THE SELF-HEALING CONCRETE – A REVIEW

Poonam Ghodke[1], Swarda Mote[2]
[1]Undergraduate final year student, BTech in Chemical Engg, Priyadarshini Institute of Engg and Technology, Nagpur, Maharashtra, India.
[2]Associate Professor, Department of Chemical Engg, Priyadarshini Institute of Engg and Technology, Nagpur, Maharashtra, India.

ABSTRACT
Concrete will continue to be the vital component for infrastructures due to its first-rate properties such as easy availability, low cost, durability, strength and convenience to cast. It can withstand the compressive forces but it is prone to cracking due to tensile forces which in turn results in the reduction of the overall life as well as increase in the vulnerability of the concrete structure. Curing of the concrete increases the possibility of cracking due to the fluctuations in the humidity and temperature. With the aging of the structure, brittleness increases as the moisture content decreases. Retrogression of the reinforcement steel bars due to introduction of corrosive chemicals through cracks, frost damage and water leakage are some of the problems encountered thus pinching the pockets and making the maintenance and repairs costlier. An expeditious self-healing crack mechanism is required which causes the decline in the chemical intrusion, thus dwindling the corrosion and thereby increasing the service life of the concrete structure. In this paper, an attempt has been made to re-mediate the cracks and fissure in the concrete by employing Microbiologically Induced Calcite Precipitation (MICP). The method results in enhancing the strength and durability of the structures by healing the cracks through microbial activities which happens to be eco-friendly. A review of this technique for future commenced use has been discussed.

KEYWORDS: *Self-healing concrete, Microbiologically Induced Calcite Precipitation (MICP), chemical intrusion, eco-friendly.*

I. INTRODUCTION

In the modern times, concrete is the most popular and widely used engineering material for the construction of infrastructures but the emergence of crevice in it is inevitable. The early age of the concrete is a crucial period, primary crack formation takes place during curing as heat is liberated which is a result of heat of hydration. In order to maintain uniform temperature throughout, water is sprayed and moist Hessian cloths are used to retain the moisture. Reinforcement steel bars are used in the structures in order to impart strength but presence of cracks results in its corrosion. Water seeping through these cracks during winter, freezes thus widening the existing crack. And if the crack occurs in the places which are difficult to reach then the repairing becomes more complicated. Frequent maintenance, monitoring and repairs are also expensive. In a nutshell, despite the number of measures taken, crack formation is quite imminent due to human errors, unskilled labor, weather conditions, etc. Microcracks cannot hamper the overall integrity of the structure as such but its widening and exposure to chemicals can have adverse effects on the strength and durability of the concrete. Cracks often occur in concrete because of the low tensile strength of the material. Rapid crack-healing is necessary since it is easier for aggressive substances to ingress into concrete through cracks than through the concrete matrix. It would be desirable if concrete cracks could be healed autonomously by releasing healing agents inside the matrix when cracks appear **(J.Y.Wang et al, 2010)**. Fixing such micro cracks is not only time consuming as well as costly but is necessary. If it is left unattended, it might result in collapsing of the entire structure.

This paper discusses about a technique used to address the concerns mentioned above. Self-healing concrete is a dead concrete pervaded with limestone producing bacterial spores of genus Bacillus along with a healing agent calcium lactate which are encapsulated in clay pellets. The process replicates the

healing of the fractures and fissures in the human body. When the crack forms, the pellets inside the concrete break and moisture seeps through the cracks thus awaken the bacterial spores to action and commencing the process of healing by producing limestone. The spores can lie dormant inside the concrete for about 200 years (**H. M. Jonkers, 2016)**. The activation of the bacterial spores occurs only when it comes in contact with oxygen and water and its germination or growth occurs with the help of the healing agent.
This paper reviews on the new way of dealing with the concrete related issues especially cracking, Microbiologically Induced Calcite Precipitation is the method that shall be solving the purpose and how the healing actually occurs with the myriad of chemical reactions involved in the process. Importance of the encapsulation process and the right bacteria to bring about the microbial healing are also discussed along with the advantages and disadvantages of the overall idea.

II. MECHANISM OF SELF-HEALING

The micro cracks that are developed inside the concrete due to the immoderate tensile forces provides the site for self-healing via bacterial activities. The bacterial spores and calcium lactate that are used as the healing agents, act as the precursors during the process. The spores along with the calcium lactate are embedded and stored into the expanded clay pellets consisting of pores and bubbles. These pellets are then distributed uniformly throughout the concrete during the mixing process. Whenever crevices are formed in such concrete, the pellets rupture thus letting the bacterial spores and chemical precursor out. The moisture and oxygen enters such micro cracks furnishing favorable environment for the multiplication of the bacteria. R. Spinks, in an article for *the Guardian*, comments on the interesting nature of this healing process: "It is only with the arrival of concrete's nemesis – rainwater or atmospheric moisture seeping into cracks – that the bacteria start to produce the limestone that eventually repairs the cracks" **(R. Spinks, 2015)**. The limestone, thus formed in approximately seven days seal the crack as wide as 0.5- 0.8mm **(Prachi Patel, 2016)**. In concrete cracks up to 0.2mm wide are healed autogenously. Such micro cracks are acceptable as these do not directly influence the safety and strength of concrete. The in-built bacteria-based self-healing process was found to heal cracks completely up to 0.5mm **(M.V.Seshagiri Rao et al, 2013)**. Prior, oxygen and water, which were responsible for degrading the quality of concrete, now triggers the process. **Fig. 1 and Fig. 2 shows the before and after healing process**

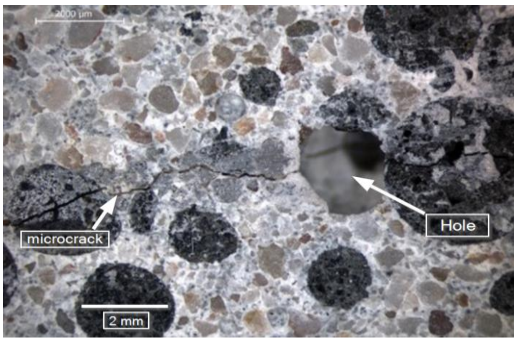

Fig.1 Before the healing process
(P. Patel, 2016)

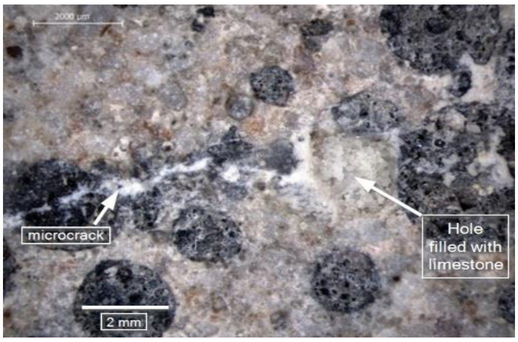

Fig.2 After the healing process
(P. Patel, 2016)

III. ENCAPSULATION PROCESS

When bacterial spores were directly added to the concrete mixture, their lifetime appeared to be limited to one-two months **(Jonkers, H.M., Thijssen, A., Muyzer, G., Copuroglu, O., and Schlangen, E,2010)**. The decrease in life-time of the bacterial spores from several decades when in dry state to only a few months when embedded in the concrete matrix may be due to continuing cement hydration resulting in matrix pore-diameter widths typically much smaller than the 1-μm sized bacterial spores **(Jonkers, H.M., Thijssen, A., Muyzer, G., Copuroglu, O., and Schlangen, E.,2010)**. Another concern is whether direct addition of organic bio-mineral precursor compounds to the concrete mixture will not result in unwanted loss of other concrete properties. So, in order to overcome this drawback encapsulation of the bacteria and the precursor has to be done.

The clay pellets must have the following characteristics before placing the healing agents into it:

1. The pellets must be able to sustain the continuous and rigorous mixing process.
2. At the same, they must be brittle enough to break during the crack formation.
3. The pellets must bind properly with the rest of the paste.
4. The pellets must allow the dissemination of bacteria and calcium lactate once it ruptures.
5. Apart from that, they must provide good thermal insulation, moisture impermeability, fire resistance and neutral pH.

The clay pellets not only represent an internal reservoir but also constitute both a structural element of concrete as well as a protective matrix for the self-healing agent **(H. M. Jonkers, V Wiktor, 2016)**. The clay pellets are lightweight and are less than 2mm in size. These pellets are heated into a rotary kiln for about 1000℃, which allows its expansion and thus formation of tiny pores or bubbles within it used for the accommodation of the process precursors. Note that adequate moisture and oxygen is necessary for the growth of the bacterium which is absent during the mixing process. **Dr. Nele De Belie**, has published a paper on Healing and Self-Healing of Concrete, has shown during their presentation how repair and consolidation of mineral phases of building materials and the healing and self- healing of concrete with the help of bacteria is possible.

IV. CHEMICAL REACTIONS FOR SELF-HEALING PROCESS

There are two pathways to achieve the Calcite or Carbonate Precipitation namely:

1. Hydrolysis of urea to form carbonate.
2. Utilizing the carbon dioxide given out by bacterial respiration.

The first pathway occurs via the hydrolysis of urea. During the reactions shown below, the cell wall of the bacterium is negatively charged, causing cations to be attracted from the surroundings (**C. Karthik, R. M Rao. P, 2016)**. In a calcium rich environment, calcium ions (Ca^{2+}) are deposited on the cell's surface. This leads to a subsequent reaction between the carbonate and the calcium ions, resulting in a precipitation of limestone on the cell's surface **(C. Karthik, R. M Rao. P, 2016).** Unfortunately, after the crack has been filled, the surface of the bacterium is coated with limestone, resulting in the death of the microorganism **(E. Gruyaert. D Snoek. K. V. Tittelboom. J. Wang).** Initial and final equations for the first pathway is as follows **(C. Karthik, R. M Rao. P, 2016)**:

System of equations:

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

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^-$$

$$H_2CO_3 + H_2O \rightarrow HCO_3^- + H_3O^+$$

$$HCO_3^- + H_2O \rightarrow CO_3^{2-} + H_3O^+$$

$$2H_3O^+ + 2OH^- \rightarrow 4H_2O$$

Net reaction:

$$CO(NH_2)_2 + 2H_2O \rightarrow CO_3^{2-} + 2NH_4^+$$

Final reaction:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

The appearance of ammonium(NH_4) as a byproduct in the above equations might have negative effects on the concrete, hence second pathway can be utilized.

Second pathway involves the use of the carbon dioxide produced due to the respiration of the bacterium. The process requires calcium rich and high pH environment. The necessity of the highly alkaline environment is that it provides high levels of hydroxide ions responsible for maintaining the spontaneity of the reactions. Equation for the second pathway is as follows **(C. Karthik, R. M Rao. P, 2016):**

$$CO_2(g) \leftrightarrow CO_2(aq)$$
$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3$$
$$H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H_3O^+$$
$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$$
$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

As mentioned before, calcium lactate is the nutrient rich food source made available to the bacteria inside the concrete. The process involves the metabolic conversion of calcium lactate to produce calcium carbonate by the bacteria. The first equation for the formation of limestone is as follows **(C. Karthik, R. M Rao. P, 2016)**:

$$Ca(C_3H_4O_3)_2 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$$

In eqn. 3 the bacteria utilize oxygen, moisture and calcium lactate to carry out its metabolic activity which results in the formation of calcium carbonate. The CO_2 resulting from the bacterial respiration can react with the portlandite($Ca(OH)_2$) present in the cement, producing even more limestone **(C. Karthik, R. M Rao. P, 2016).** Second equation for the formation of limestone is as follows **(C. Karthik, R. M Rao. P, 2016)**:

$$5CO_2 + 5Ca(OH)_2 \rightarrow 5\ CaCO_3 + 5H_2O$$

Thus, from the above equations it is quite clear that 1 mole of calcium carbonate is capable of producing 1 mole of calcium carbonate and reaction of 5 moles of carbon dioxide with 5 moles of portlandite($Ca(OH)_2$) results in the formation of another 5 moles of limestone. It is evident that large quantities of limestone can be produced through this process which is effective enough to seal of the cracks in the concrete.

V. SELECTION OF BACTERIA

The bacteria used in the process must meet two main criteria. First, it must be able to withstand the highly alkaline environment (pH ~12.8) of the concrete due to the mixing of water and cement. Second, spore germination must still continue in such harsh conditions. Genus Bacillus bacterium was eventually found to be satisfying the above requirements. These are gram-positive bacteria with thick wall cell, thus the spores are capable of surviving the extremely alkaline conditions. Spores are dormant bacterial cells with characteristic compact round shape, typically in the size range of 0.8–1 μm. Spores can remain viable up to 200 years **(H. M. Jonkers, V Wiktor, 2016)**. When environmental conditions are favorable (presence of water, nutrients, and oxygen) these spores germinate and grow into vegetative active bacterial cells **(H. M. Jonkers, V Wiktor, 2016)**.

Various other species of the same genus can be used for self-healing process namely:

- Bacillus pasteurii.
- Bacillus subtilis.
- Bacillus sphaericus.
- Bacillus cohnii.
- Bacillus pseudofirmus.
- Bacillus halodurans.

VI. APPLICATIONS OF THE SELF-HEALING CONCRETE

- Used in the cement mortar.
- In the production of brick.
- Durable roads construction.
- Erosion prevention of loose sands.
- High strength and low-cost housings.

VII. ADVANTAGES AND DISADVANTAGES OF THE SELF-HEALING CONCRETE

Advantages:

- Self-healing concrete is an effective method for sealing off cracks in the infrastructures.
- Reduction in the corrosion of steel reinforcements inside the concrete.
- Increases the moisture impermeability.
- It is an eco-friendly technique reducing carbon dioxide emission.
- It is a revolutionary concept promising better future for concrete exhibiting additional strength and durability to the structure, especially where preservation of monuments are concerned.

Disadvantages:

- The clay particles used in the self-healing concrete occupy about 20% of the total volume of the concrete by replacing the normal aggregate thus reducing compressive strength to about 20-25%.
- The concrete at present, cannot be used for the construction of sky-scrappers, however with the further advancement in the technique, one can overcome this problem.
- Cost of the healing agent calcium lactate is quite high thus making the self-healing concrete costlier than the traditional concrete. Replacements for calcium lactate which are cheap and work on the similar basis are being examined.

VIII. CONCLUSION

- Bacterial concrete is a smart concrete exhibiting human-like self-healing characteristics enhancing the strength of the structures, especially under tension.
- The overall service life of the structure is found to be increasing.
- Appropriate utilization of corrosion causing moisture as a catalyst in the process results in maintaining the quality of the concrete.
- Self-healing concrete is better than the traditional concrete because of its eco-friendly nature.
- Effective crack remediation with maximum moisture impermeability is one of the striking assets of the self-healing concrete.

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AUTHORS BIOGRAPHY

Miss Poonam Ghodke was born in Nagpur, India in 1996. She is pursuing Bachelor's degree in Chemical Engineering from Priyadarshini Institute of Engineering and Technology, RTM Nagpur University. She completed her A1 and A2 level German Proficiency in 2016-17 from Goethe Institute. She plans to study MS in Chemical Engineering in Germany.

Dr. Swarda Mote was born in Nagpur India, in 1964. She received the Bachelor in Chemical Engineering degree from the RTM Nagpur University in Year 1985 and the Master in Chemical Engineering degree from the RTM Nagpur University Nagpur, in Year,1994. She was awarded Ph.D. in Chemical Engineering from RTM Nagpur University in 2015. Her research interests include waste water treatment, Environment & Biotechnology, Chemical Engineering, Soaps and Detergents.