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Self-healing of concrete cracks by MICPS mechanism: An overview

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Abstract

Expected to its exquisite properties such as durability, easy availability, and convenience to cast, concrete will continue to be a significant infrastructure component. Concrete can tolerate the compressive forces, but it is prone to cracking due to tensile forces. Thus, the formation of a crack is a ubiquitous phenomenon in concrete, which grants different kinds of chemicals and water into the concrete structures and reduces the concrete's overall life. The possibility of cracking can increase with the curing of concrete due to the variation of humidity and temperature. Appropriate types of treatment and regular maintenance are required for repairing the cracks that develop in concrete, but it has been found that the cost needed for this is prohibitive. The use of bio concrete demonstrated very beneficially in the present scenario for the construction of durable structures. It proved to be advantageous for improving the properties of concrete and also for reducing the maintenance cost. This paper attempts to remediate the cracks and fissures in concrete by applying Microbiologically induced calcite precipitation (MICP), bacteria selection criteria, re-view of publications concerning such criteria, the crack healing efficiency, recommendations for areas of future study are also provided. A mathematical model was also introduced to research the stress-strain behaviour of bacteria, which was used to improve concrete strength to obtain the best performance. This method ensures not only enhancing the strength but also the durability of the structures. It is a process by which crack healing occurs through microbial activities, which appear to be eco-friendly After analysing several expert re-search papers, the paper concluded that the direct approach technique is the best method for applying bacteria, and that the compression and tensile strength of concrete improved with reduced water absorption, permeability, and reinforcement corrosion. The primary choice for researchers, the Bacillus bacterial community, meets the essential needs for concrete selection. A review of this technique has been discussed for the future to commence.

Keywords: MICP, mechanical strength, crack, bacteria, durability.

1. Introduction

Concrete is recyclable, and it is the most popular and universally used building material. It is durable, strong, locally available, versatile, and capable of resisting compressive load to a limit. When the load applied to concrete is more than the limit, it produces a concrete crack. (Dinesh et. al ,2017) Crack's formation in concrete is a widespread phenomenon, and it is acceptable if it remains within limits. (Jhonkers 2011) Crack formation in concrete also takes place during curing as heat is liberated. The reinforcement steel bar is used in concrete to transmit strength, and if the crack is present, it causes corrosion. (Ghodke et. al,2018) In practice, we can see properties like durability, permeability, and power of the concrete also decrease because of cracks in concrete. one of the solitary causes of structural failure is cracking. Water seeps through these cracks in winter and freezes. (Ghodke et. al, 2018) Thus, it also widens the gaps. It is always necessary to repair those cracks because the tiny minor cracks can lead to massive-sized shots and shorten the concrete's serviceability limit. Fixing problems can be complicated if damage occurs in places which is difficult to reach. For repairing the cracks in concrete several traditional repairing systems are introduced, but they are very costly and not naturally available.

Using such concrete, which has a self-healing mechanism, is one way to reduce costs while also increasing the structure's durability. It is a product that biologically produces limestone, which ultimately heals the cracks on the concrete's surface. (Bashir et. al, 2016) When a crack forms in concrete, moisture seeps through the cracks and awakens the bacterial spores to action. By producing limestone, it commences the process of healing. Inside the concrete, the spores can lie dormant for about 200 years. (Bashir et. al, 2016) The process is quite like how a fractured bone in the human body gets healed naturally. Epoxy treatments are currently used to repair the crack, but it is harmful to the environment and health.

Toxic fumes and gases evolved, which may cause severe skin problems and breathing issues. So, the use of biological techniques should be focused. (Bashir et. al,2016)] Microbiologically induced calcite precipitation (MICP) is the method that should be adopted to solve the cracking problem, which can improve concrete to get better longevity and is eco-friendly. (Soundharya et. al, 2014)

Self-healing concrete can be illustrated as concrete, which has the capability of repairing itself back to the original state. It is the green technology that embeds self-activating bacteria into concrete and fixes its cracks. The concept is happening over time, and it has been observed for about 20 years.

De Muynck et al. (2008) provide an excellent description of microbial carbonate precipitation in building materials. Microbially induced carbonate precipitation has been regarded as a promising technique for large engineering applications, according to De Belie (2010). In general, the applications are divided into four groups based on their ultimate goals:

- Consolidation and protection of concrete and stone surface layers
- Repair of defects and weaknesses cracks explicitly
- Enhancement of matrix properties
- Cementation or consolidation of loose particles, specifically soil and sands

Self-healing concrete can be used in the cement mortar. The addition of calcite-producing bacteria is a new method adopted globally to produce self-healing concrete and cement mortar. It increases the compressive strength and also durability. Scientists have already invented a technology that used bacteria to create durable and living building material that can heal their cracks. The conventional brick production method is also not eco-friendly; it leads to environmental pollution and wastage of bricks. Scientists believe this technology of brick production could be a valuable resource in extreme situations as the bricks made from this material can fix themselves after any natural disaster. Thus, they are working on bringing biology to the bricks. Merging self-healing technology into the road design process can transfer road construction by increasing the durability of roads. It also has the effect of decreasing the need for road repairs. Self-healing concrete is not currently used on an industrial scale. This innovative technology can reduce costs in the revelation of damage and the maintenance of concrete structures. It also can improve the persistence of systems. Many researchers are trying to reduce production costs by using different techniques. Hence, bacterial concrete can be efficient feedback on sustainability.

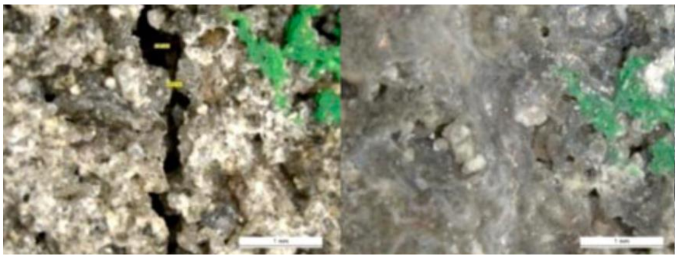

Fig. 1. Healing of a crack in mortar (average diameter 507 m) with B. sphaericus hydrogels; left: initial crack, applied at the mortar age of 28d; right: healed crack after four weeks incubation in wet–dry cycles of 1 h water submersion and 11 h at 60 percent RH (From Wang et. al 2014)).

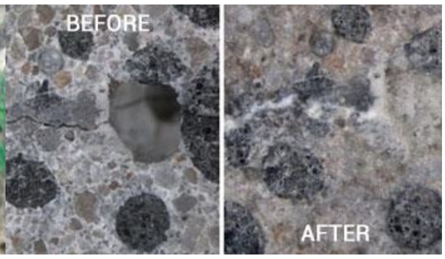

Fig. 2. Concrete before and after the healing process.

The passage of water into concrete is only possible when there are cracks in the hardened state or plastic state of concrete. After entering the concrete, the water dissolves the calcium present in the cement mortar or concrete. The basis behind the self-healing process is that the bacteria used should have the ability to convert soluble organic nutrients into insoluble inorganic calcite crystals, which will seal the cracks. (Soundharya et. al 2014) The microbial organisms used should possess long-term efficient crack sealing mechanisms throughout their lifetime serviceability. The bacteria and nutrients incorporated in concrete should not harm cement's purity and should not negatively affect the other essential raw and hardened concrete properties. (Soundharya et. al 2014) Cracks up to 0.2 mm are called micro-cracks in concrete, and these types of a crack in concrete are acceptable as they are healed autogenously, and they do not influence the safety and strength in concrete directly (Andalib, R., et at. 2016, Balam, N. H., et al. 2017) However, the bacteria-based self-healing process was found useful, and they can heal the cracks in concrete up to 0.5 mm (De Muynck, W., et al. 2010, Danish, A., et al. 2020). R. Spinks, in an article for *the Guardian*, comments on the exciting nature of this healing process: "It is only with the arrival of concrete's nemesis – rainwater or atmospheric moisture seeping into cracks – that the bacteria start to produce the limestone that eventually repairs the cracks." (Spinks, 2015)

Microbial concrete has been successful in all cases, such as sealing concrete cracks, repairing limestone monuments, durability in cementation materials, improvement in sand properties, highly durable bricks, etc. Not only this, but it also recommends building with more bearing capacity, prevention of erosion of loose sand, long-lasting river banks, repairing of monuments constructed in limestone. The production of greenhouse gases in conventional building materials is another problem that leads to global warming. This drawback can also overcome by using this eco-friendly and novel technology. In this research, a literature review of self-healing concrete is being produced, in which bacteria mediate the processing of minerals that quickly seal newly formed cracks. This process also reduces concrete permeability and thus better protects embedded steel reinforcement from corrosion. Crack-based failure is impacting a growing number of concrete buildings, causing the structure to deteriorate. The reliability of concrete buildings will be increased if this self-healing technique is used.

The research focuses on the different methods of application of Bacteria in concrete, selection criteria of bacteria for the purpose, performances of self-healing concrete, the Comparison of this technique with the traditional method, and how the use of bacteria as a self-healing agent will help concrete buildings last longer and be more sustainable. In the later part, the study will establish the best method of applying bacteria as the choice of application technique determines the cost of microbial concrete, which is higher than traditional concrete. Selection of suitable bacteria in concrete and future recommendations are also provided.

2. Literature review

Rajani V Akki, Sunil S K, Jitendra S, Dhananjay M1 (2009) have published a paper on the Compressive strength of bacterial concrete by varying E. Coli and JC3 bacteria Self-Healing Concrete. The paper was designed with two strains of bacteria called Escherichia coli and Bacillus Subtilis JC3. in nutrient broth, different standard samples were 400, 500 & 600 microlitres/liter. 15cm3 cubes of M20 grade concrete were cast by mixing grown bacterial cultures of different concentrations with cement paste and mortar.During 7, 14, and 28 days of curing , compression measuring machines were used to analyze these specimens of traditional and both bacterias at differing concentrations of 104, 105, 106, and 107. The compressive strength of M20 grade concrete was more at 28days. Compressive strength for Bacillus Subtilis JC3 increased significantly at the concentration of 10^5 cells/ml. E. Coli induced concrete at the concentration of 10^5cells/ml. It also showed better performance than conventional concrete. Compressive strength for Bacillus Subtilis JC3 was more than the compressive strength for E. Coli-induced concrete. Self-healing concrete can also be developed by using different concentrations of bacteria.

Jasira Bashir, IfrahKathwari, Aditya Tiwary and KhushpreetSingh2 (2016) have published a paper about Bio Concrete- The Self-Healing Concrete. In this paper, three different types of bacteria named Bacillus Subtilis, Bacillus sphaericus, and Bacillus pasteurii were taken, and a Comparison between compressive strength, split tensile strength, and flexural strength of bacterial concrete. Conventional concrete of M20 grade concrete was shown. The compressive, break tensile and flexural strength of M20 bio-concrete was higher than M20 traditional concrete. For bio-concrete using B. Subtilis, the percentage increase in compressive strength for seven days was 6.42% and for 28 days was 9.16% and split tensile strength for 7 days was 38.17%, .and for 28 days was 14.41% higher than conventional concrete. For bio-concrete using B. Sphaericus, the percentage increase in compressive strength for 7 days was 65.93% and for 28 days was 52.42% and split tensile strength for 7 days was 31.14%, .and for 28 days was 2.76% higher than conventional concrete. For bio-concrete using B. pasteurii, the percentage increase in compressive strength for 7 days was 29.99% and for 28 days was 29.97%, and flexural strength 7 days was 17.34% and for 28 days was 11.18% higher than conventional concrete. It reduces the chances of decaying cracks. Crack remediation using bio-concrete was better than epoxy treatments. (Achal, V., and Pan, X., 2014).

Senthil vel.M, Balamurugan.S, Navaneetha.B3, have published a paper on an Experimental study on self-healing concrete by using bacteria (Escherichia coli). In this paper, they've taken E. Coli bacteria cultured in nutrient broth. Cubes and cylinders of M30 grade concrete were cast by mixing grown bacterial cultures with cement paste and mortar. The value of the slump was 90 mm. The specimens were cured underwater at favorable temperatures for three days, 7days, 14 days, and 28 days in a water tank. A bacteria Viability Test was performed. A piece of bacterial cement mortar 365 days ago was inoculated in nutrients broth and kept in an orbital shaker for 24 hrs. After 24h incubation, a loop full of culture was taken from the broth and streaked on an agar plate. Once colonies were formed, their morphological characteristics and microscopic observations match with E. Coli. This confirms the presence of E. Coli even after 365 days in cement mortar. SHC appears to be much more efficient than usual concrete. It will transform concrete from an Eco-harming into an Eco-friendly material, as it reduces the CO2 emissions significantly (10ml to 40ml) than the conventional concrete. The traditional concrete was healing up to 40ml of E. Coli bacteria. However, more than 40 ml of the bacterial solution caused no healing for concrete. So, they preferred up to 40 ml of bacterial solution.

K. Keerthana, A. Ranjani, N. K. Amudhavalli4 (2016) have published a paper on a Comparative study on bacterial concrete using Bacillus Sphaericus and Escherichia Coli. The paper was designed with two strains of bacteria named Bacillus Sphaericus, and Escherichia Coli, which is cultured and tested in Biotech Laboratory, was used. 150mm3 cubes of M30 grade concrete (designed by using IS:10262-2009) were cast. Besides, Bacterial solutions were added at 250ml for 1 liter of water. B. sphaericus strains and E. Coli strains were added to the concrete mix at 103,106 &109 concentrations. Comparison between compressive strength, split tensile strength, and flexural strength of bacterial concrete and conventional concrete of M30 grade concrete was shown. They observed that the mechanical properties of B. Sphaericus are higher than the E. Coli. The compressive, split tensile, and flexure strength of bacterial concrete was more than the conventional concrete. The results revealed that at higher concentrations (109 cells/ml), the specimen gives more strength for both B. Sphaericus and E. Coli bacterial concrete. (De Belie, N., 2010)

H. M. Jonkers, (2011) have published a paper on Bacteria-based self-healing concrete using alkali-resistant spore-forming bacterium (Bacillus strain B2-E2-1). In this paper, a comparison between bacterial and control specimens has been made, which revealed a significant difference in permeability as well as in self-healing capacity. Test specimens (10 cm diameter, 1.5 cm thickness) were prepared by replacing 2-4 mm-sized class with similarly sized expanded clay particles (oven-dried) loaded with the biochemical self-healing agent. 50% lightweight aggregate was applied and cured for 56 days. By controlled application of compressive-tensile stress, crack formation in concrete specimen slabs was achieved. After crack formation, both sets (6 of each) of bacterial and control concrete specimens were submerged in tap water for 14 days at room temperature. Permeability of all cracked induced specimens (tap water percolation in 24 hours
period) was quantified by an automated recording. 4 out of 6 control specimens featured permeability (water percolation values between 0 and 2 ml/h). In contrast, all 6 bacterial specimens were utterly sealed and shown no measurable permeability (percolation of 0 ml water/h).

3. The chemical process to remediate cracks by bacteria

- To achieve the precipitation of calcite or carbonate, there are two pathways Ghodke et. al, 2018). They are:
  - Urea hydrolysis to form carbonate.
  - Using the carbon dioxide that bacterial respiration creates.
- Microbially induced calcium carbonate precipitation (MICCP) or microbiologically induced calcite precipitation (MICP) via urea hydrolysis is an easily controlled mechanism in which ureolytic bacteria produce high amounts carbonates in a short period. Due to simplicity, it is the most commonly studied process of precipitation is urea hydrolysis via the enzyme urease in calcium rich environment.

- In this mechanism, the degradation of urea is catalyzed by microbial urease enzyme into carbonate and ammonium. First, 1 mol of urea is hydrolyzed intracellularly to 1 mol of ammonia (Eq. (1)). Carbonate spontaneously hydrolyses to form 1mol of ammonia and carbonic acid (Eq. (2)) additionally.
- $CO(NH_2)_2 + H_2O \; NH_2COOH + NH_3$ (1)
- $NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$ (2)
- These products then form 1 mol bicarbonate, 2 mol ammonium, and 2 mol hydroxide ions. (Eq. (3)) and (4)).
- $H_2CO_3 \rightarrow HCO_3^- + H^-$ (3)
- $2NH_3 + 2H_2O \rightarrow 2NH_4^- + 2OH^-$ (4)
- The last two responses suggest an increase in PH, which shifts the bicarbonate equilibrium, resulting in carbonate ions (Eq. (5)).
- $HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \rightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O$ (5)
- Since the bacteria's cell wall is negatively charged, the bacteria draw cations from the environment, including Ca^{2+}, to deposit on their cell surface. The Ca^{2+}-ions subsequently react with the CO_3^{2-}-ions, causing $CaCO_3$ to precipitate at the cell surface, which acts as a nucleation site (Eqs. (6) and Eqs. (7))
- $Ca^{2+} + Cell \rightarrow Cell – Ca^{2+}$ (6)
- $Cell – Ca^{2+} + CO_3^{2-} \rightarrow Cell – CaCO_3 \downarrow$ (7)
- The second path involves using the carbon dioxide released by the bacterium's respiration. Calcium rich and high PH environments are required for the process. The extremely alkaline atmosphere needs to have a high level of hydroxide ions that are responsible for preserving the spontaneity of the reactions. The second route equation is as follows (Karthik et. al, 2016)–
- $CO_2(g) \leftrightarrow CO_2(aq)$
- $CO_2(aq) + H_2O \leftrightarrow H_2CO_3$
- $H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H_3O^+$
- $HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$
- $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$
- As described before, the nutrient rich bacteria made available to the bacteria within the concrete is calcium lactate. The method involves the metabolic conversion of calcium lactate by bacteria to create calcium carbonate. The first equation for limestone formation is as follows (Karthik et. al, 2016)–
- $Ca(C_3H_4O_3)_2 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$
- With the portlandite ($Ca(OH)_2$) present in the cement, the CO_2 resulting from the bacterial respiration will react, creating even more limestone. The second equation for limestone formation is as follows (Karthik et. al, 2016):
- $5CO_2 + 5Ca(OH)_2 \rightarrow 5CaCO_3 + 5H_2O$
- Therefore, it is very clear from the above equations that 1 mole of calcium carbonate can produce 1 mole of calcium carbonate and that the reaction of 5 moles of carbon dioxide with 5 moles of portlandite ($Ca(OH)_2$) results in another 5 moles of calcium carbonate. Through this process, which is efficient enough to seal the cracks in the concrete, it is obvious that large quantities of limestone can be extracted.

4. Classification and selection of bacteria

4.1 Classification of bacteria

Bacteria is a single-celled living microorganism that can be found everywhere. Sometimes they are beneficial, but sometimes they can be harmful when they cause infection. Care should be taken when dealing with bacteria. Based on their shape, gram strain, and oxygen demand, bacteria can be classified as below in the Table 1.

Early researchers used Shewanella species-related bacteria that precipitate calcite and can live in concrete's intense alkaline environment. (Achal et. al, 2011) This type of non-spore-forming bacterium can only live inside the concrete for up to 6-7 days, probably due to the clogging of pores in the concrete matrix and the precipitation of calcite that prevents nutrient flow to the bacterial cells. (Espitia-Nery, M. E., et al. 2019) This short lifespan limits its applicability for an extended time as a trustworthy self-healing agent. It is also pathogenic (Schlangen et. al, 2010) so their direct use in concrete structures is not feasible. Subsequently, some calcite precipitating, alkaline, ureolytic bacteria of *Bacillus* group have been employed by researchers such as *Bacillus pasteurii, Bacillus sphaericus*, *Bacillus cereus*, *Bacillus magaterium*, etc. (Espitia-Nery, M. E., et al. 2019, Kim, H. K., et al. 2013, Keerthana, K., 2016, Luhar, S., and Gourav, S., 2015, Mors, R., and Jonkers, H. M., 2019) Studies have shown that these bacteria that form thick membrane spores can Survive without nutrients for hundreds of years, dormant endospores can withstand to environmental chemicals, high mechanical stresses as well as ultraviolet radiations (Gupta, S., et al. 2017). However, urea's processing produces a large number of CO_2 during the ureolytic phase, and the subsequent urea hydrolysis creates ammonia, which has a pungent smell. These disadvantages prompted researchers to examine precipitating nonureolytic calcite bacteria, which are alkali-resistant. Later, the application in the concrete of aerobic alkaliphilic spore, namely *Bacillus pseudofirmus* and *Bacillus cohnii* with calcium lactate, the metabolic conversion of which lead to the precipitation of caco3 were examined by Jonkers et al. (2010). Wiktor and Jonkers (2011) showed that this form of healing agent might act as an oxygen diffusion barrier that can protect steel reinforcement against corrosion because of the oxygen consumption by aerobic bacteria during the metabolic conversion of calcium lactate. (Maheswaran et. al, 2014).

Table1
Classification of bacteria

Based on shape	Based on gram strain	Based on oxygen demand
Bacilli	Gram-Positive	Aerobic
Cocci	Gram-Negative	Anaerobic
Spirilla		

Many researchers have used many ways of bacteria in concrete. As concrete is intensely alkaline, the concrete's bacteria should fit in some criterion. The bacteria must meet two central norms. They are:

- Capability to withstand a highly alkaline environment: It requires a capable of withstanding a highly alkaline environment (PH~12.8) of the concrete as concrete is a dry material and the PH value of cement and water mixed up is up to 13. Most of the organisms cannot survive in the environment when the PH value reaches higher than 10. (Wiktor et. al, 2016).
- Spore germination's capability: The spore germination of the bacteria must have to continue in the concrete's harsh environmental condition. (Wiktor et. al, 2016).

Therefore, it is observed that the right option will be bacteria of Bacillus species that are prevalent bacteria easily accessible from the soil to meet the requirements of calcite precipitation, survival in the alkaline environment, and pathogenicity.

The spores are of very thick wall, and they activated when cracks start occurring in concrete, and they can survive in the high alkaline environment. (Soundharya et. al, 2014). There are many bacteria other than bacillus also which can survive in a high alkaline environment and can be used in concrete are given in Table 2.

4.2 Selection of self-healing techniques

Danish and Mosaberpanah (2020) reported that, particular localities and structural environments dictate various methods of self-healing to be used as seen in Table 3. Admixture, bacterial and autogenous self-healing need to be done in the cracks for healing, which makes it better suited for structural procedures under water. (Erşan et. al, 2015) For under water structures, self-healing is not suggested because of the adhesive agent being released into crack and hardened by the water that happens in cracking. In particular, all healing methods are applicable for underground structures, but when the water table is high then the self-healing is not advised because of the adhesive agent. (Erşan et. al, 2015) Cracks are often undergoing wet/dry cycles in the underground system, which causes CO_2 to be precipitated to crack and makes the conditions for bacterial and independent self-healing relevant. Since most structures have a poor eligibility or water quality open air structure, it is very difficult to apply bacterial admixtures or self-healing.

Table 2
Various types of bacteria other than bacillus used in concrete and their application

Sl. No.	Application	Types of bacteria
1.	As a crack healer	B. pasteurii Deleya Halophila Halomonasrurihalina Myxococcus Xanthus B. megaterium
2.	For surface treatment	B. sphaericus
3.	B. spharicus	Bacilllussubitilis B. sphaericus Thiobacillus

Table 3
Different structure and environment self-healing procedure (Erşan et. al, 2015)

Sl. No.	Self-healing techniques	structure environment			
		Under ground	Under water	Open air	Indoor elements
1.	Self-healing due to adhesive agent	Recommended but in absence of water	Hardly recommended	Recommended	Recommended
2.	Bacterial self-healing	Recommended	Recommended	Recommended with water requirement	Hardly recommended
3.	Autogenous self-healing	Recommended	Recommended	Recommended with water requirement	Hardly recommended
4.	self-healing due to admixtures	Recommended	Recommended	Recommended with water requirement	Hardly recommended

5. Methods of application of bacteria in concrete

The following is a description of the various methods used by researchers for adding bacteria to concrete and mortar. In comparison with traditional concrete, the costs of microbial concrete are primarily controlled by the preference of methodology of application.

5.1 Direct method

The simplest and cheapest concrete way of applying bacteria in the direct method. This is achieved by combining the bacteria and nutrients with water and then preparing concrete/mortar. The same can be added along with bacteria if an external calcium source is used. (Jonkers et. al, 2010) The direct approach is ideal for the creation of spores and bacteria according to the requirement. Bacteria concentration can be regulated. Their presence will retard the setting cycle of the concrete/mortar because the nutrients and bacteria are organic matter. (De Muynck et. al, 2008) The direct method of application and microscopic picture of the rod-shaped bacteria were used by De Muynck et al. (2008b) in precipitated calcium carbonate are shown in the Figure 3(a).

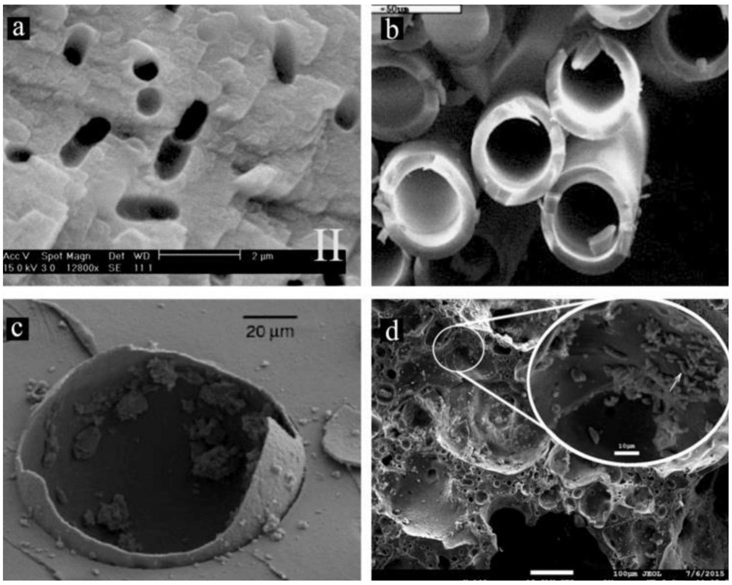

Fig. 3. SEM illustrations of (a) rod-shaped bacteria in the direct method (Johannesson et. al, 2012) (b) hollow glass fibers (Erşan et. al, 2016) (c) ruptured microcapsule (Erşan et. al, 2016) (d) bacteria in the pores of the protective material (expanded clay) (Seifan et. al, 2016).

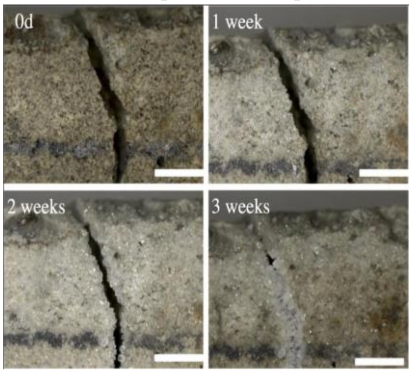

Fig. 4. Phase of crack healing with respect to time (Wang et al. 2014).

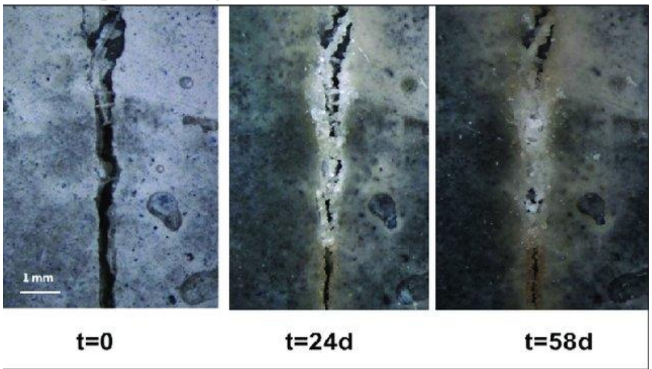

Fig. 5. Self-healing of a 0.8 mm wide crack in concrete (Jonkers et al. 2019).

5.2 *Vascular network method process*

By means of a vascular network structure similar to that in the human bone, bacteria can be added to the concrete matrix. This bone-like structure has two layers: a spongy inner and a compact outer layer (Figure 3b). (Dry, 1994. Dry (1994) suggests this method of application in which the vacuum pump was connected to one end of the network and the other end was linked to the healing agent. (Mondal et. al, 202018) In the inner layer, the bacteria are injected with adequate nutrients. During the concrete preparation, this vascular network is incorporated. The nutrients and bacteria travel to the crack location at the crack forming point, and due to the pressure gradient, the network splits. The latter was supplied into the concrete by pumping as needed. This approach, however, is both expensive and impractical, given that it would be complicated to disperse vessels equally. When casting, the vessels can collapse, and this system may affect the bond between concrete composites. (Espitia-Nery et. al, 2019).

5.3 Encapsulation method

Research indicates that adding bacteria and nutrients to the concrete matrix improves their mechanical properties, but the bacterial survival ranged from 1.9% to 7% after 10 days of healing due to a high pH (between 12 and 13) and a dried concrete state. For this reason, encapsulation is necessary to prevent environmentally friendly bacteria (Figure 3C). Different bacterial encapsulation methods have studied the content, size, distribution, and volume of capsules added into the material matrix. Capsules can improve bacterial survival and be robust enough to endure the concrete mixing process and sufficiently fragile to break up when cracks occur. To save the mechanical properties of cement from deteriorating, capsules must be able to form a tight bond with the matrix. (Wang et. al, 2104) The polyurethane and silica gel bacteria were immobilized inside the glass tube of 40 mm and 30 mm inner diameter by Wang et al. (2012). During sample preparation, it is the principal challenge of this glass encapsulation to crack capsules and ensure that the glass is not chemically bondable with concrete. To render the external layer connectable, it is possible to use concrete, reactive functional groups like epoxy group, glycidyl group, alkynyl group, etc. (Tittelboom et. al, 2010). Besides, Wang et al. (2014b) used a melamine-based microcapsule to prevent the problem with capsule breakdown at the time of concrete preparation as it can withstand the mechanical forces during preparation (see Figure 1c). The best performing bacterial encapsulation methods measured by fissure repair efficiency are microencapsulation based on melanin, followed by expanded clay coated with a geopolymer layer consisting of metakaolin and sodium silicate solution, producing maximum repair widths of 0.96 mm and 0.79 mm, respectively. Espitia-Nery et el. (2019) concluded that Melanin-based microencapsulation, accompanied by expanded clay, covered with geopolymer layer of metakaolin and sodium silicate solution, with a repair width of 0.96 et mm and 0,79 mm, respectively, were the best performing bacterial encapsulation methods measured with the efficiency of crack repair. (Jonkers et. al, 2015).

5.4 Protection method

This method includes the bacteria and protective products such as expanded clay, diatomaceous earth, granular carbon activated, zeolite, air supplies, cyclic enriched Ureolytic powder, compact denitrification core, etc. (Figure 4d). (Jonkers et. al, 2015). This method includes bacteria in concrete/mortar. (Figure 1d). The fundamental idea behind the method is the impregnation of bacteria between the protective pores. However, the properties and homogeneity of concrete may get affected by the use of protected materials. Also, it requires the cost of protection materials though this method is less costly than encapsulation one. (Espitia-Nery et el. ,2019)

6. Crack healing efficiency in microbial concrete

Figure 4 shows real imagery with a different interval of the crack-healing process, which shows a gradual reduction of crack-width with the time (0-day,1 week, 2 weeks, etc.) reported by Wang et al. (2014). The crack had nearly fully healed by 3 weeks. Cracks up to 1mm width can be independently screened, depending on the dose of bacteria and lactate-based nutrients. Jonkers et al. (2019) The autonomous waterproofing of 0.4mm large cracks is sufficient for a dose of 15kg/m3 of the auto-healing agent per m3 of the concrete mix (Figure 5). Ghosh et. al, 2009) External sources of calcium such as calcium chloride are also employed to increase microbial concrete's crack healing ability. (Espitia-Nery et. al, 2019). The presence of chloride may, however, accelerate the corrosion of the steel reinforcement. Calcium nitrate, calcium lactate, calcium glutamate, etc., have been used as alternatives to calcium chloride to prevent this.

Table 4
Impact of bacteria on crack healing properties of concrete/mortar/brick

Name of Bacterial agent	Concentration of bacterial additive	Composition of building material	Crack repair of building properties	Source link
Bacillus sphaericus	50 ml of an overnight grown culture was centrifuged during 5 minutes at 4 degree Celsius and 7000 rpm.	Cement-concrete mixture (sand – 670 kg/m^{3,} aggregates 2/8- 490 kg/m^3, aggregates 8/16- 790 kg/ m^3, CEM I 52.5 N – 300 kg/ m^3, water- 150 kg/ m^3)	TGA analysis on crack repair material showed the presence of caco$_3$ crystals only in case of active bacteria, precipitation of which may enhance the durability of the repair material.	(Velumani et.al)
Escherichia coli	10 ml	Ordinary Portland cement (53grade)- 502.7 kg/m^3 +fine aggregate- 482.32 kg/m^3 + coarse aggregate- 1172.67 Kg/m^3 + water- 186 Lit/m^3	It greatly decreases CO2 emissions (10ml to 40ml) relative to traditional concrete. The healing of traditional concrete is Up to 40 ml of E-coli bacteria, but more than 40 ml of E-coli bacterial solution is used, not repairing concrete. Up to 40 ml of bacterial solution is therefore preferred.	(Rosy et. al.)
Escherichia coli	5%,10% and 15% by mass	Portland Pozzolona cement (30 grade) -1.8 kg + Fine aggregate - 3.05 kg + coarse aggregate – 4.75 kg + water- 750 ml)	The cracks are repaired by bacteria by producing calcium carbonate that blocks and fixes the cracks. It was also discovered that that there was a maximum improvement in both compressive and tensile strength while the curing period was 7 days.	(Nirala et. al.,2019)
B*acillus subtilis*	(Optical Density) OD 1 at 600 nm (approximately 8x108 cells/ml)	Ordinary Portland cement of 43 grade concrete mix design (water: 195 kg; cement: 433.33 kg; sand: 595.7 kg and coarse aggregate: 1097.5 kg per cum of concrete), keeping a constant water/cement ratio of 0.45.	The healing process can be noticeable and complete after 7-14 days. It took more than one month to repair the hairline shrinkage cracks (limited to 1 mm).	(Sumathi et. al, 2020)
Bacillus cohnii	105 cells/mL	Cement- concrete mixture (cement- 438 kg/m^3 + FA- 710 kg/m^3 + CA – 1110 kg/m^3 + water- 21 kg/m^3)	In the Full Wet and Wet Dry pre-cracked specimens, about 90 percent and 88 percent of surface healing was noted at 28 days. Bacterial activity that plays a crack healing role has resulted in the agglomeration of calcium carbonate in the concrete micro structure.	(Balam et. al,2017)

Table 4 (Cont.)
Impact of bacteria on crack healing properties of concrete/mortar/brick

Name of Bacterial agent	Concentration of bacterial additive	Composition of building material	Crack repair of building properties	Source link
Sporosarcina pasteurii Bacillus subtilis	different cell concentrations (106, 107, 108 cells.ml^{-1})	Cement + sand+ water + aggregate	The deposition of bacterial carbonate calcite led to a reduction of around 20-30 percent of water absorption depending on the type and size of aggregate. The findings indicated that bacterial cell wall of S. pasteurii decreased water absorption and porosity more than B. subtilis.	(Neeladharan et. al)
Bacillus Subtilis	10 ml, 20 ml &30 ml	Ordinary Portland Cement 53 grade (Minimum cement content- 320 kg/m^3, maximum cement content- 450kg/m^3, water-cement ratio- .50, crushed angular aggregate of maximum 20 mm size)	It is recommended to use both the 10ml bacterial concrete form and the standard specimen cured in bacterial solution. It is also advisable to use bacterial concrete grade M25 instead of standard concrete M30. The healing property of concrete is also accomplished, because it is also used in repair methods.	(Vahabi et. al, 2015)
Bacillus licheniformis AK01	Filter- sterilized urea and $CaCl_2.2H_2O$ added into the nutrient medium. Samples were spread on NBU agar with sample dilutions ranging from 10^{-1} 10^{-6} and incubated at 37 °C for one week.	ASTM-Type 1-425 Portland cement	Because of the precipitation of calcite crystals in the pores of mortar specimens, it could increase compressive strength and minimize capillary water absorption by up to 15 and 25 percent respectively.	(Gandhimathi et. al, 2015)
Bacillus sphaericus	30mL of bacteria/mortar cube and sequentially increased up to 50mL (10, 20, 30, 40 and 50mL)	Cement + sand + aggregate + water (RO quality) M25 concrete is prepared as IS code	The fractures have grown over time. When compared to conventional concrete, this is a much better option. The bacterial filling of the small pores present in concrete was the species that increases the concrete's longevity.	(Chahal et. al, 2012)
Sporoscarcina pasteurii	105 cells/ml	Ordinary Portland cement + FA (natural sand with nominal size 12.5 mm) + CA (12.5 mm nominal size) + fly ash + water.	S. Pasteurii induces a four-times reduction in the water absorption. (26%). Increased longevity of concrete buildings. Bacterial calcite deposition observed a reduction of nearly eight times in permeability to chloride, thus the life of concrete can be increased.	(Xu et. al, 2014)

Table 4 (Cont.)
Impact of bacteria on crack healing properties of concrete/mortar/brick

Name of Bacterial agent	Concentration of bacterial additive	Composition of building material	Crack repair of building properties	Source link
Bacillus sphaericus	3 g/L	Ordinary Portland cement (CEM I 52.5), water–cement ratios (w/c) of 0.5, concrete mixture had the following composition (per m^3): 300 kg cement, 670 kg sand 0/5, 1280 kg gravel 8/16, 150 kg water (w/c 0.5).	In contrast to the use of mixed ureolytic cultures as a paste, pure cultures resulted in a more pronounced decrease in water absorption and a less pronounced shift in the chromatic component.	(De Muynck et. al, 2008)

Xu et al. (2014) correlated calcium glutamate efficacy with calcium lactate and found a higher degree of calcium glutamate precipitation by Bacillus cohnii. Pacheco-Torgal Achal (2013) and Pan (2014) compared the Bacillus species CR2 efficiency of various calcium sources such as calcium nitrate, calcium oxide, calcium acetate, and calcium chloride in calcite precipitation and confirmed that calcium chloride had obtained the optimum precipitation. (Reddy et. al, 2013).

7. Performance of self-healing concrete

Compressive strength and durability are the essential qualities of concrete. It is crucial to determine the effect of biomineralization on these attributes. Crack, pore size, and distribution have detrimental effects on concrete properties and concrete structures' service life. By reducing absorption, permeability, and diffusion as the critical mechanisms for transporting concrete, concrete durability can be increased. (Benhelal et. al 2013) Several studies have documented the effect of bio-based healing agents on the permeability and water absorption of concrete. Cracks in concrete structures can be reduced by bacteria's presence, as seen from the table. One of the most fundamental criteria for characterizing the long-term performance of concrete is water permeability resistance. The table shows that microbial concrete reduces water permeability and absorption significantly. De Muynck et al. (2008b) recorded a 65 percent reduction in water absorption by Bacillus sphaericus in mortar specimens. (Wu., M., et al. 2012) The decrease in water absorption by Sporoscarcina pasteurii due to precipitation was also demonstrated by Achal et al. (2011). From the sorptivity measure, the cubes treated with Bacillus species CT-5 were found to absorb almost six times less water than control specimens (Achal et. al 2011). Due to efficient bonding efficiency, compatibility with complex compositions, and sustainability, the bio self-healing approach's implementation commends itself over conventional treatment methods. It can fill deep microcracks as well as limit the growth of cracks. (Wiktor et. al,2011) Also, it decreases carbon dioxide emissions due to the reduction in cement production, which can minimize inspection work and maintenance costs. (Johannesson et. al 2012 and Achal et. al 2014) The other benefits of this technique are structural porosity, watertight concrete, strong compatibility between precipitated calcium carbonate and concrete formulations, and favorable thermal expansion. self-healing treatment offers cleaner, more sustainable, longer-standing, and more cost-effective building materials, and Bacterial effects on the crack-healing properties of concrete, mortar, and brick are provided in Table 4.

8. Stress-strain behavior of concrete

Concrete's stress-strain curve is a graphical representation of the material's actions under load. It is generated at different intervals of concrete compressive loading by plotting concrete compress pressure (stress). Toughness is measured by the stress-strain behavior of concrete. The test was carried out on the cylindrical specimen prepared in a 3000 KN capacity universal testing machine and the following data was obtained as shown in the Table 5.

Table 5
The stress-strain activity of bacterial concrete of grade M60 in contrast to controlled concrete (D. Belie et. al, 2010)

Controlled concrete		Bacterial concrete	
Strain	Stress (MPa)	Strain	Stress (MPa)
0	0	0	0
0.0001	3.27	0.0001	2.83
0.0002	6.41	0.0001	5.66
0.0003	9.01	0.0002	8.49
0.0004	12.98	0.0003	11.32
0.0005	15.32	0.0003	14.15
0.0006	18.65	0.0004	16.99
0.0007	21.10	0.0004	19.82
0.0008	24.55	0.0005	23.20
0.0009	28.56	0.0006	25.70
0.0010	36.00	0.0007	31.00
0.0011	38.80	0.0008	34.60
0.0012	42.30	0.0010	40.00
0.0014	47.60	0.0011	46.70
0.0016	61.00	0.0012	54.90
0.0023	72.61	0.0014	61.00
0.0027	65.70	0.0015	82.40
0.0033	36.80	0.0023	94.21
0.0034	30.30	0.0033	51.00
0.0035	29.15	0.0035	36.08

It was noticed in the mathematical model that the bacterial concrete shows a better stress and strain value compared to controlled concrete for the high concrete strength grade. (D. Belie et. al, 2010)

9. Comparison between traditional concrete and self-healing concrete

Research is still ongoing regarding self-healing concrete. Researchers are attempting different steps to ensure the closing of cracks with less interruption while keeping the cost at an acceptable rate. Self-healing concrete is much more potent than traditional concrete; a comparison of which is given below in Table 6.

10. Sustainability and economic aid of microbial concrete

According to estimates, the reconstruction and refurbishment of existing buildings such as bridges, tunnels, and retaining walls consume more than half of Europe's total construction budget, amounting to around €4 to €6 billion (Matthew n.d.).

The use of microbial concrete will reduce the cost of maintenance. Using microbial concrete will reduce this maintenance expense. The cost of manufacturing conventional concrete is currently around €80 per cubic meter, while the cost of producing microbial concrete is currently around €85 to €100 per cubic meter. The maximum rise of approximately 25% in the cost of production of the structure due to the use of microbial concrete is compensated by a reduction in the cost of maintenance, which, even if believed to be 10%, will lead to a net saving of 15% in the total cost of maintenance of approximately EUR 0.6 to EUR 0.9 billion. (Espitia-Nery et. al, 2019).

Table 6
Comparison between traditional concrete and self-healing concrete (Source: Karthik et. al 2016)

Sl No.	Properties	Traditional concrete	Self-healing concrete
1.	Cost	more	Initial cost can be higher but on the long term this is much more cost efficient due to low cost of maintenance.
2.	Durability	Less	Denser and more durable than conventional concrete.
3.	Availability	Available on large scale	On a small scale, it is still used. And still not commercially wide-spread.
4.	Safety	Less	General safety of an individual construction increases.
5.	Maintenance cost	More	Almost no maintenance cost needed.
6.	Resistance towards freeze and thaw	Less	Better
7.	Permeability	Expands	Reduces

Almost 5% to 7% of global CO2 emissions are currently from the cement industry, and, in addition, the global CO2 emissions rate suggests a growing trend that poses a significant environmental threat. (Wang et. al, 2014) This emission rate can be minimized by using microbial concrete, which decreases cement consumption for maintenance purposes and the replacement of the structure. These benefits place microbial concrete as a cost-effective and long-term solution, especially in emerging economies where infrastructure growth is rapid. Besides, to boost the new properties and mechanical properties of concrete, bacterial cells may also be added directly within the concrete matrix. Biogenic CaCO3 has distinct advantages over traditional concrete maintenance materials regarding environmental friendliness and excellent compatibility with the concrete matrix.

11. Recognitions of self-healing concrete

Quick and easy crack remediation Concrete specimens, when supplied with bacteria, nutrients, and sand, increase stiffness value and compressive strength related to those without cells.

- Improvement in compressive strength of concrete: Test results of compressive strengths are required to confirm whether the concrete mixture delivered fulfills the job specification requirement or not. So, the application of bacteria upgrades microbial concrete's effects on the compressive strength of concrete and mortar.
- Better resistance towards freeze and thaw attack: Due to the bacterial chemical process, microbial calcite application on concrete may resist freeze and thaw attack. The freezing process is decreased as it also reduces permeability.
- Reduction in corrosion of reinforcement: The application of calcite seals the path through which chemicals and water can enter the concrete. Thus, it reduces the corrosion of reinforcement and improves the life of concrete structures.
- Reduction in the permeability of concrete: Many researchers have investigated the influence of bacteria to reduce permeation. Carbonate-producing bacteria helps in this regard a lot. The carbonation test can analyze permeability. Carbonation is associated with the pore's connectivity, where larger pores give rise to higher carbonation depths. Microbial calcite precipitation is mainly due to urea lytic activity and carbonate biomineralization of bacteria.
- Reduction of maintenance and repair cost: Cementitious materials like fly ash, silica fume, ground granulated blast furnace slag (GGBS) can be used as a partial substitute for cement as a replacement of a portion of cement inside the concrete, which has proven the

enhancement of durability of concrete up to a certain extent. Nevertheless, these materials are very costly and not available. In this sense, bacterial concrete is comparatively cheap, and also its maintenance is low.

This concept is pollution-free, natural, and eco-friendly. Through this process, aesthetic appearance is not harmed. It is a revolutionary concept promising a better future for concrete, showing extra strength and durability to the structures.

12. Drawbacks of self-healing concrete

- Cost of bacterial concrete: The initial cost of bacterial concrete is higher. It can be double that of conventional one or 7-28% more. But the cost can be reduced by the growth of technique.
- Growth of bacteria is not profitable: Various types of nutrients and metabolic products are used for expanding calcifying microorganisms because they affect growth, survival, and crystal formation. The development of bacteria is not acceptable in any media and atmosphere. Extensive work should be done on the retention of nutrients and metabolic products.
- The higher cost of the investigation process: The production amount of calcite precipitation is different for different types of bacteria. To investigate this, a method called "scanning by electron microscopy" is very costly. This also requires good skills to carry out this test.
- IS codes are not available: It is problematic to consider the doses of measure the doses of bacteria to be used in concrete to get satisfying performance as this research material is new, and no code is available.

The concrete we have now cannot be used to construct sky-crappers, but one can overcome this problem further.

13. Current problems in the self-healing concrete study

The experimental studies on the self-healing of concrete cracks by researchers of home and abroad have successfully promoted substantial intelligent development. However, most of these self-repairing methods are only performed in the laboratory environment. So, it is challenging to apply them to real projects. Combined with various papers, the self-repairing properties of almost all bio-concrete have specific requirements on the width, and only small cracks can self-heal.

There are many studies on the performance of bio-concrete. Most of the research is concentrated in the field of materials. Though it uses its catalytic healing agent that catalyzes the healing of concrete base materials, the change of mechanical properties such as elastic modulus after crack heal is still unclear.

No unified assessment method for the self-repairing effect of concrete has been established. For example, healing speed, set the fracture healing rate, mechanical properties after healing, multiple healing ability, and other indicators. If there is no such evaluation method, it is impossible to judge the self-healing effect's quality. As a result, the everyday use of the structure cannot be guaranteed, and the bio-concrete also loses its application value.

14. Conclusions

- The paper illustrates the application of bacteria in concrete. It is established that the compression and tensile strength of concrete increased with decreased water absorption, permeability, and corrosion of reinforcement.

- The Bacillus group of bacteria, which has been the primary preference for researchers, meets the critical requirements for selecting bacteria in concrete, namely calcite precipitation, survival in an alkaline environment, and non-pathogenicity.
- The direct approach is the most cost-effective, realistic, and simple to implement of the various bacteria application methods in microbial concrete. It has also resulted in the most significant change in concrete's mechanical properties. However, the encapsulated approach tends to be the most promising in terms of long-term viability. Micro-crack healing in microbial concrete tends to strengthen many of the concrete's mechanical properties. The use of Bacillus pasteurii has been reported to increase compressive strength by up to 60%.
- *Bacterial concrete* is an influential concrete that exhibits human-like self-healing properties and increases structure strength, especially when it is under tension.
- Bacterial concrete is more beneficial than traditional concrete because of its eco-friendly nature and enhancing other building materials' durability.
- The chances of corrosion of reinforcement minimize the leakage proofing, reducing the cost of epoxy coating.
- Calcium carbonate precipitation also increases when (cacO3) with the increase of bacterial concentration.
- The sustainability of self-healing concrete is more.
- Bacterial concrete is also called a "small biomaterial" due to its ability to precipitate calcite continuously.
- Both economically and practically, bacterial concrete will be more efficient as it is convenient to use, and it needs skilled laborers.
- Bacterial concrete will soon emerge in the construction of a cost-effective, durable, and environment-friendly high-quality building.
- The study finally concludes that self-healing concrete will be economical and advanced than any other conventional concrete over the long-life span of any megastructure.

15. Recommendations

- Manufacturing of self-healing bacteria in extensive quantity should be focused on in future studies.
- Future studies should also focus on this mechanism's outcome on corrosion because of the accomplished usage of reinforced concrete for infrastructural construction.
- It is worth noting that the most significant results obtained for microbial concrete in terms of crack healing and property enhancement have only been short-term. The long-term durability of microbial concrete must be tested in order for it to become a viable technology.
- It is highly recommending that the use of biotechnology in self-healing should be done with appropriate precautions. Appropriate technology should be used, considering its effect on durability.

Apart from the scientific aspect, the word "bacteria" has a psychological influence on people because it is widely believed to be pathogenic. Making microbial concrete suitable for industrial applications is thus a difficult challenge, and proper education on microbes' pathogenicity should be given to the construction community.

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