© 2016 IJSRSET | Volume 2 | Issue 1 | Print ISSN : 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

A Study on Self-Healing Mechanism of Microcracks in Concrete Structures Using Bacillus Bacteria

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ABSTRACT

Corrosion of the steel reinforcement in concrete requires manual and costly repair procedures to prevent premature failure of constructions. Although preventive measures during the construction phase are often implemented but early corrosion may still occur. The primary reason for premature corrosion is crack formation in the concrete cover. Larger cracks as well as a network of finer cracks allow water, oxygen, chloride, and other aggressive corroding substances to penetrate the concrete matrix to reach the reinforcement. The objective of the paper described in this proposal is the development and application of a bio-chemical agent which, when incorporated in the concrete matrix, autonomously and actively prevents premature reinforcement corrosion in a twofold mode. The produced bio-minerals block and seal cracks resulting in a delay of further ingress of water as well as to a decrease of inward diffusion rate of chloride and oxygen. Moreover, as the metabolically active bacteria consume oxygen, the agent acts as an oxygen diffusion barrier protecting the embedded passivity steel reinforcement against corrosion. In this way the reinforcement will be protected for substantially increased periods, even after breakdown of the passivity layer, as a lack of oxygen prevents further corrosion.

Keywords: Bio Concrete, Self-Healing Compound, Cracks in Concrete, Corrosion of Steel, Repairs, Maintenance.

I. INTRODUCTION

The concept of bacterial concrete was first introduced by Henk Jonkers of Delft University of Technology in the Netherlands A novel technique is adopted in remediating cracks and fissures in concrete by utilizing microbiologically induced calcite (CaCO3) precipitation. Microbiologically induced calcite precipitation (MICP) is a technique that comes under a broader category of science called biomineralization. Bacillus subtilis JC3, a common soil bacterium can induce the precipitation of calcite. As a microbial sealant, CaCO3 exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. Microbiologically induced calcite precipitation is highly desirable because the calcite precipitation induced as a result of microbial activities, is pollution free and natural. The technique can be used to improve the compressive strength and stiffness of cracked concrete specimens. The bacterial concrete makes use of calcite precipitation by bacteria. The pioneering work on repairing concrete with MICP is reported by the research group of Henk Jonkers and others at the South Dakota School of Mines & Technology, USA. Under favorable conditions Bacillus subtilis JC3, when used in concrete, can continuously precipitate a new highly impermeable calcite layer over the surface of the already existing concrete layer. The precipitated calcite has a coarse crystalline structure that readily adheres to the concrete surface in the form of scales. In addition to the ability to continuously grow upon itself, it is highly insoluble in water. It resists the penetration of harmful agents (chlorides, sulphates, carbon dioxide) into the concrete thereby decreasing the harmful effects they cause. Due to its inherent ability to precipitate calcite continuously, bacterial concrete can be called a Smart Bio Material for repairing concrete. The MICP comprises a series of complex biochemical reactions. It is selective and its efficiency is affected by the porosity of the medium, the number of cells present and the total volume of nutrient added. The phosphate buffer or urea-CaCl2 has been found effective as nutrients. The bacteria precipitate calcite in the presence of nutrients. The optimum pH for growth of bacteria B. pasteurii is around 9. The alkaline environment of concrete with pH around 12 is the major hindering factor for the growth of bacteria. However, B. pasteurii has the ability to produce end spores to endure an extreme environment, as observed by V.Ramakrishnan and the research team. The microbial modified mortar or concrete has become an important area of research for high-performance construction materials.

Figure 1: A sample of bacterial concrete

II. METHODS AND MATERIAL

A. Bacteria Used in Bio concrete

Researchers have created a new kind of concrete glue that can patch up the cracks in concrete structures, restoring buildings that have been damaged by seismic events or deteriorated over time. But the glue isn't an adhesive or some kind of synthetic material; the researchers have custom-designed a bacteria to burrow deep into the cracks in concrete where they produce a mix of calcium carbonate and a special bacteria glue that hardens to the same strength of the surrounding concrete.

"BacillaFilla," as the researchers call it, is a genetically modified version of Bacillus subtilis, bacteria commonly found in common soil. The researchers have tweaked its genetic properties such that it only begins to germinate when it comes in contact with the highly-specific pH of concrete. Once the cells germinate, they are programmed to crawl as deep as they can into cracks in the concrete, where quorum sensing lets them know when enough bacteria have accumulated. That accumulation lets the bacteria know they've reached the deepest part of the crack, at which point the cells begin to develop into bacterial filaments, cells that produce calcium carbonate and cells that secrete a kind of bacterial glue that binds everything together. Once hardened, the bacteria are essentially as strong as the concrete itself, restoring structural strength and adding life to the surrounding concrete.

The bacteria also contains a self-destruct gene that keeps it from wildly proliferating away from its concrete target, because a runaway patch of bacterial concrete that continued to grow despite all efforts to stop it would be somewhat annoying. The researchers hope their BacillaFilla will improve the longevity of concrete structures, which can be environmentally costly to erect. It could also be deployed in earthquake stricken zones to quickly reinforce damaged buildings and reduce the number of structures that have to be razed after a disaster.

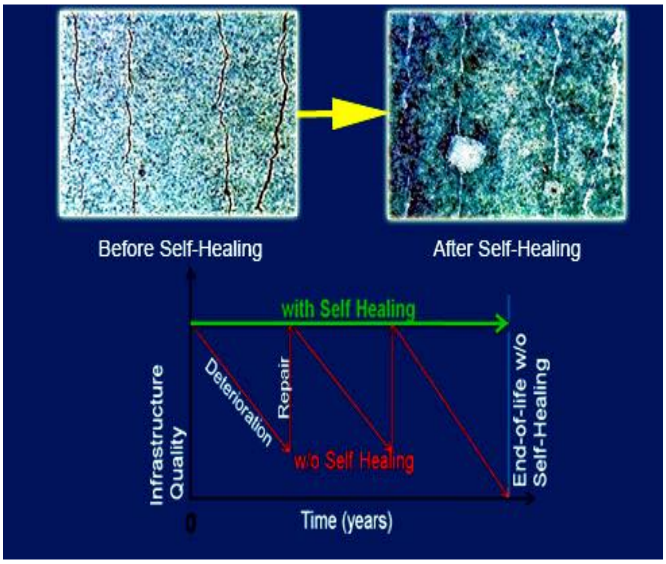

Figure 2: Function of bacteria in self-healing of concrete

Cement and water have a pH value of up to 13 when mixed together, usually a hostile environment for life, most organisms die in an environment with a pH value of 10 or above.

In order to find the right microbes that thrive in alkaline environments can be found in natural environments, such as alkali lakes in Russia, carbonate-rich soils in desert areas of Spain and soda lakes in Egypt. Strains of endolithic bacteria of genus Bacillus were found to thrive in this high-alkaline environment. These bacteria were grown in a flask of water that would then be used as the part of the water mix for the concrete. Different types of bacteria were incorporated into a small block of concrete.

Each concrete block would be left for two months to set hard. Then the block would be pulverized and the remains tested to see whether the bacteria had survived. It was found that the only group of bacteria that were able to survive was the ones that produced spores comparable to plant seeds. They are namely bacillus pasturii, bacillus filla and bacillus cohnii.

Such spores have extremely thick cell walls that enable them to remain intact for up to 200 years while waiting for a better environment to germinate. They would become activated when the concrete starts to crack, food is available, and water seeps into the structure. This process lowers the pH of the highly alkaline concrete to values in the range of pH 10 to 11.5 where the bacterial spores become activated.

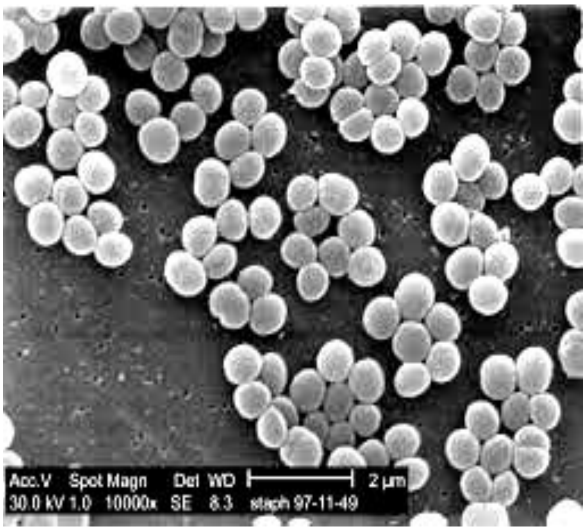

Figure 3: Bacillus cohnii

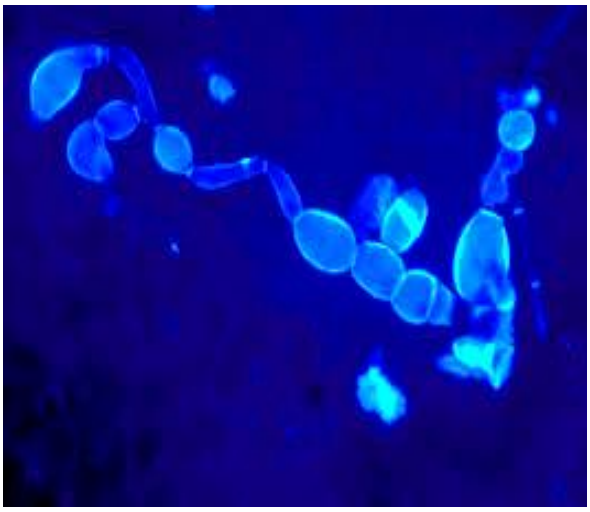

Figure 4: Bacillus filla

Figure 5: Bacillus Parturii

Helping Cut CO_2 Emissions

With concrete production a major contributor of global carbon dioxide emissions, the BacillaFilla could provide a way to repair instead of replace existing concrete structures.

“Around five per cent of all man-made carbon dioxide emissions are from the production of concrete, making it a significant contributor to global warming. Finding a way of prolonging the lifespan of existing structures means we could reduce this environmental impact and work towards a more sustainable solution.”

This could be particularly useful in earthquake zones where hundreds of buildings have to be flattened because there is currently no easy way of repairing the cracks and making them structurally sound.

B. Mechanism in Bio concrete

The cracks are formed on the surface of concrete due to many reasons like shrinkage, inadequate water for hydration. Self-healing bacterial concrete autogenously crack-healing capacity of concrete has been recognized in several recent studies. Mainly micro cracks with widths typically in the range of 0.05 to 0.1 mm have been observed to become completely sealed particularly under repetitive dry/wet cycles. The mechanism of this autogenously healing is chiefly due to secondary hydration of partially reacted cementing particles present in the concrete matrix. Due to capillary forces water is repeatedly drawn into micro cracks under changing wet and dry cycles, resulting in expansion of hydrated cement particles due to the formation of calcium silicate hydrates and calcium hydroxide. These reaction products are able to completely seal cracks provided that crack widths are small. Larger sized cracks can only be partially filled due to the limited amount of non-reacted cement particles present, thus resulting in only a thin layer of hydration products on the crack surface. With respect to crack-sealing capacity, a process homologous to secondary hydration of cement particles is the process of carbonation. The water is deliberately forced into the crack and the precursor is activated.

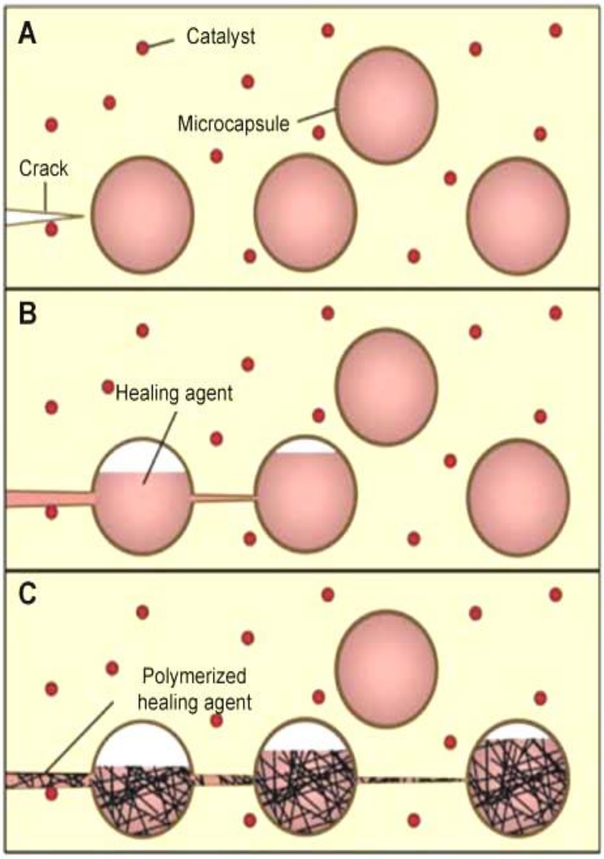

Figure 6: Healing process in concrete

The activated precursor intern induces the bacteria to react with that precursor and form a base of calcium carbonate called as limestone, the chemical equation is given below.

$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$

$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$

The bacteria can thus act as a nucleation site which facilitates in the precipitation of calcite which can eventually plug the pores and cracks in the concrete. This microbiologically induced calcium carbonate precipitation (MICCP) comprises of a series of complex biochemical reactions. As part of metabolism, B.Subtilus produces urease, which catalyzes urea to produce CO2 and ammonia, resulting in an increase of pH in the surroundings where ions Ca^{2+} and CO_3^{2-} precipitate as $CaCO_3$.

These create calcium carbonate crystals that further expand and grow as the bacteria devour the calcium lactate food. The crystals expand until the entire gap is filled. In any place where standard concrete is currently being used, there is potential for the use of bacterial self-healing concrete instead. The advantage of having self-healing properties is that the perpetual and expected cracking that occurs in every concrete structure due to its brittle nature can be controlled, reduced, and repaired without a human work crew. Bacterial self-healing concrete also prevents the exposure of the internal reinforcements. This form of self-healing concrete was created to continuously heal any damage done on or in the concrete structure. It was made to extend the life span of a concrete structure of any size, shape, or project and to add extra protection to the steel reinforcements from the elements. With this process, money can be saved, structures will last far longer, and the concrete industry as a whole will be turning out a far more sustainable product, effectively reducing its CO^2 contribution.

Temperature Sustainability Test of Bacteria

The temperature sustainability test of B. subtilis in bacterial concrete was carried out at various temperatures by A.T. Manikandan et al. and the results are tabulated in Table 1. The results revealed that B. subtilis was found to be alive at -3^o C low temperature to 80^o C high temperature.

Table 1: Temperature Sustainability Test for Bacillus Subtilis Bacteria

Temperature	Bacteria Condition
-3 ^oC	Alive
10 ^oC	Alive
20 ^oC	Alive
30 ^oC	Alive
40 ^oC	Alive

50 ^{o}C	Alive
60 ^{o}C	Alive
70 ^{o}C	Alive
80 ^{o}C	Alive
90 ^{o}C	Dead

Strength of Bacterial Concrete

The use of aerobic microorganisms (Pseudomonas aeruginosa and Bacillus pasteurii), as self-healing agents have shown 18% improvement in the compressive strength of cement mortar. Jonkers (2007) in his study has investigated the use of bacteria for the healing of cracks occurring in the concrete as self-healing agent. DeMuynck et al. (2008) have shown that durability of cementitious materials can be improved along with the deposition of carbonate by Bacillus sphaericusas surface treatment. Ramachandran et al. (2001) reported the use of bacteria for enhancing the durability of concrete as to show resistance towards the alkali, freeze-thaw attack, sulfate, drying and shrinkage. Achalet al., (2011) investigated the effects of Bacillus sp. CT-5 isolated from cement for determining the water-absorption test and compressive strength. The result showed that the compressive strength of cement mortar increased to 36 % with the addition of microbes and the treated cubes were found to absorb water six times lesser when compared to the control cubes due to the deposition of microbial calcite. This indicates that by using Bacillussp for the production of “microbial concrete” it can enhance the durability of construction materials.

Ghosh et al. (2005) described a method for improving the strength of cement–sand mortar with microbial induced mineral precipitation. The increase in the compressive strength of cement mortar (25 %) at 28th day was observed with the addition of thermophilic and anaerobic bacteria, in the range of 105 cells/ml to the mixing water. The strength improvement was due to the growth of filler material within the pores of cement–sand matrix. Ghosh et al. (2005) used the bacteria E. coli in cement mortar to enable a better comparison, but from the improvement in strength that was actually observed it is clearly evident that mostly in the internal cracks, not much oxygen exists.

Bacillus megaterium which produces calcite can improve the properties of ash brick (Rice hush and Fly ash bricks) as investigated by Dhamia et al. (2012). A significant reduction in water absorption was noticed in the treated bricks along with the increasing compressive strength due to the deposition of calcite on the voids and surface of bricks. The extracellular deposition of calcite crystals on the surface of bricks is due to the microbial activity. These findings show that this technology has a better potential towards the development of eco-friendly and durable building blocks.

Table 2: Comparison of strength of Bio concrete and conventional concrete

Strength	**No. of Days**		
	3	**7**	**28**
Compressive Strength of Conventional Concrete Cubes, N/mm^2	19.24	23.66	34.52
Compressive Strength of B Sphaericus Concrete Cubes, N/mm^2	25.16	34.58	45.72
% Increase in Strength	30.76	46.15	32.21

Effect on Concrete Permeability

The common phenomenon observed in concrete structure is the formation of crack. The resulting micro crack formation hardly affects the structural properties of construction butin due course it may reduce the durability of concrete structure and may pose a threat due to the risk of ingress of aggressive substances particularly in a wet environment. Specific healing agents can be incorporated in the concrete matrix in order to increase the often observed autonomous crack-healing potential of concrete. Bacillus sphaericus are used for designing biological self-healing concrete according to the findings of Tittelboom et al. (2010). It is reported that pure bacterial cultures alone are not able to bridge the cracks but when they are present in silica gel, the cracks become fully cured. The increase in permeability after treating the specimens with **Bacillus Sphaericus** is due to the filling of unavoidable of air bubbles present in the specimen

Advantages of Bacterial Concrete

1. Microbial concrete helps in crack remediation.
2. Improvement in compressive strength of concrete.
3. Better resistance through freeze-thaw crack reduction.
4. Reduction in permeability of concrete.
5. Reduction in corrosion of reinforced concrete.
6. Self-healing bacteria can be used in places where humans find it difficult to reach for the maintenance of the structures. Hence it reduces risking of human life in dangerous areas and also increases the durability of the structure.
7. Formation of crack will be healed in the initial stage itself thereby increasing the service life of the structure than expected life.

Disadvantages of Bacterial Concrete

1. Cost of bacterial concrete is double than conventional concrete as preparation of calcium lactate from milk is costlier.
2. Growth of bacteria is not good in some atmospheric conditions.
3. There is no I.S code for design of mix concrete in bacteria.

Applications of Bacterial or Self-Healing Concrete

1. Marine structures
2. Base wall
3. Concrete flooring
4. Tunnel lining
5. Highway bridge
6. Underground retaining wall

Figure 7: Base Wall

Figure 8: Concrete Flooring

Figure 9: Tunnel Lining

Figure 10: Highway Bridge

III. CONCLUSION AND FUTURE SCOPE

The bacteria which are known to be alkali-resistant, i.e. they grow in natural environments characterized by a relatively high pH (10-11). In addition, these strains can produce spores which are resting cells with sturdy cell walls that protect them against extreme environmental mechanical and chemical stresses. Therefore these specific bacteria may have the potential to resist the high internal concrete pH values (12-13 for Portland cement-based concrete), and remain viable for a long time as well, as spore viability for up to 200 years is documented. It is hypothesized that concrete-immobilized spores of such bacteria may be able to seal cracks by bio mineral formation after being revived by water and growth nutrients entering freshly formed cracks. Incorporation of the agent in concrete will be relatively cheap as well as easy when the agent is immobilized in porous light-weight aggregates prior to addition to the concrete mixture. It is expected that the application of the proposed sustainable bio-chemical healing agent will result in substantially decreased maintenance and repair costs of steel-reinforced concrete structures. The addition of Bacillus subtilis bacteria increases the compressive strength of concrete. The compressive strength is increased nearly 23% at 28 days for ordinary, standard and high grades of concrete when compared to controlled concrete. From the durability studies, the percentage weight loss and percentage strength loss with 5% HCl and 5% H_2SO_4 revealed that Bacterial concrete has less weight and strength losses than the controlled concrete. Durability studies carried out in the paper through acid attack test with 5% HCl and 5% H_2SO_4 revealed that bacterial concrete is more durable in terms of “Acid Durability Factor” than conventional concrete and bacterial concrete is less attacked in terms of “Acid Attack Factor” than conventional concrete. From the above proof of information, it can be concluded that Bacillus subtilis can be safely used in crack remediation of concrete structure. Although the exact nature of the produced minerals still needs to be clarified, they appear morphologically related to calcite precipitates.

IV. ACKNOWLEDGEMENT

I would like to thank Prof. Meeta Verma, Prof. Sarah Khan, Prof. Sakshi Gupta, Dr. D.K Singh, Prof. R.C Sharma and Prof. M.K Sinha for their valuable discussions on the Self-healing Bio-concrete.

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