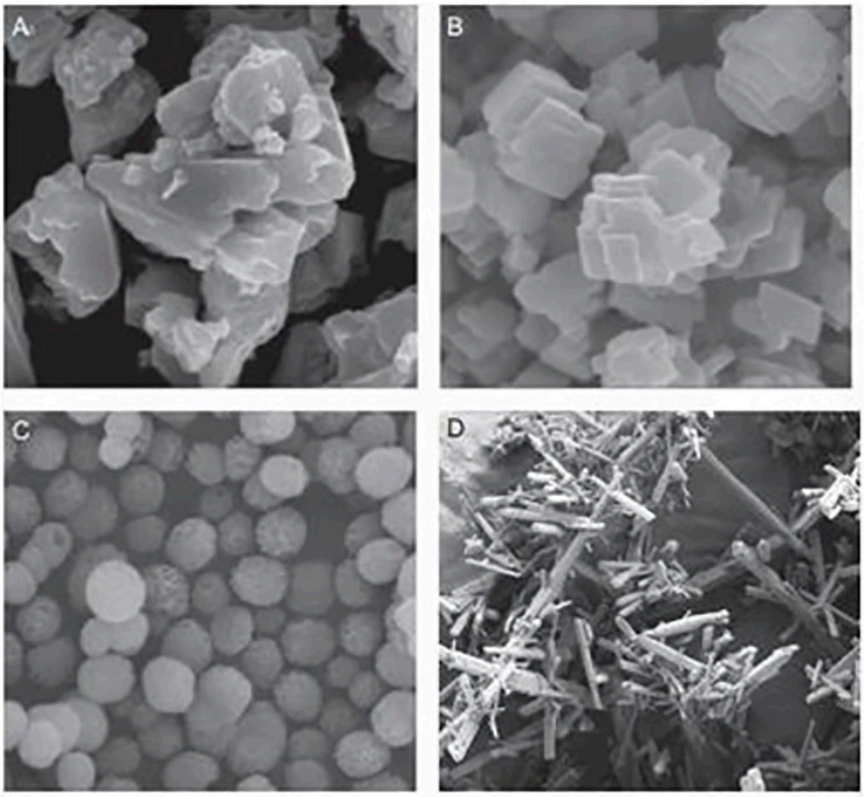

FIGURE 2
SEM images of different $CaCO_3$ types **(A)** amorphous calcite; **(B)** rhombohedral calcite; **(C)** vaterite and **(D)** aragonite (Al Omari et al. 2016).

nitrate reduction-based bio-concrete. While testing various nutrient doses, calcium formate and calcium nitrate were used as nutrient admixtures. Their wt/wt ratio was kept constant at 2.50:1. There was variation in mortar characteristics and nutrient absorption, and the ideal nutritional content range was defined as 3.5%–7%.

Nutrients influence the $CaCO_3$ precipitation in bio-concrete based on crystal size and shape formed. The absorption of organic or inorganic components can change crystal formation by specifying the crystallographic planes of the crystal. The following section is focused on the morphological aspects.

5 Morphology of $CaCO_3$ precipitate

It is essential to investigate and establish the chemical composition to determine the suitability of bacterial $CaCO_3$ precipitates in construction activities.

An essential aspect of $CaCO_3$ precipitation is its morphology. Calcite, aragonite, and vaterite are three distinct anhydrous crystalline morphs. Calcite has the group's lowest solubility and the highest thermodynamic stability. While vaterite possesses reverse characteristics, aragonite is in the middle of the solubility and thermodynamic stability charts.

The factors which affect the morphology are bacterial species, microbial excretions, and solution composition (Zhang J L et al., 2016; Qian C et al., 2019). An atomic force microscope and a scanning electron microscope are used to analyze the morphology of $CaCO_3$. The amount of organic calcium ion template in the simulated solution is affected by the pH value, which modifies the crystals' growth rate and results in different crystal shapes. The proportion of spherical or ellipsoidal particles is directly proportional to the calcium ion concentration in calcite. The relative contact area increases as the percentage of spherical/ellipsoidal particles increases. The adhesion between the particles is directly proportional to the temperature of $CaCO_3$ crystal disintegration. Scanning electron micrographs of different carbonate forms are shown in Figure 2. Based on its crystalline structure, calcite is considered the most desirable form of $CaCO_3$ for concrete applications.

According to Bhaskar et al., 2017 the precipitation morphology of *Sporosarcina ureae* tended to be denser rhombohedral-shaped crystals, whereas that of *Sporosarcina pasteuri* tended to be scattered. Amiri and Bundur (2018) confirmed that different calcium sources result in diverse precipitation morphology. The first and second peaks of TGA curves appear at 610°C and 735°C for $CaCl_2$ and 628°C and 768°C for $Ca(CH_3COO)_2$, respectively. TGA research revealed that specimens with $Ca(CH_3COO)_2$ obsessed more with calcite than those with $CaCl_2$ (at 600°C) because calcite is more stable than vaterite.

6 Results and conclusion

A huge number of bacteria are investigated in concrete, and each one is identified with its significant qualities. According to the test results, bacteria have a limited life span during the direct addition process, which limits self-healing efficiency but increases the strength properties of concrete. A few studies also investigated direct spraying of the bacterial solution over the fracture, which yielded good results. To extend the life of bacteria, various encapsulating strategies have been tried and polymer-based encapsulation is the most widely used self-healing option. Along with bacterial concrete, the use of extra nutrients in concrete is gaining popularity as a new self-healing approach. Future research could concentrate on combining these extra cementitious materials with encapsulated microorganisms, which could be a viable solution for improving self-healing efficiency. Based on the above results, the following conclusions are drawn.

- Microbial $CaCO_3$ precipitation is a biogeochemical mechanism causing precipitation in concrete. It helps in fracture remediation, corrosion prevention, reducing porosity, and decreasing water permeability.
- Most bacteria that result in the precipitation of $CaCO_3$ also produce ammonia, which is highly undesirable in concrete.
- Bacteria encapsulation protects the spore from damage during the hydration process, as the spore's size is larger than the pore size in concrete.
- Nutrients should be explored further to develop an effective multiple-nutrient system to improve bacterial precipitation efficiency. A mix of low-cost nutrients would reduce the total cost of bio-concrete.
- To commercialize this technology, a multidisciplinary approach with a comprehensive knowledge of the mechanism of bacterial $CaCO_3$ precipitation is necessary.

Author contributions

Conceptualization, RB, JR, and AK; data collection and review, RB; investigation, RB; data curation, RB, JR, and AK; writing—original draft preparation, RB, JR, and AK; writing—review and editing, JR and AK; supervision, JR and AK.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Alshalif, A. F., Irwan, J. M., Othman, N., and Anneza, L. H. (2016). Isolation of sulfate reduction bacteria (SRB) to improve compress strength and water penetration of bio-concrete. *MATEC Web Conf.* 47, 01016. doi:10.1051/matecconf/20164701016

Al Omari, M. M. H., Rashid, I. S., Qinna, N. A., Jaber, A. M., and Badwan, A. A. (2016). Calcium carbonate. *Profiles of drug substances, excipients and related methodology* 41, 31–132. doi:10.1016/bs.podrm.2015.11.003

Amiri, A., and Bundur, Z. B. (2018). Use of corn-steep liquor as an alternative carbon source for biomineralization in cement-based materials and its impact on performance. *Constr. Build. Mater.* 165, 655–662. doi:10.1016/j.conbuildmat.2018.01.070

Bhaskar, S., Hossain, K. M. A., Lachemi, M., Wolfaardt, G., and Kroukamp, M. O. (2017). Effect of self-healing on strength and durability of zeolite-immobilized bacterial cementitious mortar composites. *Cem. Concr. Compos.* 82, 23–33. doi:10.1016/j.cemconcomp.2017.05.013

De Muynck, W., Debrouwer, D., De Belie, N., and Verstraete, W. (2008). Bacterial carbonate precipitation improves the durability of cementitious materials. *Cem. Concr. Res.* 38 (7), 1005–1014. doi:10.1016/j.cemconres.2008.03.005

Erşan, Y. Ç., Gruyaert, E., Louis, G., Lors, C., De Belie, N., and Boon, N. (2015). Self-protected nitrate reducing culture for intrinsic repair of concrete cracks. *Front. Microbiol.* 6, 1228. doi:10.3389/fmicb.2015.01228

Erşan, Y. Ç., Hernandez-Sanabria, E., Boon, N., and De Belie, N. (2016). Enhanced crack closure performance of microbial mortar through nitrate reduction. *Cem. Concr. Compos.* 70, 159–170. doi:10.1016/j.cemconcomp.2016.04.001

Ersan, Y. Ç. (2021). Self-healing performance of biogranule containing microbial self-healing concrete under intermittent wet/dry cycles. *Politeknik Derg.* 24 (1), 323–332. doi:10.2339/politeknik.742210

Erşan, Y. U. S., and Akin, Y. (2018). Optimizing nutrient content of microbial self-healing concrete. in 6th International Symposium on Life-Cycle Civil Engineering (IALCCE). Ghent, Belçika, 28-31 January 2019, 2241–2246.

Farrugia, C., Borg, R. P., Ferrara, L., and Buhagiar, J. (2019). The application of Lysinibacillus sphaericus for surface treatment and crack healing in mortar. *Front. Built Environ.* 5, 62. doi:10.3389/fbuil.2019.00062

Ghosh, P., Mandal, S., Chattopadhyay, B. D., and Pal, S. (2005). Use of microorganism to improve the strength of cement mortar. *Cem. Concr. Res.* 35 (10), 1980–1983. doi:10.1016/j.cemconres.2005.03.005

Hong, M., Jang, I., Son, Y., Yi, C., and Park, W. (2021). Agricultural by-products and oyster shell as alternative nutrient sources for microbial sealing of early age cracks in mortar. *Amb. Express* 11 (1), 11–15. doi:10.1186/s13568-020-01166-5

Irwan, J. M., Anneza, L. H., Othman, N., Alshalif, A. F., Zamer, M. M., and Teddy, T. (2016). Calcium lactate addition in bioconcrete: Effect on compressive strength and water penetration. *MATEC Web Conf.* 78, 01027. doi:10.1051/matecconf/20167801027

Jena, S., Basa, B., Panda, K. C., and Sahoo, N. K. (2020). Impact of Bacillus subtilis bacterium on the properties of concrete. *Mater. Today Proc.* 32, 651–656. doi:10.1016/j.matpr.2020.03.129

Joshi, S., Goyal, S., and Reddy, M. S. (2021). Bio-consolidation of cracks with fly ash amended biogrouting in concrete structures. *Constr. Build. Mater.* 300, 124044. doi:10.1016/j.conbuildmat.2021.124044

Khaliq, W., and Ehsan, M. B. (2016). Crack healing in concrete using various bio influenced self-healing techniques. *Constr. Build. Mater.* 102, 349–357. doi:10.1016/j.conbuildmat.2015.11.006

Li, M., Fu, Q., Zhang, Q., Achal, V., and Kawasaki, S. (2015). Bio-grout based on microbially induced sand solidification by means of asparaginase activity. *Sci. Rep.* 5, 16128. doi:10.1038/srep16128

Liu, Z., Chin, C. S., and Xia, J. (2022). Novel method for enhancing freeze-thaw resistance of recycled coarse aggregate concrete via two-stage introduction of denitrifying bacteria. *J. Clean. Prod.* 346, 131159. doi:10.1016/j.jclepro.2022.131159

Nosouhian, F., Mostofinejad, D., and Hasheminejad, H. (2015). Influence of biodeposition treatment on concrete durability in a sulphate environment. *Biosyst. Eng.* 133, 141–152. doi:10.1016/j.biosystemseng.2015.03.008

Qian, C., Zhou, H., and Wang, K. (2019). Factors affecting morphology of microbially induced calcium carbonate. *J. Microbiol. Exp.* 7 (2), 101–114. doi:10.15406/jmen.2019.07.00249

Siddique, R., Nanda, V., Kadri, E. H., Khan, M. I., Singh, M., Rajor, A., et al. (2016). Influence of bacteria on compressive strength and permeation properties of concrete made with cement baghouse filter dust. *Constr. Build. Mater.* 106, 461–469. doi:10.1016/j.conbuildmat.2015.12.112

Sidhu, N., Goyal, S., and Reddy, M. S. (2022). Biomineralization of cyanobacteria Synechocystis pevalekii improves the durability properties of cement mortar. *Amb. Express* 12 (1), 59–12. doi:10.1186/s13568-022-01403-z

Smitha, M. P., Suji, D., Shanthi, M., and Adesina, A. (2022). Application of bacterial biomass in biocementation process to enhance the mechanical and durability properties of concrete. *Clean. Mater.* 3, 100050. doi:10.1016/j.clema.2022.100050

Son, Y., Min, J., Jang, I., Yi, C., and Park, W. (2022). Development of a novel compressed tablet-based bacterial agent for self-healing cementitious material. *Cem. Concr. Compos.* 129, 104514. doi:10.1016/j.cemconcomp.2022.104514

Thiyagarajan, H., Maheswaran, S., Mapa, M., Krishnamoorthy, S., Balasubramanian, B., Murthy, A. R., et al. (2016). Investigation of Bacterial activity on Compressive Strength of cement mortar in different curing MediaSustained delivery of doxorubicin by porous CaCO3 and chitosan/alginate multilayers-coated CaCO3 microparticles. *J. Adv. Concr. Technol. surfaces A Physicochem. Eng. aspects* 353 (2-3), 132–139. doi:10.1016/j.colsurfa.2009.11.004

Wang, J., Van Tittelboom, K., De Belie, N., and Verstraete, W. (2012). Use of silica gel or polyurethane immobilized bacteria for self-healing concrete. *Constr. Build. Mater.* 26 (1), 532–540. doi:10.1016/j.conbuildmat.2011.06.054

Xiang, J., Qiu, J., Wang, Y., and Gu, X. (2022). Calcium acetate as calcium source used to biocement for improving performance and reducing ammonia emission. *J. Clean. Prod.* 348, 131286. doi:10.1016/j.jclepro.2022.131286

Xiao, X., Tan, A. C., Unluer, C., and Yang, E. H. (2022). Development of a functionally graded bacteria capsule for self-healing concrete. *Cem. Concr. Compos.* 136, 104863. doi:10.1016/j.cemconcomp.2022.104863

Zhang, J. L., Wu, R. S., Li, Y. M., Zhong, J. Y., Deng, X., Liu, B., et al. (2016). Screening of bacteria for self-healing of concrete cracks and optimization of the microbial calcium precipitation process. *Appl. Microbiol. Biotechnol.* 100 (15), 6661–6670. doi:10.1007/s00253-016-7382-2

Zhu, T., Lin, Y., Lu, X., and Dittrich, M. (2018). Assessment of cyanobacterial species for carbonate precipitation on mortar surface under different conditions. *Ecol. Eng.* 120, 154–163. doi:10.1016/j.ecoleng.2018.05.038