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Review

# Bacteria based self healing concrete – A review

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## HIGHLIGHTS

- Effect of bacteria on concrete properties.
- Bacteria are able to calcium carbonate precipitation in concrete.
- Micro organism based self-healing is a capable solution for sustainable improvement of concrete.

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## ABSTRACT

This paper reviews the types of bacteria used in concrete and the ways it can be applied as a healing agents. This paper also gives a brief description of the various properties of concrete which vary with the addition of bacteria. Micro-cracks are inherently present in concrete. This causes degradation of concrete leading to ingress of deleterious substances into concrete, resulting in deterioration of structures. Due to this concrete needs to be rehabilitated. To surmount these situations self-healing techniques are adopted. By the addition of urease engendering bacteria along with calcium source results in calcite precipitation in concrete. Bio-mineralization techniques give promising results in sealing the micro-cracks in concrete. The freshly composed micro-cracks can be sealed up by perpetual hydration process in concrete. The ureolytic bacteria which include Bacillus Pasteurii, Bacillus Subtilis which can engender urea are integrated along with the calcium source to seal the freshly composed micro cracks by $CaCO_3$ precipitation. For the amelioration of pore structure in concrete, the bacterial concentrations were optimized for better results. The literature shows that Encapsulation method will give better results than direct application method and also shows that the use of bacteria can increase the strength and durability properties of concrete.



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## 1. Introduction

One of the most widely used materials for construction is concrete. Concrete is weak in tension and strong in compression and cracks are inevitable in concrete. Once cracks form, in concrete it may reduce the life span of the concrete structures. Various repairing techniques are available to repair the cracks but they are highly expensive and time-consuming processes. There are moderate techniques to repair the cracks in concrete by itself called self-healing concrete. Bacteria with calcium nutrient source are added into the concrete at the time of mixing. If any cracks will be formed in concrete bacteria precipitate calcium carbonate. This will seal the cracks. The strength of the Bacterial concrete will be more than the normal concrete. Strength and durability of structural concrete can be increased by a biotechnological method based on calcite precipitation.

Crack size more than 0.8mm is more difficult to be repaired however with the use of bacteria cracks can heal with the calcite precipitation [5]. Lightweight aggregates added in the place of fine aggregate leads reduction of strength of bacteria based mortar. The strength of bacterial lightweight mortar was more than normal lightweight mortar. This can be used where light weight structures are required. These light weight aggregates are good carrier for bacteria, which increases the healing efficiency and structural durability [8]. The addition of bacteria in Rice husk ash concrete can increase strength properties of concrete due to calcite precipitation at all ages of concrete [10]. Maximum of 24% can be increased in the M50 grade concrete, with maximum calcium carbonate precipitation [12]. The strength of fly ash concrete can be increased by adding Sporoscarcina Pasteurii bacteria which also reduces the porosity and permeability. This results in an increase of compressive strength by a maximum of 22% and reduction in water absorption by four times of normal concrete [16].

Recently, the self-healing approaches have been exhibiting promising results in remediating the cracks in the earlier stages of formation of cracks [40]. On the other hand precipitation of calcite in the concrete specimens by hydro gel encapsulation, capsules, and vascular systems seem to be proficiently adept at self-healing in the construction activities and researches. Fig. 2 illustrates the possible self-healing mechanisms, by the application of cementitious materials in concrete. Different calcium sources may be adopted for the precipitation of calcite by the bacteria. For improving the properties of concrete such as durability the recent advances like Biotechnology and Nanotechnology are used. The objective of this study is to review the various properties of concrete which vary with the addition of bacteria. And the types of bacteria used in concrete for calcium carbonate precipitation.

## 2. Self healing approach and ways of applying bacteria in concrete

### 2.1. Self healing approach

A perfect self-healing system should sense the damage or cracks which can set of the release of the healing agent. Self-healing techniques are good approaches for rehabilitation of micro-cracks in concrete. The autogenously healing techniques show good results in healing of micro-cracks on the surface of the concrete. The addition of bacteria will form a pervious layer on the cracks of concrete, which conforms the precipitation of calcium carbonate [32,39].

Concrete is a highly alkaline material, the bacteria added is capable of withstanding alkali environment [24,26]. Micro biologically induce calcium carbonate precipitation helps to fill the micro cracks and bind the other materials such as sand, gravel in concrete [23]. The involvement of microorganism in calcite precipitation can increase the durability of concrete. By converting urea into ammonium and carbonate Bacillus Sphaericus can precipitate $CaCO_3$ in the high alkaline environment [22]. Cracks less than 0.2 mm in concrete can be filled by concrete itself. But if cracks are more than 0.2 mm then concrete fail to heal itself which create a passage to deleterious materials. In self-healing concrete, formation of any cracks, leads to activation of bacteria from its stage of hibernation. By the metabolic activities of bacteria, during the process of self-healing, calcium carbonate precipitates into the cracks healing them. Once the cracks are completely filled with calcium carbonate, bacteria returns to the stage of hibernation. In future, if any cracks form the bacteria gets activated and fills the cracks. Bacteria act as a long lasting healing agent and this mechanism

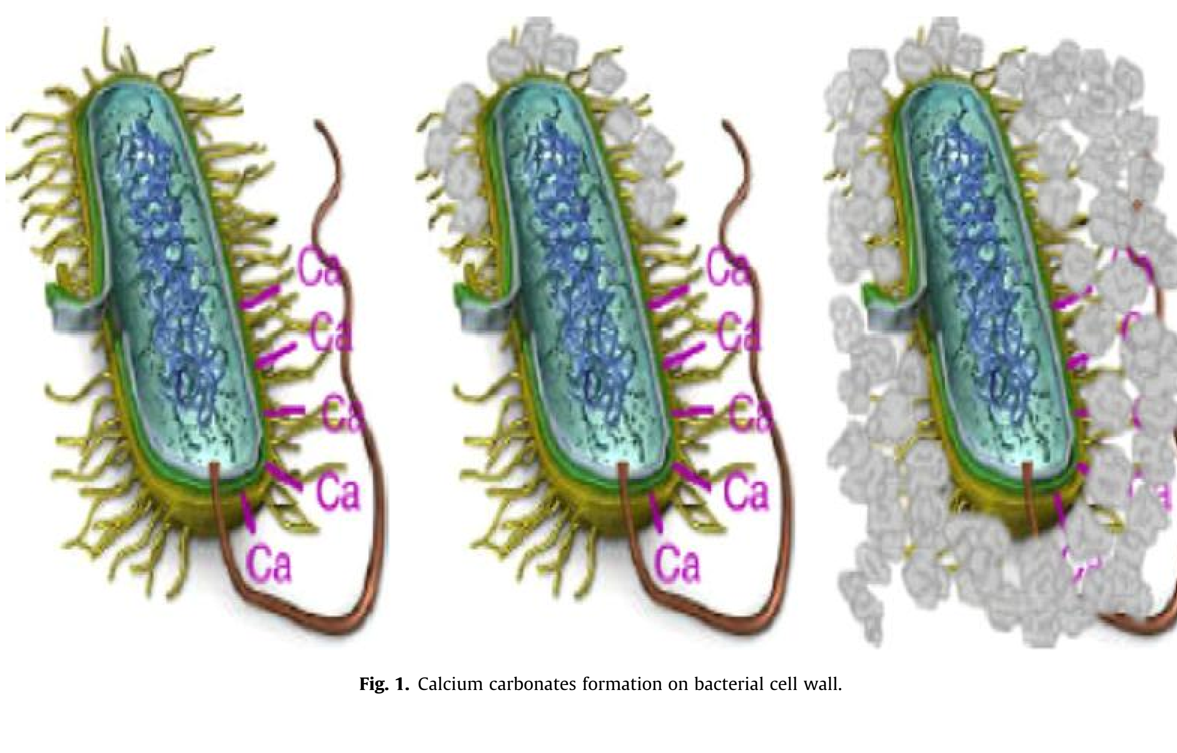


**Fig. 1.** Calcium carbonates formation on bacterial cell wall.

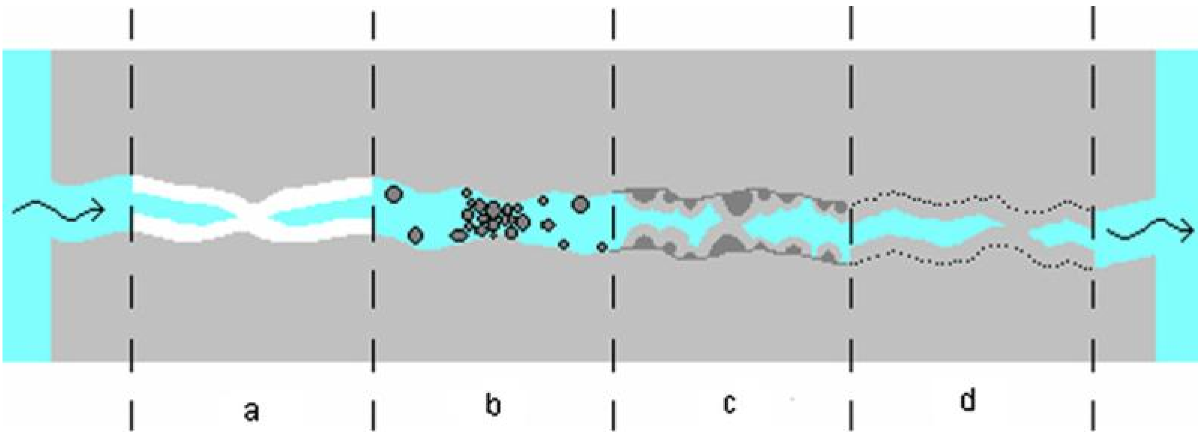


**Fig. 2.** Possible self-healing mechanisms for cementitious materials.

**Table 1**
Different metabolic pathways of bacterial calcium carbonate precipitation [46].

| Autotrophic bacteria | Heterotrophic bacteria | | | | |
|---|---|---|---|---|---|
| non-methylotrophic methanogenesis | Assimilatory pathways | Dissimilatory pathways | | | |
| | Urea decomposition | Oxidation of organic carbon | | | |
| an oxygenic photosynthesis | | Aerobic | | Anaerobic | |
| | | Process | e–acceptor | Process | e–acceptor |
| oxygenic photosynthesis | Ammonification of amino acids | Respiration | $O_2$ | $NO_x$ reduction | $NO_3^-/NO_2^-$ |
| | | Methane oxidation | $CH_4/O_2$ | Sulfate reduction | $SO_4^2$ |

is called as Microbiologically Induced Calcium Carbonate Precipitation (MICP).

Many bacteria can mediate the formation of calcium carbonate according to their metabolic pathways given in Table 1. It has been reported that, precipitated calcium carbonate, is more abundant in heterotrophic processes compared to autotrophic processes. Autotrophs are organisms that produce complex organic compounds, such as carbohydrates, from simple substances, generally using energy from light (photosynthesis) or chemical reactions (chemosynthesis); whereas heterotrophs are organisms that cannot fix carbon to form their own organic compounds and need organic carbon sources for growth. The microbial produced calcium carbonate and which forms a mineral layer that covers the bacterial cells [46,49].

The pathway that has been studied most for engineering purposes is probably the decomposition of urea by bacteria, with the aid of the bacterial urease enzyme. As a component of metabolism, bacteria species gives urease, that catalyzes urea to carbonate and ammonium that results in an increase of pH and carbonate concentration in the bacterial surroundings. These components further hydrolyze to ammonia ($NH^{4+}$) and carbonic acid ($CO_3^{2-}$) that leads to the formation of calcium carbonate. The process of making urease for the hydrolysis of urea CO $(NH_2)_2$ into carbonate ($CO_3^{2-}$) and ammonium ($NH^{4+}$) is be as follows [22].

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (1)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \quad (2)$$

$$H2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (3)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^- \quad (4)$$

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \quad (5)$$

The cell wall of the bacteria is negatively charged, the bacteria draw cations from the environment, together with $Ca^{2+}$, to deposit on their cell surface. The $Ca^{2+}$ ions react with the $CO_3^{2-}$ prime to precipitation of calcium carbonate at the cell surface that serves as a nucleation site. Fig. 1 shows the image of calcium carbonates precipitation on bacterial cell wall.

$$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+} \quad (6)$$

$$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3 \downarrow \quad (7)$$

Several micro organisms have the ability to precipitate calcium carbonate by means of urealysis. A thorough review of literature has revealed certain applications of bacteria. The Bacillus Subtilis bacteria can increase the strength of the concrete with lightweight aggregate and graphite nanoplatelets [3]. Bacillus Aerius bacteria in rice husk ash concrete was investigated and it was observed that the durability of concrete has been increased [10]. Bacillus Megaterium bacteria were used in concrete and results shows 24% increase in compressive strength [12]. The deposition of calcium carbonate in concrete by Bacillus Sphaericus improves the durability of concrete [13]. The Sporoscarcina Pasteurii bacteria used in fly ash concrete has shown improvement in strength and durability of fly ash concrete through self-healing effect [16]. The Sporoscarcina Pasteurii bacteria used in silica fume concrete, it was found that there is an improvement in strength and durability of silica fume concrete through self-healing effect [17]. Bacillus Sphaericus bacteria was used in concrete to check the surface treatment and the results reveal that bacterial carbonate precipitation can be used as an alternative surface treatment for concrete [18].

### 2.2. Mechanism of applying the healing agents in concrete

As per literature the healing agent can be applied in concrete by two methods: Direct application and Encapsulation. Previous liter-

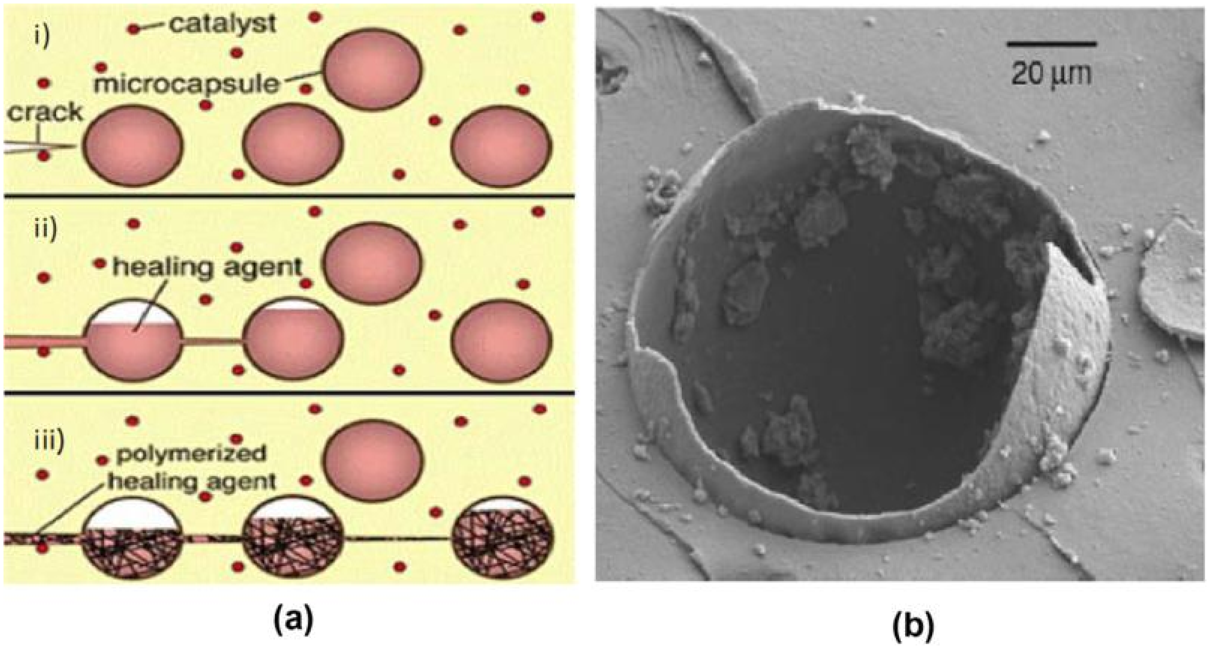


**Fig. 3.** (a) Simple process of microcapsule approach: (i) Formation of cracks in matrix; (ii) process of releasing healing agent; (iii) process of crack healing and (b) ESEM image displaying a ruptured microcapsule.

ature revealed that the application of healing agent in concrete by direct, incorporation of bacteria in light weight aggregates (LWA) and graphite Nano platelets (GNP); it has been revealed that GNP as a good carrier compound for bacteria and it has given better results in healing of cracks [3]. The application of healing agent by the direct method used for finding optimum concentration of bacteria for strength purpose and the optimum concentration was $30x10^5$cfu/ml [12]. Another suggested method is the impregnation of lightweight aggregates by bacteria solution and then their encapsulation in a polymer based coating layer for improvement the self-healing overall performance of concrete [9]. Fig. 3a illustrates the self-healing approach, by the application of microencapsulation method integrating healing agent for self-healing of materials. As soon as the crack ruptures the embedded microcapsules, the healing agent is released into the crack faces by using capillary movement. Now the healing agent associates with the embedded catalyst, activating polymerization and safeguard the closure of the near-by cracks. Fig.3b shows the image of a typical ruptured microcapsule [43]. The self-healing by encapsulation has the ability to provide high-quality self-healing, in terms of the wider range of crack width that can be healed and earlier reaction to cracking in the matrix [35]. Hydro gel encapsulation method was also used and the specimens with hydro gel encapsulated bacterial spores included had an improved self-healing effectiveness both regarding the amount of precipitation and crack healing [13]. The direct method of application of Shewanella bacteria species into the concrete was investigated and results showed that a 25% increase in 28 days compressive strength of cement mortar [41]. Based on literature; Encapsulation method showed good results in self-healing efficiency with respect to crack closer and the amount of calcium carbonate precipitation, which is due to uniform distribution and protection of bacteria in the alkaline environment. The method used for healing, width and the depth of the cracked healed using the method is shown in Table 2. The major advantages and disadvantages of using bacteria and encapsulation for healing are tabulated in Table 3.

## 3. Effect of bacteria on properties of concrete

### *3.1. Hydration kinetics*

The addition of bacteria spore powder in concrete either accelerate or retard the setting time of concrete depending on the calcium source supplied. The nutrients to bacteria are supplied in

**Table 2**
Self-healing techniques and measured variable.

| Approach | Crack depth & width | Reference |
|---|---|---|
| Micro-encapsulation | Maximum depth of 35 mm crack was filled | [1] |
| Bacteria direct application | Maximum depth of 27.2 mm was filled | [42] |
| Bacteria and Encapsulation | Healing of maximum crack width of 0.970 mm was reported | [14,25,30,44,45] |

**Table 3**
Summarized contrast between specific techniques [48].

| Strategy | Advantage | Disadvantage |
|---|---|---|
| Bacteria | 1. Biological activities and pollution free and natural way | 1. Measures should be taken to protect the bacteria in concrete. Many prerequisites to be met |
| Encapsulation | 1. Healing agent discharge on requirement<br>2. Potential effectiveness under many damage measures | 1. Complexity in casting<br>2. Possible difficulty of healing agent release |

the form of calcium lactate, calcium nitrate, and calcium formate. The addition of calcium lactate can retard the setting time, calcium formate and calcium nitrate can accelerate the setting time of concrete [4,34].

### 3.2. Compressive strength

The strength of the structural concrete has been improved by a Bio-technological method based on calcite precipitation. Microbial cells attained good nourishment during initial curing period, as the cement mortar was permeable. But these cells were adapting to a new atmosphere. Due to the high PH of cement, there is a possibility for bacterial cells to grow slowly in the initial period and accustoms to high PH conditions in the curing period. During the process of cell growth, calcite precipitates on surface of the cell and also in the cement mortar matrix, which may be due to the presence of various ions in the media. This results in less porosity and permeability of the cement mortar. The flow of nutrients and oxygen to the bacterial cells gets stopped if many of the pores in the matrix are plugged at a time. In due course, the cell either gets dead or turns into endospores. Thus the behaviour of increased compressive strength with microbial cells can be explained [47]. By introducing Bacillus megaterium bacteria of concentration $30 \times 10^5$ cfu/ml in concrete, precipitation of calcite was higher in higher grade concrete as compared to the lower grade concrete so, higher grade concrete imparts more strength as compared to the lower grade concrete. The maximum development rate of strength for the highest grade of 50 MPa concrete is as high 24% in strength [12]. Cement was replaced with 10% of fly ash and the inclusions of $10^5$cells/ml Sparcious pasteurii bacteria were included. 20% enhancement in compressive strength of structural fly ash concrete was observed, which is due to the deposition of calcium carbonate on cell surfaces of microorganism [16]. The compressive strength of the bacteria added to silica fume concrete improved due to the precipitation of $CaCO_3$. Microstructure analysis of concrete using XRD, SEM confirmed that calcium carbonate was present in the concrete [17]. The compressive strength of concrete with Sparcina pasteurii accompanied with Bacillus subtilis bacteria ($2 \times 10^9$cells/ml) is 20% more than concrete without bacteria as observed for 28 days [31].

Cement was replaced with different fly ash concentrations of 10%, 20%, and 40% in mortar, bacterial cell improved mortar compressive strength by 19%, 14% and 10%, compared to control specimens [29]. GNP acts as a good carrier compound for uniform distribution of bacteria resulting in maximum crack healing efficiency. The addition of Bacillus subtilis bacteria along with GNP, the compressive strength of concrete increased in all ages due to microbial precipitation of calcium carbonate [3]. The 28 days compressive strength increased when compared to control cement mortar by incorporating the reactive spore powder in cement mortar [4]. Deposition of $CaCO_3$ on the cell surfaces and in the pores of cement-sand matrix plugs the pores in the mortar and causes improvement in the compressive strength by Bacillus sp. CT-5 [50,51]. Table 4. gives the details of bacteria used, bacterial concentration and the values of compressive strength; these may vary depending on the calcium source supplied to the bacteria.

### 3.3. Water permeability

The penetration of aggressive substances that are accountable for degradation of concrete under pressure gradient is determined by permeability and hence is considered to be the fundamental property for portraying the durability of concrete. This depends on the features of pore network of cementitious materials quantified by porosity, tortuosity, specific surface, size distribution, connectivity, and micro cracks. These parameters are amongst others, controlled by the water/cement (w/c) ratio, the particle size distribution, the age of hardened cementitious materials and the intrusion of aggressive substances [21]. $CaCO_3$ deposition in concrete resulted in a decrease of water absorption and permeability of concrete specimens. Studies [16] revealed that addition of S. Pastteurii bacteria in fly ash concrete lead to a decrease in porosity and permeability of concrete. Water absorption was found to be reduced fourfold with a concentration of $10^5$cells/ml bacteria in concrete.

In bacterial concrete pores are filled with calcium carbonate precipitation by bacteria [17]. Cubes cast with the addition of Bacillus Megaterium and its nutrients absorbed more than three times less water than control specimens due to microbial calcite deposition [29]. The addition of Bacillus Aerius bacteria causes the reduction in water absorption and porosity due to calcite precipitation which in turn increases the durability of concrete structures [10]. At 28 days, all control cement bag house filter dust concrete specimens show high to moderate permeability but AKKR5 bacterial ($10^5$ cells/ml) concrete specimens show high to low permeability due to pores filled with calcium carbonate [20]. The quality of the recycled aggregate was improved due to microbial precipitation this will reduce water absorption of recycled aggregate [27,38].

### 3.4. Chloride ion permeability

Corrosion of reinforcing steel due to chloride ingress is one of the most prevalent environmental attacks that lead to the deterioration of concrete structures. The rate of chloride ion ingress into concrete is primarily dependent on the internal pore structure of concrete. The pore structure, in turn, depends on other factors such as the mix design, curing conditions, the degree of hydration, utilization of supplementary cementitious materials, and construction practices. The Rapid chloride permeability test is performed by monitoring the amount of electrical current that passes through a sample. Based on the charge that passes through the sample, a qualitative rating is composed of the concrete's permeability. The resistance of concrete towards chloride permeation can be enhanced by including bacteria in concrete. It was observed that the average

**Table 4**
Various types of bacteria and their compressive strength results.

| S.NO | Bacteria used | Best results | Bacterial concentration | Reference |
|---|---|---|---|---|
| 1 | Bacillus sp. CT-5 | Compressive strength 40% more than the control concrete | $5 \times 10^7$ cells/mm$^3$ | [42] |
| 2 | Bacillus megaterium | Maximum rate of strength development was 24% achieved in highest grade of concrete 50 Mpa | $30 \times 10^5$ cfu/ml | [12] |
| 3 | Bacillus subtilis | Improvement of 12% in compressive strength as compared to controlled concrete specimens with light weight aggregates | $2.8 \times 10^8$ cells/ml | [3] |
| 4 | Bacillus aerius | Increase in compressive strength by 11.8% in bacterial concrete compared to control with 10% dosage of RHA | $10^5$ cells/ml | [10] |
| 5 | Sporosarcina pasteurii | Compressive strength 35% more than the control concrete | $10^5$ cells/ml | [17] |
| 6 | AKKR5 | 10% increase in compressive strength as compared to control concrete | $10^5$ cells/ml | [20] |
| 7 | Shewanella Species | 25% increase in compressive strength of cement mortar compared with the control mortar | 100,000 cells/ml | [24,41] |

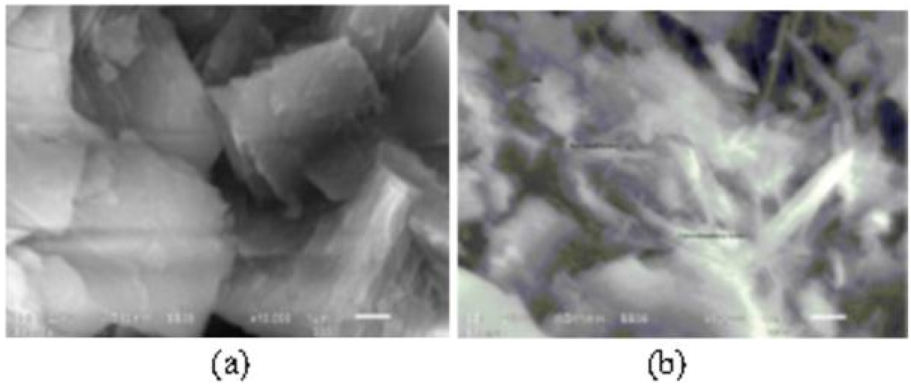


**Fig. 4.** SEM Images (a) control concrete (b) Bacterial calcite precipitation in 10% silica fume concrete.

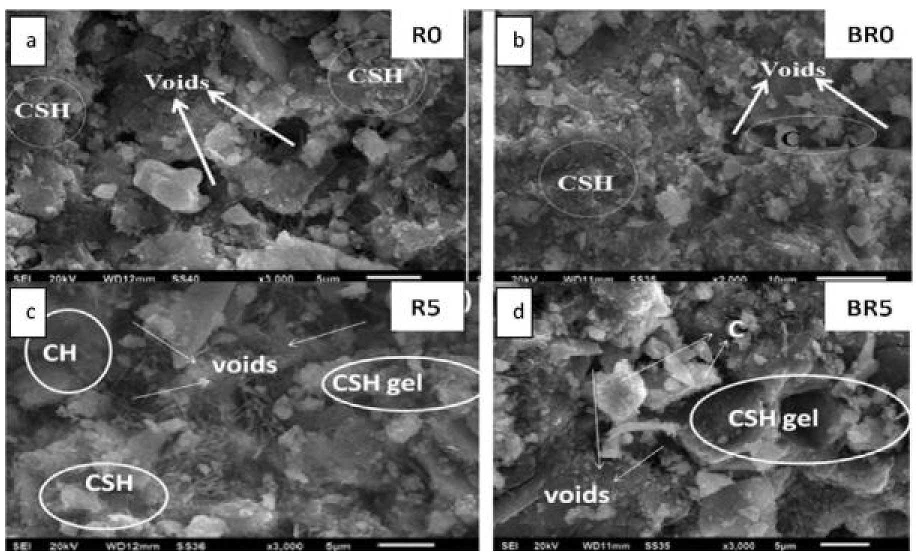


**Fig. 5.** SEM images of (a) Normal concrete (R0) (b) Bacterial concrete (BR0) (c) 5% of RHA Concrete (R5) (d) Bacterial concrete with 5% RHA (BR5).

number of coulombs through bacteria containing concrete was 11.7% less compared to the concrete without bacteria. It was also observed that using Sparcious Pasteurii and Bacillus Subtilis reduce the concrete chloride penetration; it also improves the mass reduction trend of sulfate exposed concrete [31]. Addition Bacillus Aerius bacterial cells in concrete can reduce the total charge passed through control and RHA concrete specimens. Bacterial concrete shows the minimum charge passed at all curing ages. Charge passed in bacterial concrete specimen decreased by 55.8%, 49.9% and 48.4% with respect to normal concrete at the age of 7, 28 and 56 days [10]. The inclusion of Sparcious Pasteurii with optimum bacterial concentration ($10^5$ cells/ml) for 10% silica fume concrete showed good resistance towards rapid chloride penetration (380 coulombs) [17]. It was observed that, with Sporoscarcina pasteurii bacteria of $10^5$-cells/ml concentration for all fly ash concretes, there was a maximum reduction in chloride ions; however, concrete with 30% fly ash concrete resulted only in 762 coulombs penetration which is very low. The service life of concrete structures exposed to de-icing salts or marine environments is well defined by the ability of concrete to resist the penetration of chloride ions [16].

### 3.5. Microstructure

Calcite precipitation in mortar and concrete was visualized by SEM analysis. Rod-shaped bacteria associated with calcite crystals were found. Due to this deposition, the impermeability of the concrete is improved as this deposition acts as a barrier to harmful substances as that enter the sample [29]. The addition of bacteria into the concrete can improve the microstructure of concrete by mineral precipitation. This has been verified by SEM, EDS and XRD analysis. The researcher stated that an addition of $30 \times 10^5$cfu/ml concentration of Bacillus Megaterium bacteria had (38.76%) maximum weight of calcium compared with other proportions of bacteria and in absence of bacteria in concrete [12].

The SEM analysis showed the different calcite crystals embedded with bacteria. It was observed that calcite is present in the form of calcium carbonate as the high amounts of calcium were found in the sample, and this was confirmed by using EDX and XRD analysis. It can increase the durability of concrete [28,37]. Fig. 4 shows the SEM images of control concrete and bacterial concrete. These images can conform the calcite crystals in bacterial concrete [17]. The strength of RHA concrete was improved by the addition of bacteria, due to the deposition of calcium carbonate in pores and this was confirmed by using SEM images. Fig. 5 shows the SEM images of normal concrete and bacterial RHA concrete. It could be clearly seen that in bacterial concrete the voids are filled calcite [10].

The deposition of calcium carbonate within the cracks of the test samples was confirmed by the results obtained using microstructures. Thus with the increase of signal transmission rate of ultrasonic pulse velocity, the water absorption, chloride permeability and acid ingress are decreased [7,9,36].

## 4. Practical applications

Before introducing this concept commercially a large scale demonstration is required. Also, the problem of optimization of nutrient media needs to be addressed. Shrinkage, corrosion and carbonation properties of concrete are yet to be studied in detail. A thorough inspection of the aforementioned properties will shed light on the real-time behaviour of microbial self-healing concrete. Although this concept has shown promising results in the lab, its efficiency in protecting larger concrete elements needs to be tested further under non-ideal temperature ranges, high salt concentrations and at later ages of concrete element. Precise service life estimation can be achieved only through an in-depth knowledge of the self-healing efficiency and its variability, and this is the key to promoting this concept among contractors and owners.

## 5. Conclusion

The importance of this work is to understand, the use of urease-producing bacteria isolates, such as Bacillus subtilis, bacillus pasteuri species in healing of cracks in concrete. The study has reviewed different types of bacteria that can be used for healing cracks. This study has also identified that bacteria has a positive effect on the compressive strength of Portland cement mortar cubes and concrete. The advantage of using bacteria decreases water penetration and chloride ion permeability. The present study results recommends that using the "microbial concrete" can be an alternative and high quality concrete sealant which is cost-effective, environmental friendly, and eventually leads to improvement in the durability of building materials.

## References


[1] E. Mostavi, S. Asadi, M.M. Hassan, M. Alansari, Evaluation of self-healing mechanisms in concrete with double-walled sodium silicate microcapsules, J. Mater. Civ. Eng. 27 (12) (2015) 4015035.
[3] W. Khaliq, M.B. Ehsan, Crack healing in concrete using various bio influenced self-healing techniques, Constr. Build. Mater. 102 (2016) 349–357.
[4] M. Luo, C. Qian, Influences of bacteria-based self-healing agents on cementitious materials hydration kinetics and compressive strength, Constr. Build. Mater. 121 (2016) 659–663.
[5] M. Luo, C.X. Qian, R.Y. Li, Factors affecting crack repairing capacity of bacteria-based self-healing concrete, Constr. Build. Mater. 87 (2015) 1–7.
[7] C.C. Hung, Y.F. Su, Medium-term self-healing evaluation of engineered cementitious composites with varying amounts of fly ash and exposure durations, Constr. Build. Mater. 118 (2016) 194–203.
[8] E. Tziviloglou, V. Wiktor, H.M. Jonkers, E. Schlangen, Bacteria-based self-healing concrete to increase liquid tightness of cracks, Constr. Build. Mater. 122 (2016) 118–125.
[9] W. De Muynck, D. Debrouwer, N. De Belie, W. Verstraete, Bacterial carbonate precipitation improves the durability of cementitious materials, Cem. Concr. Res. 38 (2008) 1005–1014.
[10] R. Siddique, K. Singh, M. Kunal, V. Corinaldesi Singh, A. Rajor, Properties of bacterial rice husk ash concrete, Constr. Build. Mater. 121 (2016) 112–119.
[12] R. Andalib, M.Z. Abd Majid, Hussin, Optimum concentration of Bacillus megaterium for strengthening structural concrete, Constr. Build. Mater. 118 (2016) 180–193.
[13] J. Wang, J. Dewanckele, V. Cnudde, S. Van Vlierberghe, W. Verstraete, N. De Belie, X-ray computed tomography proof of bacterial-based self-healing in concrete, Cem. Concr. Compos. 53 (2014) 289–304.
[14] J.Y. Wang, D. Snoeck, S. Van Vlierberghe, W. Verstraete, N. De Belie, Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete, Constr. Build. Mater. 68 (2014) 110–119.
[16] N. Chahal, R. Siddique, A. Rajor, Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete, Constr. Build. Mater. 28 (2012) 351–356.
[17] N. Chahal, R. Siddique, A. Rajor, Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of concrete incorporating silica fume, Constr. Build. Mater. 37 (1) (2012) 645–651.
[18] W. De Muynck, K. Cox, N. De Belie, W. Verstraete, Bacterial carbonate precipitation as an alternative surface treatment for concrete, Constr. Build. Mater. 22 (5) (2008) 875–885.
[20] R. Siddique, V. Nanda, Kunal, Influence of bacteria on compressive strength and permeation properties of concrete made with cement baghouse filter dust, Constr. Build. Mater. 106 (2016) 461–469.
[21] Q. Tri, N. Maes, G. De Schutter, D. Jacques, G. Ye, Determination of water permeability of cementitious materials using a controlled constant flow method, Constr. Build. Mater. 47 (2013) 1488–1496.
[22] K. Van Tittelboom, N. De Belie, W. De Muynck, W. Verstraete, Use of bacteria to repair cracks in concrete, Cem. Concr. Res. 40 (1) (2010) 157–166.
[23] N. Kaur, M.S. Reddy, A. Mukherjee, Improvement in strength properties of ash bricks by bacterial calcite, Ecol. Eng. 39 (2012) 31–35.
[24] R. Siddique, N. Kaur, Effect of ureolytic bacteria on concrete properties, Constr. Build. Mater. 25 (10) (2011) 3791–3801.
[25] J. Wang, K. Van Tittelboom, N. De Belie, W. Verstraete, Use of silica gel or polyurethane immobilized bacteria for self-healing concrete, Constr. Build. Mater. 26 (1) (2012) 532–540.
[26] F. Bravo, D. Silva, N. Boon, W. Verstraete, N. De Belie, Screening of bacteria and concrete compatible protection materials, vol. 88, 2015, pp. 196–203.
[27] J. Qiu, D. Qin, S. Tng, E. Yang, Surface treatment of recycled concrete aggregates through microbial carbonate precipitation, Constr. Build. Mater. 57 (2014) 144–150.
[28] M. Luo, C.X. Qian, Performance of Two Bacteria-Based Additives Used for Self-Healing Concrete, pp. 1–6.
[29] V. Achal, X. Pan, N. Özyurt, Improved strength and durability of fly ash-amended concrete by microbial calcite precipitation, Ecol. Eng. 37 (4) (2011) 554–559.
[30] N. Zakari et al., Tests and methods of evaluating the self-healing efficiency of concrete: a review, Constr. Build. Mater. 112 (2016) 1123–1132.
[31] F. Nosouhian, D. Mostofinejad, H. Hasheminejad, Concrete durability improvement in a sulfate environment using bacteria, 28(1) (2016) 1–12.
[32] R. Pei, J. Liu, S. Wang, M. Yang, Use of bacterial cell walls to improve the mechanical performance of concrete, Cem. Concr. Compos. 39 (2013) 122–130.
[34] Y. Zhang, H.X. Guo, X.H. Cheng, C.À. Caco, C.À. Ca, Role of calcium sources in the strength and microstructure of microbial mortar, Constr. Build. Mater. 77 (2015) 160–167.
[35] G. Souradeep, H.W. Kua, Encapsulation Technology and Techniques in Self-Healing Concrete, no. 2007, 2007, pp. 1–15.
[36] V. Wiktor, H.M. Jonkers, Quantification of crack-healing in novel bacteria-based self-healing concrete, Cem. Concr. Compos. 33 (7) (2011) 763–770.
[37] H.K. Kim, S.J. Park, J.I. Han, H.K. Lee, Microbially mediated calcium carbonate precipitation on normal and lightweight concrete, Constr. Build. Mater. 38 (2013) 1073–1082.
[38] A.M. Grabiec, J. Klama, D. Zawal, D. Krupa, Modification of recycled concrete aggregate by calcium carbonate biodeposition, Constr. Build. Mater. 34 (2012) 145–150.
[39] H.M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, E. Schlangen, Application of bacteria as self-healing agent for the development of sustainable concrete, 36 (2010) 230–235.
[40] S. Anne, O. Rozenbaum, P. Andreazza, J. Rouet, Evidence of a bacterial carbonate coating on plaster samples subjected to the Calcite Bioconcept biomineralization technique, Constr. Build. Mater. 24 (6) (2010) 1036–1042.
[41] P. Ghosh, S. Mandal, B.D. Chattopadhyay, S. Pal, Use of microorganism to improve the strength of cement mortar, 35 (2005), 1980–1983.
[42] V. Achal, A. Mukerjee, M.S. Reddy, Biogenic treatment improves the durability and remediates the cracks of concrete structures, Constr. Build. Mater. 48 (2013) 1–5.
[43] J. Bollinger, J. Britton, N. Gisin, P. Knight, P. Kwiat, I. Percival, Autonomic healing of polymer composites, 409 (2001) 1804–1807.
[44] B. Dong, N. Han, M. Zhang, X. Wang, H. Cui, F. Xing, A microcapsule technology based self-healing system for concrete structures, 7(3) (2013) 1–11.
[45] C. Qian et al., Self-healing and Repairing Concrete Cracks Based on Bio-mineralization, 630 (2015) 494–503.
[46] N. De Belie, J. Wang, Bacteria-based repair and self-healing of concrete, vol. 373, 2015.
[47] K. Santhosh, V.R. Ramachandra, et al., Remediation of concrete using micro-organisms, ACI Mater. J. (2001).
[48] M. Wu, B. Johannesson, M. Geiker, A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material, Constr. Build. Mater. 28 (1) (2012) 571–583.
[49] N. De Belie, Application of bacteria in concrete : a critical review, pp. 56–61, 2016.
[50] V. Achal, A. Mukherjee, M.S. Reddy, Microbial Concrete : Way to Enhance the Durability of Building Structures, 23 (2011) 730–734.
[51] M.S. Reddy, Lactose mother liquor as an alternative nutrient source for microbial concrete production by Sporosarcina pasteurii, 2009, pp. 433–438.