Bacterial Concrete for the Development of Sustainable Construction—A Review

S. Jena, B. Basa, and K. C. Panda

Abstract Concrete which is vastly utilized in building materials has its own disadvantages, one being the phenomenon of crack formation which allows the passage of water, CO_2 and other chemicals into the concrete. The incoming materials cause decrement in strength along with durability and ductility. These materials also have adverse effects on reinforcements. If the cracks are not healed as soon as they are formed, they might expand and become larger allowing passage of more amount of materials causing greater problems. That's why the best solution is to prevent the formation of cracks from the very beginning. Self-healing concrete provides one such solution. In self-healing concrete, the concrete material is capable of healing the cracks formed beforehand, on its own. Microbial actions help in this. The basic principle of self-healing concrete is the formation of calcium carbonate precipitate by bacterial action. This introduction of bacterial concrete paves the way to the production of more durable, sustainable, crack-free and more efficient concrete. The usage of bacteria in concrete justifies its name, microbial concrete or biological concrete (in short bio concrete). The bio concrete causes less pollution and is economic as well. This paper aims at defining bacterial concrete and its effects on concrete properties and describing its merits and few demerits.

Keywords Concrete · Strength · Durability · Self-healing · Bacteria

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K. K. Pathak et al. (eds.), *Recent Trends in Civil Engineering*, Lecture Notes in Civil Engineering 77, https://doi.org/10.1007/978-981-15-5195-6_46

1 Introduction

In the recent era, concrete is the most utilized infrastructural material. As the ingredients for concrete are commonly available, it is easy to use it as a building material. Concrete is economically advantageous, can be equipped into the required shape and can withstand high temperature. Although the compressive strength of concrete is high, it has many drawbacks like it has low crack resistance, less tensile strength and less ductility. Fierce environmental factors along with consistent sustained pressure result in declination of self-life of concrete. While designing a concrete structure, strength and durability must be kept in mind. A major problem in concrete is the crack formation on its surface, which is due to the low tensile strength of concrete [1, 2]. Cracks in concrete lead to the reduction of strength and durability and make concrete sensitive to the deleterious environment [3]. Also cracks pave way to chloride attack, carbonate attack and sulphate attack, as a result of which corrosion of steel reinforcement and deterioration of concrete take place. The formation of crack is generally intercepted by manual examination and repairs by using synthetic fillers or cement [4]. But these repairs are not cost effective and not possible for deep cracks [5, 6]. Thus, emerging a favourable and inventive way to heal the cracks of concrete is the call of nature, i.e. self-healing concrete. Many self-healing techniques like adhesive-based, autogenous, bacteria-based and mineral admixtures based have been introduced [7]. Among these methods, bacteria-based self-healing of cracks is the most effective one [1–3, 5, 8–16].

Ureolytic bacteria was first time used as a healing agent by Gollapudi et al. (1995) for cracks which assists the enzymatic hydrolysis of urea to ammonia and carbon dioxide [9]. On the other hand, Ramakrishnan et al. (2001) first introduced the concept of utilizing microbiologically induced calcite ($CaCO_3$) precipitation [17]. When bacterial techniques were applied in fresh concrete, it produces calcite precipitation in the void of concrete which decreases the permeability and increases the strength of concrete. Deposition of calcite on the concrete specimen by the bacteria leads to the reduction of gas permeability and uptake of capillary water. Crystals of calcium carbonate deposition on the concrete specimen results in the decrease in water absorption up to 85%. Bacterial carbonate precipitation affects the durability of the concrete specimen with different porosity. Due to bacterial calcite precipitation, permeability and sorptivity of concrete decrease. Depending upon porosity, water absorption is reduced from 65 to 90% due to bacterial carbonate precipitation [18]. Due to the execution of the bacterial approach in concrete, the durability property of concrete has been improved effectively [10, 13, 19–21]. This research paper highlights about bacteria, its self-healing mechanism and crack remediation techniques along with various advantages and disadvantages of bacterial concrete on its various properties.

2 Bacteria, Its Growth and Reproduction

Bacteria are unique species having simple structure but large diversity. Bacteria is the plural form of bacterium. The plasma membrane of bacteria having all the properties acts as a cell membrane. It serves as the area of transport of protein and nutrients. Bacterial species were the first to evolve in non-oxygenic atmosphere. They are prokaryotes as they do not have membrane-bound cell organelles in their body.

In the case of prokaryotic unicellular organisms, reproduction and cell growth are two mutually inclusive events, i.e. reproduction takes place by means of cell growth. Cell growth is the most common method of asexual reproduction among unicellular organisms. The bacterial cells grow up to a certain amount by taking nutrients from their surrounding atmosphere and then the parent cell divides into two new daughter cells by binary fission. DNA, mesosomes and other cell organelles divide into two equal parts. Each cell is a duplicate of the other.

Bacteria can be cultured in a laboratory by using a suitable growth medium (solid or liquid). Culture means letting the bacteria grow and reproduce in a predetermined condition in a medium inside a laboratory. Agar plates are the most commonly used solid growth media which contain all required nutrients for bacterial growth. Selective nutrient medium is required for detecting specific organisms. Liquid mediums are helpful for the culture of enormous volumes of bacteria. Naturally, it becomes difficult for bacteria to grow and to do cell division in artificial conditions which becomes unsuitable for them, but the usage of gel or liquid media containing natural resources are quite helpful in speeding up their rate of cell division, i.e. they do not have to struggle for collecting nutrients, they get ready-made nutrients. There are four stages in which bacterial growth in a nutrient medium takes place. First, bacteria need to adapt to their new environment, which is a quite slow phase, as they require some time to comprehend the condition they are in. This phase is known as the lag phase, where the rate of growth is slow and bacterium prepares itself for the upcoming high growth rate. The second phase is the log phase. In this phase, bacteria take up the nutrient at a faster rate, and metabolism is done at a higher speed. The third phase is the stationary phase. Here, the growth curve becomes horizontal. Due to the heavy usage of nutrients, now the nutrient medium starts depleting. The cellular activity along with metabolism keeps on decreasing. The final phase is the death phase in which all of the nutrient media are finished and bacteria die due to lack of nutrients.

3 Self-healing Mechanism

The main purpose of self-healing concrete is that it should be able to sense when the damage just begins, so that it can properly utilize its healing properties. For treating the microcracks, the self-healing technique is genuinely a good approach. The mixture of bacteria in concrete results in forming a layer of hard calcite, which autogenously heals the concrete [8, 22].

As concrete has high alkalinity, the bacteria which are added to it should have the capability of surviving in such adverse conditions [23, 24]. The calcite precipitate formed by bacteria helps in filling the microcracks and acts as a binding material for sand and gravel [25]. The addition of microorganisms to concrete helps in increasing its durability. *Bacillus sphaericus* bacteria can form calcite precipitation in a very alkaline medium by the conversion of urea into ammonia and carbonate [14]. Concrete itself can fill the cracks which are lesser than 0.2 mm in size. It is the cracks having size more than 0.2 mm which need to be taken care of, as they create pathways for water and other chemicals into the concrete. In the case of self-healing concrete, once any crack is formed, it immediately leads to the activation of bacteria from its dormancy. The metabolic activities of bacteria lead to calcium carbonate precipitation, which in turn, forms a hard layer and blocks the concrete. After the cracks are completely blocked, the bacteria again enter the dormancy period. The bacteria act as a good source for self-healing concrete, and the process is known as Microbiologically Induced Calcium Carbonate Precipitation (MICP).

The underlying principle of bacterial concrete is the formation of calcium carbonate precipitation around particles to bind quite loosely attached particles that helps in the strengthening of concrete. Commonly, urease producing bacteria serve this purpose [26, 27].

1 mol of urea when hydrolysed gives rise to 1 mol of ammonia (NH_3) and 1 mol of carbamic acid (NH_2COOH) [28]. Further carbamic acid when reacts with water produces 1 mol of bicarbonate and 2 mol of ammonia. Bicarbonate gets reduced to bicarbonate ion and H^+ ion. Also, the 2 mol of ammonia when reacts with water give ammonium ion and OH^-. The last reaction results in an increase in pH, due to which the reaction shifts towards right producing more carbonate ions (law of mass action)

$$\begin{aligned} &2NH_3 + 2H_2O \leftrightarrow HCO_3^- + H^+ + 2NH_4^+ \\ &+ 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \end{aligned} \tag{1}$$

We know that the cell wall of bacteria is negatively charged. Therefore, it attracts Ca^{2+} cations from the surrounding environment. The previously deposited ${CO_3}^{2-}$ ions react with these Ca^{2+} ions forming $CaCO_3$ precipitation at the cell wall which acts as the site for nucleation.

$$\text{Cell} - Ca_2^+ + CO_3^{2-} \rightarrow \text{Cell} - CaCO_3 \downarrow \tag{2}$$

The amount of deposited or non-reacted lime particles determines the potential of the concrete for self-healing.

4 Effect on Mechanical Properties of Concrete

4.1 Setting Time

In MICP process, bacteria are induced in the concrete mixture by replacing water with cultured bacteria along with nutrient medium [29]. Sometimes a decrease in hydration of cement is observed [30]. This may be due to the various minerals or constituents of the nutrient medium and various carbon and nitrogen sources. The frequently used Yeast extract as a part of the nutrient medium retards the hydration process [16, 31]. Calcium chloride, which is used to increase the calcite precipitation, accelerates the hydration of cement [32]. But it affects the durability of steel reinforcement for which it can't be used in concrete. Calcium nitrate which is used as the calcium source also accelerates the hydration process [33]. In general, setting time reduces when calcium lactate is used and increases when calcium nitrate and calcium formate are used [34, 35]. The main focus of the research being the decrement of the overall cost of materials and production of an economic biological concrete system, the chemical should be chosen in such a way that there is less migration of them causing the addition of chemicals from time to time, which in turn might be able to reduce the cost related to the purchase of chemicals.

4.2 Compressive Strength

Compressive strength plays a vital role in determining the durability of concrete. Hence, research in bio concrete is an essential field from the application point of view. When bacteria species are injected into concrete and mortar, it shows a significant increase in the compressive strength of concrete. By using bacterial sample Bacillus sp CT-5, the author observed that bacterial specimen gives strength of 31Mpa and compressive strength increases about 36% with respect to concrete without bacteria after 28 days of curing [26]. In the concrete containing Bacillus Sphaericus, increase in compressive strength of 30.76, 46.15 and 32.21% at 3, 7 and 28 days occurs. Split tensile strength increases by 13.75, 14.28 and 18.35% in a period of 3, 7 and 28 days, respectively [36]. Bacillus subtilis bacteria was introduced in concrete by using various bio influenced self-healing technique such as carrier compound namely lightweight aggregate and graphite nano platelets. By using carrier compound lightweight aggregate, there is an increase of 12% of compressive strength as compared to concrete without bacteria and by using graphite nano platelets, there is 9.8% increase in compressive strength as compared to concrete without bacteria [2]. Bacillus Haloduransstrain KG1 was used along with replacing Cement Kiln Dust with cement from 0 to 20%. With 10% CKD, 7.15 and 26.6% increase in strength at 28 and 91 days of test was observed [37]. By using Bacillus cereus 38% and by Bacillus pasturii 29% increase in compressive strength takes place after 28 days curing [38]. Bacillus Subtilis JC3 was used with a cell concentration of 10^4,10^5,10^6

and 10^7 cells per ml. The highest strength was achieved by cell concentration 10^5 cells/ml, which gives 23% increase in strength after 28 days of curing [39]. Addition of bacteria Bacillus Subtilis JC3 leads to an increase in the compressive strength by 13.93% at a curing period of 28 days whereas in the case of split tensile strength, there is an increase in strength by 12.60% at 28 days [40]. By adding B. Subtilis, the compressive strength of the structure increases about 23% at a curing period of 28 days for ordinary concrete when compared to controlled concrete [41]. Both dead and live bacterial cells of B. Pasturii were used with different cell concentrations and found that the live cells having a smaller number of cells per ml, if allowed to grow for a longer period, increase the compressive strength of cement mortar. As per the results, a marginal increase of up to 10% of compressive strength was observed by adding B. Pasturii [23].

Shewanella species was used with 10–10^7 cells/ml concentration and the highest strength, i.e. 25% increase in strength in comparison to control concrete was achieved with cell concentration of 10^5 cells/ml [42]. In the case of Bacillus cohnii, a change in the ongoing process was observed. In this case, the highest strength increment of 49.18% was observed with a concentration of 10^7 cells/ml [43]. Also in the case of Bacillus subtilis, the highest strength is observed in 10^5cells/ml concentration [44]. In fly ash based concrete, Sporoscarcina pasteurii was used with concentration of 10^3, 10^5 and 10^7 cells/ml and the highest increment of compressive strength, i.e. 22% is observed with 10^5 cell/ml bacterial concentration [20]. A similar result is observed in the case of AKKR5 where there is 10% increment in compressive strength as compared to control concrete with 10^5 cell/ml concentration [45]. In the case of Bacillus megaterium, the highest strength was observed with cell concentration of 30×10^5 cfu/ml [46]. With Bacillus aerius, the highest strength is achieved with the cell concentration of 10^5 cells/ml. There is an increase in compressive strength by 11.8% in bacterial concrete compared to control with 10% dosage of RHA [47]. From literature, it is observed that for the highest value of compressive strength, the optimum cell concentration should be in between 10^5 and 10^7 cells/ml. Different bacteria with their optimum cell concentration for best compressive strength are shown in Fig. 1. In addition to all the studies, the authors would like to present the results of their ongoing studies involving two bacteria, i.e. Bacillus subtilis and Bacillus cohnii. The study shows that by using Bacillus subtilis with 10^5 cells/ml, the highest strength is achieved, i.e. 66.7 Mpa, which is similar to the value mentioned for obtaining the best strength in the previous literature. In the case of Bacillus cohnii bacterial species, the highest strength of 60.7 Mpa is achieved with cell concentration of 10^5 cells/ml, which was not the case in the previous literature, since there, the strength was the highest when cell concentration was 10^7 cells/ml. Graphical comparison between present work and existing literature is furnished in Figs. 2 and 3.

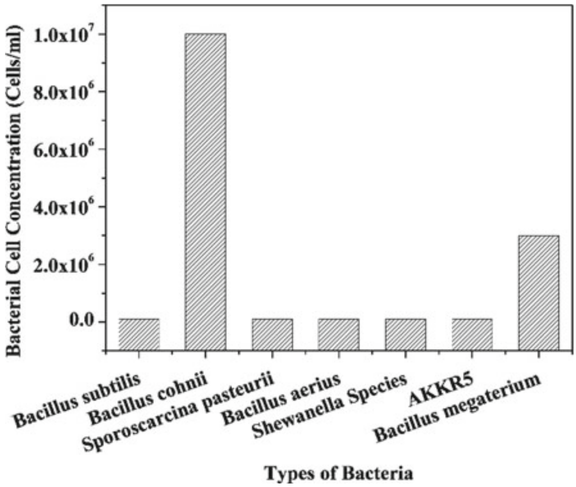

Fig. 1 Various types of bacteria with optimum cell concentration for the highest compressive strength

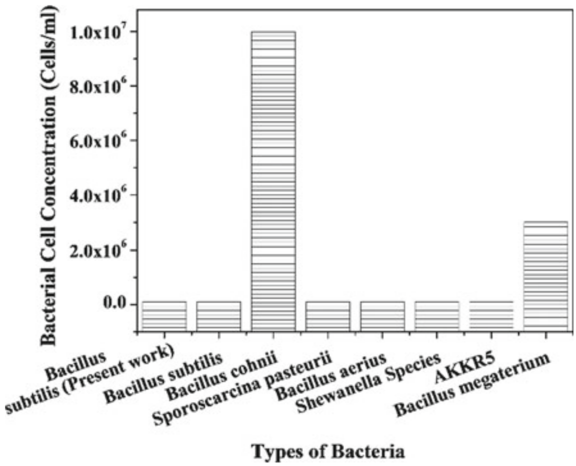

Fig. 2 Comparison of present work containing *Bacillus subtilis* with previous literature

4.3 Reduction in Permeability

Permeability is one of the key features by which the durability of concrete is affected. Concrete having a very high amount of permeability results in the percolation of water and pollutants, which affects the concrete durability along with integrity. Hence, low permeability is a must for having a long activity period. Using bacterial concrete helps in decreasing the permeability of concrete. Since the calcite precipitation because of bacterial concrete mainly occurs at the surface of concrete, it acts as the covering system that helps in covering the pores [48]. Figures 4 and 5 show the SEM image where calcite is deposited on the concrete surface which in turn blocks the pores and decreases permeability. Carbonation test (surface treatment) results in decrement in

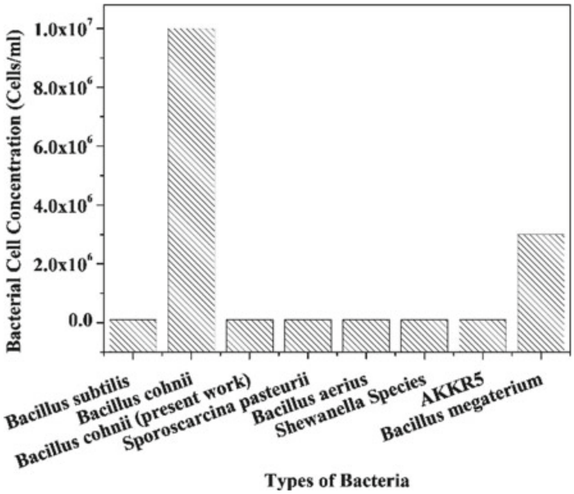

Fig. 3 Comparison of present work containing *Bacillus cohnii* with previous literature

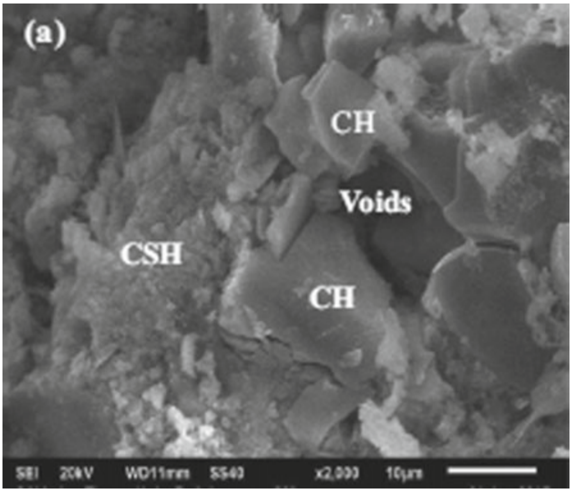

Fig. 4 SEM of concrete without bacteria [56]

gas permeability which leads to a method of examining the permeability because it is known that decrease in gas permeability which further leads to increment in resistance for carbonation and chloride entry. An increment in resistance of concrete for alkali, drying shrinkage, freeze thaw attack by addition of bacterial cells was observed. The impact of calcite precipitation on permeability was a part of the study, who used S. *Sphaericus* and reported a significant amount of decrement in concrete permeability [13]. Research has been done on the effects of *Bacillus pasteurii* bacteria on the permeability of concrete and observed a significant reduction in permeability of water in cement cubes incorporated with the bacterial species [49]. It also observed the same effects when they used *Sporosarcina pasteurii* in concrete cubes. Many

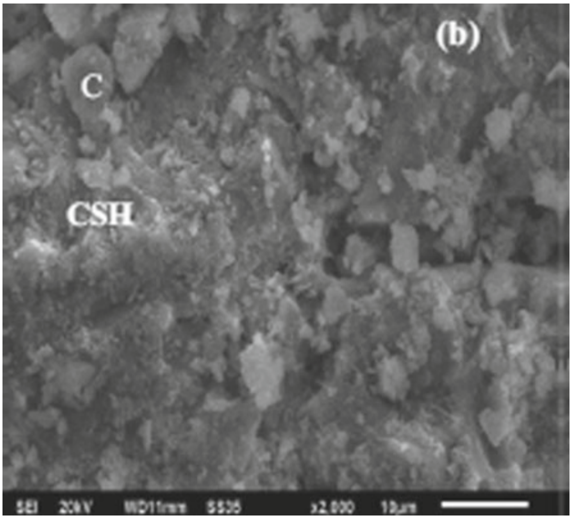

Fig. 5 SEM of concrete with bacteria [56]

believe that this reduction in water permeability of concrete specimen with bacteria content is due to the calcite deposition in the voids of concrete [26]. When concrete specimens were treated with *Bacillus* sp. CT-5, they showed reduction up to six times in water absorption of concrete in comparison to control specimen [50]. When the effect of *Sporosarcina pasteurii* was studied on concrete with fly ash, it showed reduction up to 8 times in chloride permeability. This might be possible because of the deposition of calcite in concrete. When mortar specimens were incorporated with *Bacillus sphaericus* spores that are hydrogel encapsulated, the permeability reduces up to 68% [51]. Concrete with fly ash content incorporated with bacteria showed a decrement in water absorption up to four times. As bacteria concentration increases, the capacity for absorption of water decreases. When bacteria contain 10^5 cells/ml bacterial concentration, then the reduction in water absorption is maximum. Overall with respect to the control specimen, there is a decrease in water absorption in the presence of bacteria [52]. The deposition of a layer of calcium carbonate on the surface and inside the pores of the concrete specimens resulted in a decrease in water absorption. When the quantity of carbonation is higher in concrete containing bacteria, the surface reaction causes an increment in resistance to chloride attack, which in turn helps in decreasing the permeability along with porosity [53–55].

5 Crack Remediation

By using bacteria in concrete, the main focus revolves around healing of cracks in concrete with the help of calcium carbonate deposited by microbial action. Ramachandran et al. used S. pasteurii bacteria along with calcium chloride and urea solution to repair the cracks successfully [10]. Sporoscarcina pasteurii was used with calcium chloride and nutrient medium to seal the cracks [57]. L. sphaericus was used by incorporating in silica gel matrix along with nutrients and calcium sources to seal the cracks. It was observed that in comparison to the control mix, crack was healed by using the bacteria [14].

Jonkers et al. were the first ones to include Bacillus cohnii endospores in cement stone so that it would induce calcium carbonate precipitates [8]. Wiktor and Jonkers again used the same species of bacteria to infuse lightweight coarse aggregates into the concrete to protect the bacteria. L. phaericus endospores were used in a mixture of concrete and it was noticed that cracks of size up to 970 μm were sealed up automatically by bacterial specimens, whereas cracks up to size 250 μm could be healed by nonbacterial specimens. A decrease in water permeability of concrete (apparently 10 times less) indicated that the cracks were autogenously healed by the bacterial specimens [16]. Bacillus subtilis with highest cell concentration, i.e. 10^7 cells/ml heals the crack more efficiently. It is observed that with higher bacterial cell concentration, the cracks healed effectively in comparison to lower cell concentration [58]. Crack healing with different cell concentrations of bacteria is shown in Fig. 6. Encouraging results have been witnessed, but there is still scope for the development of reliable and cost-friendly concrete specimen for self-healing concrete [59].

6 Drawback

Even though bacterial concrete is useful in reducing the repairing cost of concrete that might become enlarged with the course of time, the total cost in forming the concrete mixture is almost 28% more than conventional concrete [46, 49, 50]. There is no concrete design that makes sure of 100% performance of bacterial concrete. The right amount of bacteria and the perfect type keeps changing from time to time [46, 51, 52]. Some bacteria like Shewanella species, Leuconostoc mesenteroides, Pseudomonas aeruginosa, Escherichia coli, Acinetobacter species, etc. are harmful to human health as they cause various diseases [53]. So, there is a common belief among people that if they live in a bacterial filled environment, it will have adverse effects on their health. But bacteria species like *Bacillus pasteurii, Bacillus sphaericus and Bacillus lentus* are effectively used in concrete because they do not affect the health of human [46–60].

7 Conclusion

In recent times, self-healing concrete is the talk of the town because of its biological techniques. Calcium carbonate precipitation by microorganisms is the perfect solution to the problem of crack formation in concrete. The metabolic reactions occurring inside of microorganisms such as photosynthesis, urea hydrolysis and sulphate-reduction cause all-round development in concrete quality as they produce calcium

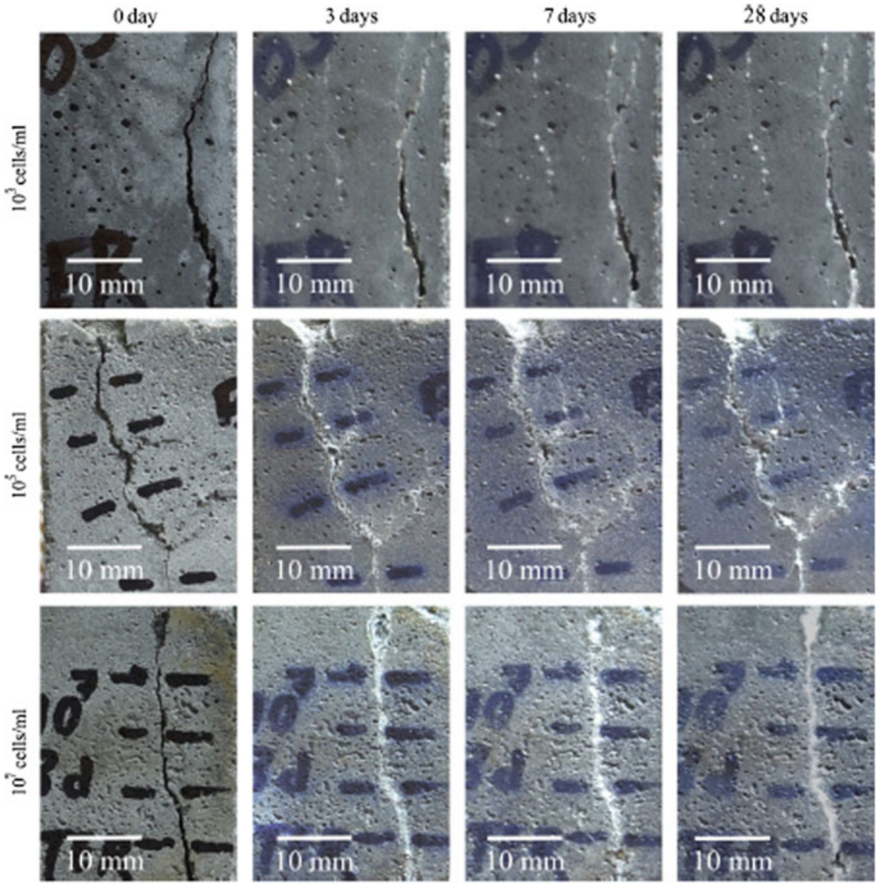

Fig. 6 Crack healing with different bacterial cell concentrations [58]

carbonate precipitate as the byproduct. Self-healing concrete which contains bacteria positively affects different kinds of attributes like durability, self-life strength, permeability and water and chloride absorption. Researchers have found that the utilization of biotechnology in self-healing concrete enhances the durability along with strength and decreases the permeability of concrete. There is a common belief that a bacteria filled environment negatively affects their health and causes diseases. It is hoped that in future, people will understand the value of using self-healing bio concrete and realize its importance and start using it widely as a substitute for conventional concrete. Moreover, the usage of self-healing concrete is a reassuring method for having better quality infrastructure.

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