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A Critical Review on Bacterial Concrete

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Abstract: ***Concrete, a strong, durable material composed of cement, aggregate and water, is the most used building material in the world. Concrete has an ultimate load bearing capacity under compression but the material is weak in tension. So, it cracks under loading. That is why steel bars are embedded in the concrete for the structure to carry tensile loads. Steel bars takes the load when concrete fails under tension. The concrete protects the steel reinforced bars from the environment and prevents corrosion. However, the cracks in the concrete form a major problem which affects the durability of the structures. Water and other salts seep through these cracks, corrosion initiates, and thus reduce life of concrete. So there was a need to develop a bio material, a self-repairing material which can remediate the cracks and fissures in the concrete. The goal of our study is to apply bacterially precipitated CaCO3 to heal the cracks in concrete. This technique is highly desirable because microbial activities are pollution free and natural. In this study, a Bacillus bacterium (Bacilluspasteuriior Bacillus subtilus) has been used to induce CaCO3 precipitation. This phenomenon is called Microbiologically Induced Calcite Precipitation (MICP). Use of these bio mineralogy concepts in concrete leads to invention of new material called-Bacterial concrete. Bacterial concrete is a material, which can successfully remediate cracks in concrete.***

Keywords: Bacillus bacterium, MICP, corrosion, fissures, bacterial concrete, precipitation

1. Introduction

Cracking in concrete is a main concern throughout the world because it causes loss of strength and reduces its durability. Many traditional methods are in use for crack repair like impregnation of cracks with epoxy based fillers, latex binding agents such as acrylic, polyvinyl acetate, butadiene styrene, etc. But, they are not compatible, very costly, reduce aesthetic appearance and need constant maintenance. Thus, there is a need for an eco-friendly remediation leads to the development of concept of bacterial concrete and hence improvement of strength of building materials. Microbiologically Induced Calcite or Carbonate (CaCO3) Precipitation (MICP) is a technique that can be used for the self-healing of the concrete. MICP is highly desirable because the Calcite precipitation induced because of microbial activities is eco-friendly, pollution free and natural. This technique also improves the compressive strength and stiffness of cracked concrete.

Bacteria: Types of bacteria used in concrete are Bacillus subtilis Bacillus pseudofirmus, Bacillus pasteurii, Bacillus sphaericus, Escherichia coli, Bacillus cohnii, Bacillus balodurans. To find the right bacteria we have to check whether it can survive in a high alkali environment (i.e.) up to pH 13. That kind of bacteria was mainly found in carbonate rich soils in deserts of Spain, alkali lakes in Russia, soda lakes in Egypt. For isolating the bacteria, soil samples are collected in test tubes, and some amount of water is added in to the test tube, then 1ml of this sample is taken and is mixed with 9ml of distilled water in it, then the concentration becomes 10-1. After this take 1ml solution from 1^{st} test tube to the 2^{nd}

test tube and again add 9ml of distilled water in 2^{nd} test tube. Repeat the above 3 steps 4 to 5 times. Then the concentration of solution becomes 10-4 to 10-6. The bacteria are cultivated at 37^{o}C. Initially 12.5g of nutrient broth (calcium lactate) is added to a 500 ml conical flask containing distilled water. Then it is covered with a cotton plug and is made air tight with rubber band and paper. It is then sterilized using a cooker for about 10-15 minutes. Now the solution is clear orange in colour before the addition of the bacteria. Later the flask is then opened and an exactly 1ml of the bacterium is added and is kept in a shaker at a speed of 150-200 rpm overnight. After 24 hours the bacterial solution was found to be whitish yellow turbid solution.

Preparation of bacterial concrete: There are 2 ways to prepare bacterial concrete, by direct application and by encapsulating light weight aggregate. By the method of direct application bacterial spores and calcium lactate are added while making the concrete and mixed. In this method, when the crack occurs in the concrete bacterial spores break and bacteria comes to life and feed on the calcium lactate and limestone is produced which fill the cracks. By encapsulation method the bacteria and its food, calcium lactate, are placed inside clay pellets and concrete is made. About 6% of the clay pellets are added for making bacterial concrete. When concrete structures are made with bacterial concrete, when the crack occur, the clay pellets are broken and bacterial mechanism occurs and hence the concrete s healed. Minor cracks can be treated by using bacterial concrete. Among these two-methods encapsulation method is most commonly used.

2. Mechanism of self-healing concrete

Basically there are 2 types of self-healing mechanisms:
a) Autogenous mechanism
b) Autonomous mechanism

Traditional concrete mixes consists 20-30% of un-hydrated cement, when exposed to moisture through cracks it hydrates, fills up and heal the cracks. In this case the hydration process may start again and hydration products may fill and heal the crack. Mainly micro cracks with widths in the range of 0.05 to 0.1mm are completely sealed under repetitive dry/wet cycles. This inherent mechanism is known as autogenous healing.

Autonomous self-healing is defined as an intentionally designed self-healing mechanism. Bacterial concrete is a product that will biologically produce limestone to heal cracks that appear on the surface of concrete structures. Specially selected types of the bacteria Bacillus, along with a calcium-based nutrient, and nitrogen and phosphorus, are added to the ingredients of the concrete when it is being mixed. However, when a concrete structure is damaged then water starts to seep through the cracks, the spores of the bacteria evolve on contact with the water and nutrients. Bacteria gets activated and starts to feed on the calcium lactate. As the bacteria feeds oxygen is consumed and the soluble calcium lactate is converted to insoluble $CaCo_3$ (limestone). The limestone solidifies on the cracked surface, thereby sealing it up. The consumption of oxygen during the bacterial conversion of calcium lactate to limestone has an extra advantage. Oxygen is a vital element in the process of corrosion of steel and when the bacterial activity has consumed it all, it increases the durability of steel reinforced concrete constructions. Chemical equations involved in bacterial concrete mechanism are:

$$CO\ (NH_2)_2 + H_2O \rightarrow NH_2COOH + NH3 \quad (1)$$

$$NH2COOH + H2O \rightarrow NH3 + H2CO3 \quad (2)$$

$$H_2CO_3 \rightarrow HCO_3 + H+ \quad (3)$$

$$2NH3 + 2H2O \rightarrow 2NH4+ + 2OH- \quad (4)$$

$$HCO_{3-} + H^+\ 2OH^{--} \rightarrow CO_3^{2-} + 2H_2O \quad (5)$$

$$CO3^{2-} + Ca^{2+} \rightarrow CaCO3 \quad (6)$$

$$CO\ (NH2)2 + 2H2O + Ca2+ \rightarrow 2NH4+ + CaCO3 \quad (7)$$

1ml of urea is hydrolyzed intra cellular to 1ml of ammonia and 1ml of carbonate, which is reported in Eq. (1) According to Eq. (2), carbonate hydrolyzes to ammonia and carbonic acid. Eq. (3) and (4) show former products subsequently equilibrate in water to form bicarbonate, ammonium and hydroxide ions. The later cause's pH increase resulting in the formation of carbonate ions Eq. (5), which in the presence of soluble calcium ions precipitate as CaCo3 Eq. (6). Eq. (7) is the overall react ion, which show that ammonium and calcium carbonate are the products of added urea and calcium to the system.

3. Literature Review

V. Ramakrishnan et al (2001), had described about Microbiologically Induced Calcite precipitation (MICP). MICP is the technique called bio mineralization by which living organism form inorganic solid. They use bacillus pasteruii as a microbial sealant. They found that the MICP is cost effective and it is natural process for development of calcite. They quantified calcite precipitation by XRD analysis and visualized by scanning electron microscope.

Chava Srinivas. et al, (2004) High volume fly ash can be incorporated into M20 grade concrete, thus maximizing the use of FA. Considering the stress – strain behavior, the ductility of bacterial concrete is more than that of fly ash added bacterial concrete

Narayana.P.S.S. et al, **(2004)** the improvement in compressive strengths at 28 days with 5% addition of micro silica is 20% more compared with 0% addition. The addition of micro silica has improved the resistance of bacterial concrete to the attack of acids and sulphates.

P. Ghosh et al (2005). Had investigated on use of microorganism to improve the strength of cement mortar. A method of strength improvement of cement-sand mortar by the micro biologically induced mineral precipitation was described. A thermophilic anaerobic micro-organisms is incorporated at different cell concentrations with the mixing water. The study show that 25%increase in 28day compressive strength of cement mortar was achieved with the addition of about 10^5 cell/ml of mixing water.

Chiara Barabesi et al, (2007) had studied about calcium carbonate formation by Bacillus subtilis, in order to identify genes involved in the bio mineralization process. The genes have putative functions linked to carboxylic acid metabolism.

HenkM.Jonkers and Erik Schlangen (2007), have published a paper on Development of a bacteria-based self healing concrete. In this paper Bacillus cohnii, Bacillus halodurans and Bacillus pseudofirmus species were obtained from the German Collection of Microorganisms and Cell cultures. They have used both bacteria and mineral precursor compounds mixed with the paste and thus therefore formed as an integral material.

Meera C M and DrSubha (2007), had published a paper on Strength and Durability assessment Of Bacteria Based Self-Healing Concrete. In this paper they have discussed about the effect of Bacillus subtilis JC3 on the strength and durability of concrete. They used cubes of sizes 150mm x 150mm x 150mm and cylinders with a diameter of 100mm and a height of 200mm with and without addition of micro organisms, of M20 grade concrete. It was observed that the compressive strength of concrete showed significant increase by 42% and increase in the tensile strength by 63% for a bacteria concentration of 105cells/ml at 28 days. For durability assessment, acid durability test, chloride test and water absorption test were done. The Water Absorption Test, showed that the concrete will become less porous due to the formation of Calcium Carbonate, due to which it resulted in lesser water absorption rate. Chloride test results showed that the addition of bacteria decreases weight loss, due to Chloride exposure and enhances the Compressive Strength.

Willem De Muynck et al, (2008) had reported the effects of bacterial carbonate precipitation on the durability of mortar specimens with different porosity. The surface deposition of calcium carbonate crystals decreased the water absorption with 65 to 90% depending on the porosity of the specimens. As a consequence, the carbonation rate was decreased by about 25–30%. An increased resistance towards freezing and thawing was also noticed. The results obtained with the bio deposition treatment were similar as those obtained with conventional surface treatments

E Schlangen et al (2010), studied about the use of bacterial concrete in water retaining structures. A method in which relatively large cracks in reinforced concrete can be filled and the path to the reinforcement is blocked is discussed. This method is useful for water retaining structures. Cracks can be filled in this way and leakage can be stopped. Especially in underground structures were repair is difficult or impossible Bacterial concrete has a big future**.**

K. VanTittelboom et al. (2010), has studied about use bacteria to repair cracks in concrete. Ureolytic bacteria such as bacillus, sphaericus, were able to precipitate CaCO3 in their micro environment by conversion of urea into ammonium and carbonate. The bacterial degradation of urea locally increases the pH and promotes the microbial deposition of carbonate as calcium carbonate in a calcium rich environment. These precipitated crystals can thus fill the cracks.

Sunil Pratap Reddy (2010) et al, proposed to use bacillus subtilis, which can produce calcite precipitates on suitable media supplemented with a calcium source. Cement mortar cubes with 4 different cell concentrations were cast and control specimen was also cast. This study showed a significant increase in the compressive strength was observed due to the addition of bacteria for a cell concentration of 105 cells per ml of mixing water. So, bacteria with a cell concentration of 105 cells per ml of mixing water was used in the investigation. Compressive strength is increased up to 14.92% at 28 days by addition of bacillus subtilis when compared to conventional concrete.

V.Achal et al. (2011), had reported about the effect of calcifying bacteria on permeation properties of concrete structures. Sporasarcinapasteurii (Bp M-3) was used. An inexpensive industrial waste, corn steep liquor (CSL), from starch industry was used as nutrient source for the growth of bacteria and calcite production, and the results obtained with CSL medium were comparable to those obtained with standard medium, indicating the economization of the bio calcification process. The results suggest that calcifying bacteria play an important role in enhancing the durability of concrete structures.

J.Wang et al (2012), has reported on use of silica gel or polyurethane immobilized bacteria for self-healing concrete. In this research, the possibility to use silica gel or polyurethane as the carrier for protecting the bacteria was investigated. Experimental results show that silica gel immobilized bacteria exhibited a higher activity than polyurethane immobilized bacteria, and hence, more $CaCO_3$ precipitated in silica gel (25% by mass) than in polyurethane (11% by mass) based on thermo gravimetric analysis.

Navdeep Kaur Dhami (2012) et al, purposed to investigate the potential of Bacillus megaterium to produce calcite and improve properties of Fly ash bricks and Rice husk ash bricks. They found that the treated bricks have showed improved compressive strength and reduction in frost attack, water absorption due to calcite deposition on the surface and voids of bricks. SEM images, X-ray diffraction and energy dispersive X-ray analysis confirmed the precipitates formed as CaCO3 are calcite crystals. These observations suggest that this technology has the potential of producing durable and eco-friendly building blocks.

R.Pei et al. (2013). Had reported about use of bacterial cell walls to improve the mechanical performance of the concrete. The role of bacterial cell walls of Bacillus subtilis as a concrete admixture to improve the mechanical performance of concrete. The bacterial cell walls are known to mediate microbial induced carbonate precipitation, a process in which CaCO3 is formed from Ca2+ ions and dissolved CO2.

Kartik M. Gajjar (2013), had Purposed to use the bacteria named bacillus lentus a common soil bacterium to induce calcite precipitation. He found the effectiveness of this technique by comparing strength and durability of cracked specimens remediated with bacteria and those of the control specimens. The experiment study found that with addition of bacteria improves the compressive Strength around 17.3% at 28th day and 17.6% at 56th day. The flexural strength is not much increased in 28th and 56th day.

MayurShantilalVekariya (2013), had found that the microbial activity is most economical, self-repairing building material. Work of various researchers has improved our understanding on the possibilities, advantages and limitations of biotechnological applications on building materials. Enhancement of compressive strength, reduction in permeability, water absorption, and reinforced corrosion has been seen. This technique is desirable but it require more research study and the microorganism requires some favourable condition.

H.K. Kim (2013) et al, investigated that the characteristics of microbiological precipitation of calcium carbonate on normal and lightweight concrete by two types of bacteria, Sporosarcinapasteurii and Bacillus sphaericus. SEM images and energy dispersive spectroscopy (EDS) spectra were used to observe the shapes and distributions of the calcium carbonate crystals. A capillary water absorption test of the concrete specimens was conducted to evaluate the effects of precipitation of calcium carbonate on the properties of moisture transport, which may affect the durability of the concrete. They found that B. sphaericus precipitated denser calcium carbonate crystals than S. pasteurii.

Jagadeesha Kumar B G, R Prabhakara and Pushpa (2013), published a paper on Effect of Bacterial Calcite Precipitation on Compressive Strength of Mortar Cubes. Three bacterial strains Bacillus flexus, Bacillus pasturii and Bacillus sphaericus were used. Among the three strains of bacteria, Cubes treated with Bacillus flexus, which is not reported as bacteria for calcite precipitation has shown maximum compressive strength than the other two bacterial strains and control cubes. All the three strains of bacteria were tested for urease activity. The change of the color of the media from yellow to pink indicated that it is urease positive. All the three strains were urease positive.

NavneetChahal et.al (2013), has showed that strength and durability was increased by using FLY ASH amended concrete by microbial calcite precipitation. Sporoscarcinapasteurii bacteria is used on fly ash concrete. In this work the cement was partially replaced with 10, 20 and 30 percentage of fly ash. Different concentrations (0, 103,105,107 cells/ml) of bacteria were used in the concrete.

The compressive strength test shows 22% increase in compressive strength for 105 concentration. Water absorption reduced 4 times. Chloride permeability reduced nearly 8 times. Water absorption and chloride penetration also reduced more for the concentration 105 with 10% silica fume.

Ravindranatha, N. Kannan, LikhitM (2014), have published a paper on Self-Healing Bacterial Concrete. In this paper a comparison study was made with concrete cubes and beams subjected to compressive and flexural strength tests with and without the bacterium Bacillus pasteurii. The microbe proved to be efficient in enhancing the properties of the concrete by achieving a very high initial strength increase. The calcium carbonate produced by the bacteria has filled some percentage of void volume thereby making the texture more compact and resistive to seepage.

R.Siddique et al. (2014), had reported on the influence of bacterial treated cement kiln dust on properties of concrete. During cement manufacturing, cement kiln dust (CKD) is generated which represents significant environment concern related to its emission, disposal and reuse due to high alkalinity. Concrete specimens were prepared with 0%, 5%, 10% and 15% untreated and treated cement kiln dust replacing cement. Test results indicated that 7.15% and 26.6% increase in strength of concrete was achieved at 28 and 91 days, respectively, with the addition of bacterial treated 10% CKD whereas reduction in water absorption (20%) and porosity (12.35%) was observed at 91 days.

Senthilkumar et al. (2014), had Compared the strength characteristics of microbial cement mortars. It deals with comparative studies on strength characteristics in microbial cement mortars which were treated by enterobacteria sp. The calcium carbonate crystals formation and the surface morphology of cement mortar were investigated by XRD and SEM. Cement mortar specimens with and without addition of bacterial species were casted and ~ 44% increase in compressive strength, ~56% in tensile strength was noticed while compared to control specimen (without bacteria). Surface treatment of specimen with bacteria resulted around ~40% decrease of water absorption.

S.Krishnapriyaetal (2015), purposed to use three type of bacteria named Bacillus megaterium (BSKAU), Bacillusnlicheniformis (BSKNAU) andbacillus flexus (BSKNAU). Cracks were induced in the beam specimens by introducing a thin copper plate of thickness 0.3 mm up to a depth of 10 mm in the fresh concrete. The plates were removed before final setting of concrete such that a crack was clearly visible in the beam specimens. The specimens were removed from moulds after 24 hours and cured in water. The mix design which was use is M25.They found that the Bacillus megaterium MTCC1684 exhibited high urease activity and Bacillus licheniformis BSKNAU is close to Bacillus megaterium MTCC 1684.

V Srinivasa Reddy, M V SeshagiriRaoand S Sushma (2015), had reported on Feasibility Study on Bacterial Concrete and cost analysis was made. This paper describes about the effect of bacterial cell concentration of Bacillus subtilis JC3, on the strength, by determining the compressive strength of standard cement mortar cubes of different grades, incorporated with various bacterial cell concentrations. The cost analysis showed an increase in cost of2.3 to 3.9 times between microbial concrete and conventional concrete with decrease of grade. And nutrients such as inexpensive, high protein- containing industrial wastes such as corn steep liquor (CSL) or lactose mother liquor (LML) effluent from starch industry can also be used, so that overall process cost reduces dramatically.

FarzanehNosouhian (2015) et al, evaluates microbial surface treatment in order to prevent sulphate ions penetration. Five groups of concrete specimens were cast and cured and were then surface treated applying 3 different microbial suspensions using Sporosarcinapasteurii, Bacillus subtilis and Bacillus sphaericus bacteria. Durability was assessed through the mass losses, volume changes, water absorption and compressive strength. A durability loss index (DLI) for the concrete which was introduced in this paper demonstrated that surface treatment of concrete by S. sphaericus bacteria produced the most durable concrete in a sulphate environment amongst all the tested biological treatments and specific cell concentrations tested in this study.

RA. B. Depaaand T. Felix Kala (2015), had reported about Investigation of Self-Healing Concrete using Silica Fume and GGBFS as Mineral Admixtures. In this paper cubes have been prepared by adding silica fume in percentage of 2.5%, 5%,7.5%, 10%, 12.5% as a binder in addition to adding cement to concrete and also by replacing 35% and 55% of cement with GGBFS. The concrete mix containing cement replaced with 35% GGBFS has given maximum compressive strength value. Further when silica fume is added as mineral admixture, the mix has given maximum strength at 12.5% addition of silica fume.

MohitGoyal and P. Krishna Chaitanya (2015), published a paper on Behavior of Bacterial Concrete as Self-Healing Material. In this paper they have carried out laboratory investigations to compare the different Bacterial Concrete parameters of bacterial concrete with ordinary concrete and concrete, in which 70% cement was partially replaced with 30% of Fly Ash and 30% of GGBS. In this paper, Bacillus pasteurii, is used to prepare M25 concrete. Various tests such as slump flow test, compressive strength, flexural strength and split tensile strength were conducted for different specimens of, bacterial concentrations of 40ml, 50ml and 60 ml for each specimen. There was significant improvement of compressive strength by 30% in concrete mix with bacteria and more than 15% in fly ash and 20% in GGBS. It was observed that bacterial concrete achieves maximum split tensile strength and flexural strength when 50 ml bacterial solution was used.

Chithra P Bai and Shibi Varghese (2016), had published a paper on an experimental investigation on the strength properties of fly ash based Bacterial concrete. In this paper, The bacteria Bacillus Subtilis was used for study with different cell concentrations of 103 , 105 and 107 cells/ml for preparing the bacterial concrete. Cement was partially replaced by 10%, 20% and 30% of fly ash by weight for making the bacterial concrete. Concrete of grade M30 was used and tests such as Compressive strength, Split tensile strength, Flexural strength and Ultrasonic Pulse Velocity were conducted after 28 and 56 days of water curing. For fly ash concrete, maximum compressive strength, split tensile strength, flexural Strength and Ultrasonic Pulse Velocity values were obtained for 10% fly ash replacement at 105 cells/ml.

N. Ganesh Babu and Dr.S.Siddiraju (2016), had published a paper on an experimental study on strength and fracture properties of self-healing concrete. The percentages of bacteria selected for the study are 3.5% and 5% by weight of cement. In addition, calcium lactate was used at 5% and 10% replacement of cement by weight. Bacillus pasteurii is used for different bacterial concentrations for M40 grade of concrete. With the addition of calcium lactate at 10% (optimum percentage) and bacteria to concrete, there is considerable increase in compressive strength. Hence calcium lactate along with 3.5% and 5% bacteria can be used as an effective self-healing agent.

4. Conclusions

1) From the study we can predict that the lifetime of bacterial concrete is more than conventional concrete. So, the use of bacterial concrete can create new job opportunities for the experts.
2) In bacterial concrete interconnectivity of pores is disturbed due to persisting of pores with calcite crystals. As interconnected pores are significant for permeability, the water permeability is decreased in bacteria treated specimens.
3) Silica gel can be used for protecting bacteria in high pH environment. This resulted in increase in ability to fill the cracks more efficiently than the bacterial concrete without silica gel which was confirmed by ultrasonic pulse velocity tests and SEM images.
4) When bacterial concrete is completely developed, it may become yet another alternative method to replace OPC and its dangerous effect on environmental pollution result in the crack sealing. Hence can be used for construction as it is resistant to corrosion.
5) There are many advantages of bacterial concrete, it primarily reduce the maintenance costs, repair costs and hence results in increase of durability of the structures.
6) CKD (cement kiln dust) can be used to replace some amount of cement. SEM and XRD recommended that bacterial treated 10% CKD concrete increased calcium silicate hydrate and formation of non-expansive ettringite in pores dense the concrete structure which increases compressive strength and reduces permeability and porosity.
7) Bacterial concrete is useful for water retaining structures. Cracks can be filled by self-healing technique and leakage can be stopped. Especially in underground structures were repair is difficult or impossible, bacterial concrete has a big future.
8) The cost of the bacterial concrete, according to the opinions of researchers is nearly 30% more than the conventional concrete, depending upon the type and concentration of bacteria. But the maintenance cost of bacterial concrete will be very less when compared to conventional concrete.
9) The cost increase of bacterial concrete is mainly due to calcium nutrient (calcium lactate is very costly). The cost can be reduced by replacing calcium lactate with corn steep liquor (CSL) (industrial waste of starch industry), wheat bran, or sugar based nutrients.
10) If microbiology laboratory is developed, the isolation, culture and growth of bacteria can be done at negligible cost. Hence it can be cost effective also.

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