A Review on the Bacterial Concrete Properties

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Abstract. A very commonly used and widespread building material, concrete has various limits of using it, one of which is crack formation. Formation of larger cracks let water and CO₂ enter into the building materials which in turn react along with other chemicals causing an eye catching reduction in strength and durability. If immediate remedies are not taken to heal the cracks, it might lead to more serious problems like bigger cracks, more leakage of water, reduced strength, costlier to repair. Hence the best way to deal with such situation and to heal concrete even before it starts spreading is self-healing concrete. Self-healing concrete is the most recent and most current cutting-edge technological development in the field of building materials. Self-healing bacteria has the capacity to heal itself. The underlying principle of this mechanism is forming calcium carbonate precipitate with the help of bacteria as a blocking material for cracks. This new and innovative introduction of bacteria into the building materials show new light on production of sustainable, durable, strong concrete having prolonged life period. Due to the introduction of bacteria in concrete, the name becomes bacterial concrete. Bacterial/microbial concrete is pollution free, economic and cost effective. This paper aims at defining bacterial concrete, mechanism and its effects on concrete properties.

1. Introduction
For ages now, concrete has been ruling the infrastructure world. It has gained a lot of recognition as the commonly used material for construction. Even though it has a lot of utilities, there are still two void spaces that concrete fails to fill. Firstly it has strong compressive strength and weak tensile strength, secondly crack formation is quite easy in concrete [1, 2]. Even smaller cracks in concrete result in further bigger problems, which include reducing life span of concrete [3]. Further weakening of reinforcement is resulted due to percolation of water, chloride attack, sulphate attack, carbon attack. In conventional method, crack formation is detected by doing examination manually, and usually repaired by filling it with cement [4]. But these repairs are costly and quite hard to do for deeper cracks [5, 6]. People prefer innovative ways over conventional ones and in these new methods, self-healing concrete is being used widely [7]. Self-healing concrete as its name describes, can heal cracks on its own. In this concrete, bacteria species are mixed with calcium and nutrient medium and injected while preparing concrete mixture. The cracks allow water into concrete which then form calcite precipitate around bacterial cells, which again in turn completely deal the cracks forming a permanent block. This review paper throws light on kinds of bacteria species, their morphology, mechanism of precipitate formation, and the effect of microbial organisms on strength of concrete.
2. About Bacteria

2.1. Bacteria
Bacteria species (singular: bacterium) are unicellular, simple and the most abundant microorganisms. Although bacteria are very simple in structure, they show extensive metabolic diversity. Bacteria are called prokaryotes due to absence of membrane bound structure inside their body. Bacteria have ability to survive in very adverse conditions. Bacteria are categorized into four types on the basis of their shape: the rod-shaped bacillus, the spherical coccus, the spiral Spirillum, the comma shaped Vibrium. Bacteria occur almost everywhere. They live in extreme conditions where survival of any other species is next to impossible. Some of the bacteria species also live inside bodies of other organisms as parasites. Bacteria also help in nutrient cycling, as some them are capable of nitrogen fixation, purification etc. bacteriology is a branch of science that includes study of bacteria in laboratory.

2.2. Morphology of Bacteria
Bacteria have varieties of shapes and sizes. Bacterial cells have a different kind of anatomy from that of eukaryotes. Their cells are comparatively smaller in size than of eukaryotic cells. They are normally 0.5 to 5 mm in size. A few bacterial species like Thiomargarita amibiensis and Epulopiscium fishelsoni are up to 0.5 mm long and are visible to the naked eye. Eubacteria are true bacteria due to presence of rigid cell wall. Archaeabacteria are special because they live in harsh environments like extremely salty areas, hot springs, marsh areas. The mycoplasma are micro-organisms that lack a cell wall and are the smallest organisms (0.3 micrometres) that can live without oxygen. One of the situations that help an organism in surviving in adverse conditions is less expenditure of energy. In bacteria, large surface area to volume ratio helps in achieving this goal, it helps in environments having less nutrient supply. The cell wall and cycloskeleton of bacteria helps in deciding the shape of bacteria. The cycloskeleton which includes flagella, cilia help bacteria in locomotion, avoiding preys and pili help in conjugation.

3. Self-Healing Process and Basic Mechanism

3.1. Self-Healing Process
The main idea behind using self-healing concrete in construction is to automate the detection of crack formation in its initial stage only, so that it becomes easy to heal them primarily. When a mixture of concrete and bacteria is prepared, it results in forming calcite precipitation layer, which helps in healing crack [8, 9]. A general criteria for selection of the bacterial species to be added is that it should be highly alkaline in nature considering the fact that concrete itself is alkaline and has adverse conditions[10, 11]. The calcite precipitation layer blocks the path of and acts binds sand and gravel [12]. Bacillus sphaericus is a species of bacteria that acts in very alkaline medium and can convert urea into ammonia and carbonate [13]. Cracks of size greater than 0.2 mm cause main problem to concrete as they allow chemicals and water to enter. Cracks of lesser size can be healed themselves. In self-healing concrete, a small crack formation leads way to the entry of water, air, chemicals into concrete causing dormant bacteria to be active. These bacteria chemically produce a hard calcite layer which blocks the path of the cracks. After that, bacteria again become dormant. As the bacterial species are involved, this process is better called Microbiologically Induced Calcium Carbonate Precipitation abbreviated as MICP.

3.2. Reactions Involving in Self-Healing
The way bacterial concrete works is by forming calcium carbonate precipitation and forming a tight bind around otherwise loose bound particle. It heals concrete. Most common bacteria are urease producing bacteria [14, 15].
1 mole of urea when hydrolysed, gives rise to 1 mole ammonia and 1 mole of carbamic acid (NH₂COOH), which is shown Eq. 1 [16].

\[
\text{CO(NH}_2\text{)}_2 + H_2\text{ONH}_2 \rightarrow \text{COOH + NH}_3 \quad (1)
\]

These products form 1 mole of bicarbonate and 2 moles of ammonia, which is shown in Eq. 2.
4. Impact of Bacteria on the Properties of Concrete

4.1. Compressive Strength

Compressive strength is one of the determining factors for concrete durability. Therefore, the application of bio concrete to find out its true potential is quite a complicated area for research purpose. Inclusion of bacteria in concrete and mortar caused a significant amount of progress in compressive strength of concrete. The underlying principle is that crystals of calcium carbonate would precipitate on the bacterial cell surface and gradually form a block which leads to pores and cracks which would lead to shortening the supply of oxygen, water and other nutrients, making it an unfavourable condition for bacteria to grow. The cells of the bacteria either become dead or turn into endospores to act as organic fibres which also help in improvement of concrete strength [17]. Various tests have been conducted to study the effect of bio concrete on compressive strength of concrete and mortar [18-21]. In all these experiments, various types of microorganisms have been added into the concrete mixture and all significant changes have been marked. Experiments were carried out by including varying concentrations of the species Bacillus pasteurii in the sample cement mortar specimens. A remarkable 18% increment in compressive strength was observed at an interval 28 days and it was due to the presence of sufficient quantity of organic substances in the mixture [17]. Positive potential of a microorganism was experimented that belong to Shewanella species (thermophilic anaerobic bacteria) on compressive strength of concrete. They reported a 25-30% increment in the compressive strength after a time period of 28 days [22]. Bacillus pseudofirmus was chosen along with Bacillus cohnii to add into the concrete and a 10% increment in the compressive strength was noticed [20]. When Bacillus cohnii bacteria species is added, it increases concrete strength up to certain cell concentration which again shows decreasing levels with passing time [23]. However, 36% increment in compressive strength was observed by mixing of Bacillus sp. CT-5 to mortar specimen [14]. Bacillus Pasturii now known as Sporosarcina Pasturii was used (both live and dead bacteria cell) which shows an increment in compressive strength up to 10% [11]. 22% increment in the compressive strength of concrete containing fly ash was observed when the concrete specimens were treated with the bacterial species Sporosarcina pasteurii. In this experiment, three percentages (10, 20 and 30) of fly ash by weight acted as a replacement for cement and three disparate bacterial cell concentration 10^3, 10^4 and 10^7 cells/ml were used. This increment in compressive strength was mainly due to deposition of bacterial cells which blocked the pores [24]. By using Bacillus Sphaericus microorganisms which is in dormant condition, there is 30.76%, 46.15% and 32.21% increase in compressive strength and 13.75%, 14.28% and 18.35% increase in split tensile strength in a period of 3.7 and 28 days respectively [25]. By utilizing and comparing two types of bacteria like Bacillus Cereus and Bacillus Pasturii, it is observed that with Bacillus Cereus compressive strength increases up to 38% and with Bacillus Pasturii increment in strength was 29% [26]. Bacillus subtilis was used with cell concentration from 10-10^6 cell/ml and highest strength was achieved with 10^6

\[\text{NH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow 2 \text{NH}_3 + \text{H}_2\text{CO}_3\]  \hspace{1cm} (2)

Bicarbonate decomposes into bicarbonate ion and H ion, which is shown Eq. 3.

\[\text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+\]  \hspace{1cm} (3)

This reaction causes an increased pH, for which the reaction shifts towards right (law of mass action), which is seen in Eq. 4.

\[\text{HCO}_3^- + \text{H}^+ + 2\text{NH}_3 + \text{2OH}^- \rightarrow \text{CO}_3^{2-} + 2\text{NH}_4^+ + 2\text{H}_2\text{O}\]  \hspace{1cm} (4)

Bacterial cell wall attracts Ca^2+ cations from the surrounding environment, which is shown in Eq. 5. The previously deposited CO_3^{2-} ions react with these Ca^2+ ions to form CaCO_3 precipitation, shown in Eq. 6.

\[\text{Ca}^{2+} + \text{Cell} \rightarrow \text{Cell} \cdot \text{Ca}^{2+}\]  \hspace{1cm} (5)

\[\text{Cell} \cdot \text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{Cell} \cdot \text{CaCO}_3\downarrow\]  \hspace{1cm} (6)
cells/ml. It may be due to its ability to form calcite which block the pores of concrete structure [27]. *Bacillus subtilis* bacteria was used with two carrier compound which are Graphite Nano platelets and Light weight aggregate. As compared to control specimen (Concrete without bacteria), there is increase of 12% of compressive strength in case of Light weight aggregate and 9.8% of compressive strength in case of Graphite Nano platelets [2].

#### 4.2. Water Permeability

Permeability of concrete is its physical property that controls the rate of absorption of liquid by it. Durability of concrete mainly depends on this aspect as aggressive and hazardous materials mixed in water can penetrate it if the concrete mass is more permeable and vice versa. Porosity in concrete is formed due to improper compaction leaving air pockets, space left due to evaporation of water, inadequate water/cement (w/c) ratio, improper curing and formation of micro cracks [28]. Deposit of Calcium Carbonate (CaCO$_3$) is found to be helpful in reducing permeability of concrete specimens [29]. Studies revealed a marked decrease in porosity and there by permeability in test samples by adding *S. Pasteurii* bacteria in fly ash concrete. Concentration of bacteria in water at $10^5$cells/ml resulted in fourfold reduction in water absorption in concrete. Presence of bacteria in bacterial concrete causes Calcium Carbonate precipitation which fills the pores in it [25]. *Bacillus Halodurans strain KG1* was used in concrete with cement kiln dust. It was observed that there is 20% less water absorption in comparison to concrete without bacteria [30]. Water absorption is found to be less than one third in the specimens that are cast by adding *Bacillus Megaterium* along with its nutrients and they do so by depositing microbial calcite [18]. Injection of *Bacillus Aerius* bacteria also result in the same effect and helps in increased durability of concrete structures by reducing the permeability [31]. Concrete specimens with AKKR5 bacterial ($10^5$ cells/ml) showcase moderate to very low permeability as the calcium carbonate precipitate fills the concrete pores [32]. Microbial precipitation improves the quality of recycled aggregates with reduction in water absorption [33, 34].

#### 4.3. Chloride Permeability

Reinforced concrete structures get deteriorated by chloride attack resulting in corrosion of reinforcing steel. Internal pore network of concrete plays a major role of accessing ion of chloride into it. The pore structure depends on factors like mix design, use of admixtures, construction practices, degree of hydration and curing process etc. Chloride permeability test is carried out by calculating how much electrical current is passing across a concrete specimen. On the basis of the charge passing across it, concrete’s permeability is assessed. Adding bacteria to the concrete, its resistance to chloride permeation can be enhanced. The effect of bacterial carbonate precipitation on the durability of concrete with different porosity was observed. *Bacillus Sphaericus* bacteria was used for this research work. The result shows that the surface deposition of carbonate crystals decreased the chloride migration about 10 to 40% [35]. It was noticed that the average number of coulombs in concrete that contains bacteria was 11.7% less in comparison to the concrete that has no bacterial addition. Use of *Sparcious Pasteurii* and *Bacillus Subtilis* are found to decrease the chloride penetration in concrete [36]. In rapid chloride tests, injection of *Bacillus Aerius* bacteria in concrete can cause effective reduction in the net amount of charge passing through RHA and control concrete specimens at all curing ages. At the age of 7, 28 and 56 days it was found that charge passed in concrete specimen having bacteria to be decreased by 55.8%, 49.9% and 48.4% respectively, in comparison to nonbacterial concrete [32]. The addition of *Sparcious Pasteurii* ($10^5$ cells/ml) in concrete with 10% silica fume resulted in optimum resistance for chloride penetration (380 coulombs) [24]. In case of fly ash concrete, it was observed that, the chloride ion concentration was reduced by maximum amount by adding *Sporosarcina Pasteurii* ($10^5$ cells/ml concentration) i.e. concrete having 30% fly ash content gave 762 coulombs penetration which is a quite less amount. The activity period of concrete specimens that are allowed to come in contact with de-icing salts or marine environments is measured by the capability of concrete to prevent chloride ions penetration [24]. *Bacillus Cereus* and *Bacillus Pasturii* of various cell concentrations were utilized in
cement concrete. By utilizing bacteria, the chloride entrance of bacterial sample decreases as compared to control concrete [26].

4.4. Corrosion
Large infrastructures fail mainly cause of corrosion, which affect steel when reinforced concrete is mainly exposed to chloride ions, which essentially react with steel, eating it inside and creating void. For this reason, necessary attention needs to pay to reduce concrete’s permeability. In order to avoid corrosion, sufficient measures are needed to be taken to reduce the permeability of concrete. Because, higher permeability of concrete allows unnecessary water, chloride ions along with chemicals which cause corrosion of steel within. When calcium carbonate precipitation occurs, it blocks entry of substances and reduces [20]. In a trial method, when bacteria species like Sporosarcina pasteurii and Bacillus sp. CT-5 [18] were mixed with concrete, it showed large decrement in steel’s corrosion. Bacteria, blocks the water absorption by cracks by forming calcite precipitation, hence provides longer average self-life to reinforcement bars [22, 37-49].

5. Conclusions
This research paper provides brief introduction on the bacteria types, their morphology and properties of self-healing concrete. One of the main goals was to know the underlying mechanism of how urease producing bacteria can help in healing of cracks. It highlights how permeability and compressive strength of concrete are highly affected by the presence of bacterial specimen. The percentage of water and chloride permeability of concrete is highly reduced when bacterial specimens are present in the concrete, the reason being their ability to block the cracks. Biological reactions which involve bacteria protect concrete from freeze-thaw-attack and it in turn enhances concrete’s properties positively. The self-healing concrete reduces crack formation and heals already existing ones, thus it can be safely assumed that this concrete can effectively act as a replacement of conventional concrete.

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