OPEN ACCESS

Available online at www.ijasbt.org

International Journal of Applied Sciences and Biotechnology

A Rapid Publishing Journal

APPLIED SCIENCES		BIOTECHNOLOGY
Biochemistry	Immunobiology	Microbial biotechnology
Molecular biology	Bioinformatics	Medical biotechnology
Microbiology	Novel drug delivery system	Industrial biotechnology
Cell biology	Pharmacology	Environmental biotechnology
Cytology	Neurobiology	Nanotechnology
Genetics	Bio-physics	
Pathology	Botany	
Medicinal chemistry	Zoology	
Polymer sciences	Allied science	
Analytical chemistry	Earth science	
Natural chemistry		

S Gupta et al. (2013). Int J Appl Sci Biotechnol, Vol. 1(3): 85-89
DOI: 10.3126/ijasbt.v1i3.8582

Mini Review

International Journal of Applied Sciences and Biotechnology

ISSN: 2091-2609

BIOLOGICALLY INDUCED SELF HEALING CONCRETE: A FUTURISTIC SOLUTION FOR CRACK REPAIR

Shivani Gupta, Chhavi Rathi and Suman Kapur*

Department of Biological Sciences, Birla Institute of Technology and Sciences (BITS Pilani), Hyderabad Campus, Hyderabad- 500078, India

Corresponding author email: skapur@hyderabad.bits-pilani.ac.in

Abstract

Concrete is a mixture of cement, water, sand and other aggregates in adequate proportions. Its high tensile strength and ability to withstand a vast range of environmental changes makes it the first choice for construction material. One of the major problems associated with concrete is its permeability because penetration of gases and/or liquids from the surrounding environment into the concrete, followed by physical and/or chemical reactions within its internal structure/s leads to irreversible damages. Although cement has autonomous capacity to heal, however cracks <0.2mm width can only self-heal. Biomineralization is one of the best eco-friendly techniques to tackle the problem of cracks in concrete structures. Biologically induced self-healing is beneficial in addressing all the drawbacks of concrete matrix. The most promising technology for producing crack resistant/highly self healing concrete in near future seems to be "BacillaFilla": genetically modified version of *Bacillus subtilis*, is a "custom –designed" bacteria to embed 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 as of the surrounding concrete.

Key words: Concrete, Self-healing, Bio-mineralization, Biologically induced self-healing, Cracks.

Introduction

Concrete is today's material of choice for construction world-wide because of its strength and cost effectiveness. Concrete is a mixture of cement, water, sand and other aggregates in adequate proportions. It has high tensile strength and can withstand vast range of environmental changes quite effectively. Properties such as strength, permeability, crack formation and corrosion properties define the overall quality of concrete mortar. Since concrete is composed of aggregates of various sizes connected with hydration products generated by mixing cement and water, cracks in concrete can occur at any stage of the service life due to volume instabilities such as autogenous shrinkage and/or drying shrinkage. Once cracking sets in anywhere in reinforced concrete member, not only the stiffness reduces but corrosion of supporting iron bars also occurs as a result of penetration of rain water and oxidizing substance (Mihashi and Nishiwaki, 2012). 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. However, there are several disadvantages associated with these in vogue repair systems, namely i) different thermal expansion coefficient/s compared to concrete, ii) weak bonding, iii) environmental & health hazards along with iv) high cost of the polymers/chemicals.

Although cement has autonomous capacity to heal but cracks smaller than 0.2mm width can only self-heal. Biomineralization is one of the best eco-friendly techniques to tackle the problem of cracks in concrete structures. Biomineralizationis defined as a biological process in which organism/s create a local micro-environment with conditions that allow optimal extracellular chemical precipitation of a mineral phase. Biomineralization processes involve calcium carbonate ($CaCO_3$) precipitation, which can occur by two different mechanisms: biologically controlled and/or induced (Lowenstan and Weiner, 1988). In biologically controlled mineralization, the growing organism controls the process to a large extent, i.e. nucleation and growth of the mineral particles. The organism synthesizes minerals in a form that is unique to that species and independent of environmental conditions. Examples of controlled mineralization are magnetite formation in magneto-tactic bacteria (Bazylinski *et al.*, 2007) and silica deposition in the unicellular algae and diatoms, respectively (Barabesi *et al.*, 2007). The calcium carbonate production by bacteria is generally regarded as "induced" as the type of mineral produced is largely dependent on the environmental conditions and no specialized structures or specific molecular mechanism are thought to be involved (Rivadeneyra *et al*., 1994). The technology of calcium carbonate deposition or microbial concrete is called as "Microbially Induced Carbonate Precipitation" (MICCP) (Dhami *et al*., 2012). This review article aims to provide an overview about the problem of cracks in concrete, biologically induced self-healing solutions using microbes with its associated advantages and challenges.

Self-Healing Property of Cement

There are many drawbacks associated with concrete production and structures as well. It is estimated that cement production alone contributes 7% to global anthropogenic carbon dioxide emissions, due to the sintering of limestone and clay at a temperature of 1500 degree Celsius. So, from an environmental viewpoint, concrete does not appear to be a sustainable building material (Jonkers *et al*., 2010). Permeability of concrete poses a major problem because penetration of gases and/or liquids from the surrounding environment. The ensuing physical and/or chemical reactions within internal structures of concrete lead to irreversible damage (Vahabi *et al*., 2012) as this causes corrosion in the embedded metal structures used to reinforce the building. Cracks occur in concrete due to various mechanisms such as shrinkage, freeze-thaw reactions and mechanical compressive and tensile forces. Although micro cracks (width smaller than 0.2 mm) do not affect strength properties of concrete structures directly but they contribute to material porosity and permeability which leads to ingression of aggressive chemicals such as chlorides, sulfates and acids that results in concrete matrix degradation and premature corrosion of the embedded iron reinforcement hampering the structures durability in the long term (Jonkers and Schlangen, 2008).

Several studies have shown that concrete structures have a certain capacity of autonomous healing of micro cracks (Neville, 2002; Reinhardt and Jooss, 2003; Li and Yang, 2007; Worrell *et al*., 2001). The actual capacity of micro crack healing is primarily related to the composition of the concrete mixture. In the autonomous self-healing process dissolution and re-precipitation of calcium carbonate occurs. The crack-penetrating water would not only dissolve calcite ($CaCO_3$) particles present in the mortar matrix but would also react together with atmospheric carbon dioxide with partially hydrated lime constituent such as calcium oxide and calcium hydroxide according to the following reactions:

$$CaO + H_2O \longrightarrow Ca(OH)_2 \qquad (1)$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O \qquad (2)$$

Biologically induced self-healing or MICCP is beneficial in addressing all the above drawbacks of concrete matrix. The bacteria induce precipitation in between the pores of the cement matrix thereby reducing the pore size and consequently increasing the strength and decreasing the permeability at the same time.

Mechanism of Biologically Induced Self-Healing

Calcium carbonate precipitation is governed by four key factors: (i) calcium (Ca^{2+}) concentration, (ii) concentration of dissolved inorganic carbon (DIC), (iii) pH and (iv) availability of nucleation sites (Ariyanti *et al*., 2011; Muynck, 2010; De Belie, 2010). The primary role of microorganism in carbonate precipitation is mainly due to their ability to create alkaline environment (high pH and [DIC] increase) through their various physiological activities (Hammes and Verstraete, 2002).

Three/four main groups of microorganism that can induce calcium precipitation are: (i) photosynthetic microorganism such as cyanobacteria and microalgae; (ii) sulphate reducing bacteria (iii) some species involved in nitrogen cycle and iv) lactate metabolism. The MICCP phenomenon appearing in aquatic environment is caused by photosynthetic microorganisms. Photosynthetic microorganisms use CO_2 in their metabolic process (eqn. 3) which is in equilibrium with HCO_3^- and CO_3^{2-} as described in eq. 4 given below. Carbon dioxide consumption by photosynthetic microorganisms shifts the equilibrium resulting in increase in pH (eqn. 5) (Ariyanti *et al*., 2011). When this reaction occurs in the presence of calcium ion in the system, calcium carbonate is produced as described at chemical reaction in eqn.6.

$$CO_2 + H_2O \longrightarrow (CH_2O) + O_2 \qquad (3)$$

$$2HCO_3^- \Longleftrightarrow CO_2 + CO_3^{2-} + H_2O \qquad (4)$$

$$CO_3^{2-} + H_2O \Longleftrightarrow HCO_3^- + OH \qquad (5)$$

$$Ca^{2+} + HCO_3^- + OH^- \Longleftrightarrow CaCO_3 + 2H_2O \qquad (6)$$

Another pathway uses sulphur reducing bacteria (SRB). Abiotic dissolution of gypsum ($CaSO_4.H_2O$) (eqn. 7) produces a system rich in sulfate and calcium ions. In the presence of organic matter and absence of oxygen, SRB reduces sulphate to H_2S and HCO_3^- as described in eqn. 8. When the H_2S degasses from the environment, pH of system will increase and precipitation of calcium carbonate ensues (Ariyanti *et al*., 2011).

$$CaSO_4 + H_2O \longrightarrow Ca2^+ + SO_42^- + 2H_2O \qquad (7)$$

$$2(CH_2O) + SO_4^{2-} \longrightarrow HS^- + HCO_3^- + CO_2 + H_2O \qquad (8)$$

Urease enzyme activity in microorganisms has been used as a tool to induce precipitation of calcium carbonate (Bekheet and Syrett, 1977; Mc.Connaughey, 2000). Hydrolysis of urea by urease enzyme in hetero-trophic microorganism produces carbonate ions and ammonium. This mechanism results in higher pH and enrichment of carbonate ion (Hammes and Verstraete, 2002). One mole of urea is hydrolyzed intra-cellularly to one mole of ammonia and one mole of carbamate (eqn. 9), which spontaneously hydrolyses to one mole of ammonia and one mole carbonic acid (eqn. 10). Ammonia and carbamate subsequently equilibrate in water to form bicarbonate and 2 moles of ammonium and hydroxide ions as described in eqn. 11 and 12.

$$CO\,(NH_2)_2 + H_2O \rightarrow H_2COOH + NH_3 \quad (9)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3` \quad (10)$$

$$2NH_3 + 2H_2O \rightarrow 2NH^{4+} + 2OH^- \quad (11)$$

$$2OH^- + H2CO_3 \rightarrow CO_3^{2-} + 2H_2O \quad (12)$$

Overall reaction:

$$CO\,(NH_2)_2 + 2\,H_2O \rightarrow 2NH^{4+} + CO_3^{2-} \quad (13)$$

The presence of calcium ions in the system leads to calcium carbonate precipitation once a certain level of super-saturation is reached. The Calcium Carbonate precipitation mechanism induced by urease activity is illustrated in Fig1. (adapted from Hammes and Verstrate, 2002)

History and current status of biological induced mineralization:

For the bacteria to mineralize there are certain properties it should possess. Firstly, the bacteria should be resistant to high pH (alkali resistant). Secondly, the bacteria should be able to produce copious amounts of minerals needed to plug or seal the freshly formed crack. Since concrete structures are designed to last at least 50 to 100 years, bacteria should remain viable for a long period of time. Therefore a specific group of alkaliphilic spore-forming bacteria were selected to be used in biological induced mineralization. Several species from the genus *Bacillus* have been used for incorporation into concrete. Thirdly, as the concrete matrix is oxygenic due to ingress oxygen (diffusion through matrix capillaries) incorporated bacteria also need to be oxygen brilliant (Jonkars *et al*., 2010). Fourthly, the bacteria should be resistant to high calcium ion concentration and should produce calcium carbonate at greater amounts. Fifthly, it should be able to withstand high pressure conditions as if embedded inside the matrix and should remain viable for long periods of time. Lastly, the bacteria used should be non-pathogenic.

Furthermore, Urea is an important organic nitrogen carrier in natural environment and is commonly used as an agricultural fertilizer (Nieslen *et al*., 1998). Several research groups have explored free as well as immobilized microorganisms for inducing self healing capability in concrete, which have been summarized in Table 1.

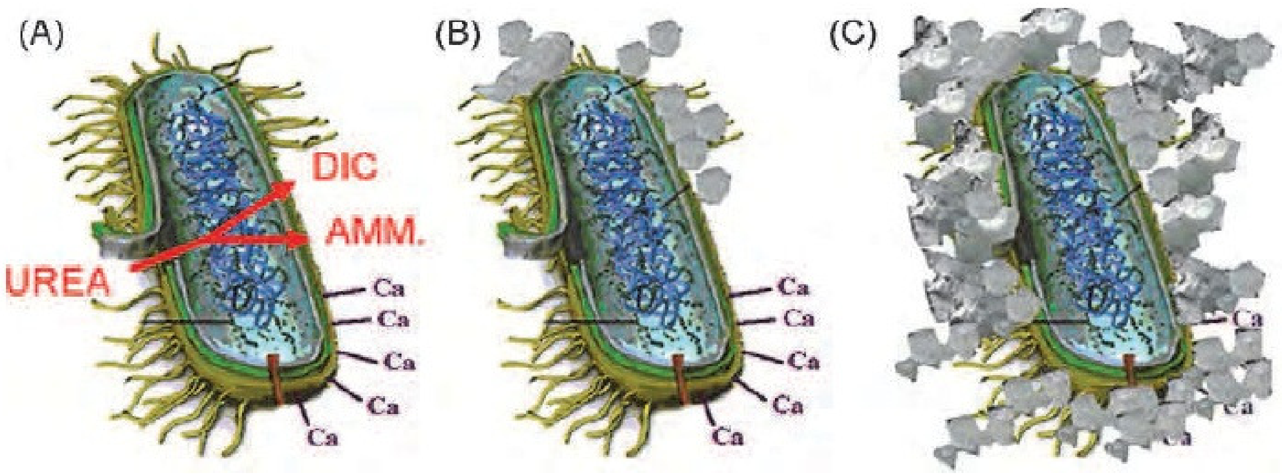

Fig 1: Illustration of calcium Carbonate precipitation mechanism induced by urease enzyme activity in microorganism

(A) Ca ions attracted to bacterial cell. Urea is added, dissolved carbon (DIC) and Ammonia (AMM) are released into environment. (B) The whole cell is encapsulated; (C) Calcium Carbonate precipitation ensues.

Table 1: Different Bacterial populations and their potential for bio mineralization

S. No	Microorganism Used	Proposed Mechanism	Major finding	Author (Year)
1	*Bacillis pasteurii, Pseudomonas aerugiinosa*	Urease metabolism	• Used as sealant • increased Compressive • Growth inhibited in high alkaline environment • High efficiency in shallow cracks. • *P. aerugiinosa* contributions were insignificant.	Ramachandran *et al*., 2001
2	*Bacillis pasteurii*	Poly Urethane (PU) immobilized, Urease metabolism	• Cells retained high metabolic rate. • Protected from adverse environment. • No change in rate of metabolism due to immobilization. • Accumulation of calcite in deeper cracks.	Bang *et al*., 2001
3	-	Poly Urethane immobilized urease enzyme	• Rate of precipitation lower than free enzyme.	Bachmeiri *et al*., 2002
4	*Bacillus sphaericus*	Silica sol incorporated Urease metabolism	• Incorporation with calcium source. • Effective in sealing cracks of 0.01mm-0.6mm. • Reduced concrete permeability	De Belie and De Muynck., 2008
5	*Bacillus cohnii, Bacillus halodurans, Bacillus pseudofirmus*	Two component self- healing system	• Substrate and microbes added into the concrete. • Formation of 100µm sized calcite particles, superior in filling large cracks.	Jonkers and Schlangen., 2008
6	*Bacillus sphaericus*	Encapsulation of bacteria, nutrient and PU in glass rod	• Higher the concentration of microbe more was the precipitation. • PU contributed to increase in strength.	Wang *et al*., 2010
7	*Bacillus pseudofirmus* and *B.cohnii*	Two component Healing system ; Bacteria and calcium lactate	• 20-80µm sized mineral-like precipitate on crack surface. • Functionality limited to young cement. • Decrease in nitrogen loading in environment.	Jonkars *et al*., 2010
8	Microalgae (*Chlorella*)	Photosynthetic Pathway	• Renewable source • Easily cultivatable • No optimization done yet	Ariyanti et al., 2011

Challenges Ahead

There are commercial products available based on traditional methods used for crack repair like CPR # 400-A binding paste, Thompsons emergency MASTIC, DAP but no product is yet available based on biologically induced self-healing. Biologically induced self-healing is a promising technology to increase the strength, life and durability of concrete structures. But there are several challenges to implement this in the practical world. Applying the bacterial mixture externally not only increases the cost but also needs manual inspection at regular intervals. The major challenge faced is about keeping the cells viable for a longer duration of time till the concrete structure is present. It has been found that bacterial spores are viable in young concrete but with time the microbial viability decreases. Moreover, the bacteria should acts as healing agent innumerable times once it has been incorporated. This can only be possible when new spores are generated once the crack is repaired. The impregnation of microbes in PU or sol-gel offers a solution to increase the viability but optimization of this has yet to be accomplished. Moreover, using microalgae and other microorganisms for crack remediation has as yet not been fully investigated.

Future Prospects

Promising results on the use of microorganisms for the improvement of durability of building materials have drawn the attention of research groups all over the world. It is clear that the work done by several research groups, focusing on different materials, can only improve our understanding on the possibilities and limitations of biotechnological applications on building materials. Investigations are still going on the retention of nutrient and metabolic products, as they have an influence on survival, growth and biofilm formation. The most promising technology for producing crack resistant/highly self healing concrete in near future seems to be "BacillaFilla": is a genetically modified version of *Bacillus subtilis*. It has been "custom-designed 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" developed at Researchers at the University of Newcastle in the UK (Dilow, 2010).

References

Ariyanti D, Handayani NA, and Hadiyanto (2011) An overview of Biocement production from microalgae. *Internat. J. Sci Eng*. **2(2)**: 30-33.

Bachmeier KL, Williams AE, Warmington, JR and Bang SS (2002) Urease activity in microbiologically-induced calcite precipitation. *J. Biotechnol*. **93(2)**: 171–181.

Bang SS, Galinat JK, and Ramakrishnan V (2001) Calcite precipitation induced by polyurethane-immobilized Sporosarcina pasteurii. *Enzyme Microb. Technol.* **28 (4–5)**: 404–409.

Barabesi C, Galizzi A, Mastromei G, Rossi M, Tamburini E and Perito B (2007) *Bacillus subtilis* gene cluster involved in calcium carbonate biomineralization. *J. Bacteriol*. **189(1)**: 228–235.

Bazylinski DA, Frankel RB, and Konhauser KO (2007) Modes of biomineralization of magnetite by microbes. *Geomicrobiol. J.* **24**: 465–475.

Bekheet IA and Syrett P (1977) Urea-degrading Enzymes in Algae. *European Journal of Phycology.* **12(2)**: 137-143.

Belie ND and SS (2010) Microorganisms versus Stony Materials: A Love-Hate Relationship. *Materials and Structure.* **43:** 1191-1202.

De Belie, N, and De Muynck, W (2008) Crack repair in concrete using biodeposition. In: Proc. of ICCRR, Cape Town, South Africa.

Dhami NK, Reddy SM, and Mukherjee, A (2012). Biofilm and Microbial Applications in Biomineralization concrete, *Advanced Topics in Biomineralization,* Dr. Jong Seto (Ed.), ISBN: 978-953-51-0045-4, In Tech.

Dillow, C. Bacteria Can Fill Cracks in Aging Concrete. Popsci.com. 11/16/10. Accessed 11/30/10.

Hammes F, and Verstraete, W (2002) Key Roles of pH and Calcium Metabolism in Microbial Carbonate Precipitation. *Environ Sci Biotechnol.* **36**: 118-136.

Jonkers HM, Thijssen A, Muyzer G, Oguzhan C, and Schlangen E (2010) Application of bacteria as self-healing agent for the development of sustainable concrete, *Ecological Engineering.* **36:** 230-235.

Jonkers HM., and Schlangen E (2008) Development of a bacteria-based self healing concrete: Tailor made concrete Structures - new solutions for our society. Taylor & Francis Group, London.

Li VC, and Yang E (2007) Self healing in concrete materials: Self healing materials -An alternative approach to 20 centuries of materials science. Springer, the Netherlands.

Lowenstan HA, and Weiner S (1988) On biomineralization. Oxford University Press, New York

Mc.Connaughey TA (2000) Community and Environmental Influences on Reef Coral Calcification. *Limnology and Oceanography.* **45(7)**: 1667-1671.

Mihashi H, and Nishiwaki T (2012) Development of engineered self healing and self repair stat-of-the-art-report. *J adv conc technol.* **10:** 170-184.

Muynck WD, Belie ND, and Verstraete W (2010) Microbial Carbonate Precipitation in Construction Materials: A Review. *Ecological Engineering.* **36:** 118-136.

Neville AM (2002) Autogenous healing - A concrete miracle? *Concrete Int.* **24(11)**: 76-82.

Nielsen TH, Bonde TA, and Sorensen J (1998) Significance of microbial urea turnover in N cycling of three Danish agricultural soils. *FEMS Microbial. Eco.* **25(2):** 147–157.

Ramachandran SK, Ramakrishnan V, and Bang SS (2001) Remediation of concrete using micro-organisms. *ACI Mater. J.* **98:** 3–9.

Reinhardt HW, and Jooss M (2003) Permeability and self-healing of cracked concrete as a function of temperature and crack width. *Cement and Concrete res,* **33:** 981-988.

Rivadeneyra MA, Delgado R., Del Moral A, Ferrer MR and Ramos-Cormenzana A (1994) Precipitation of calcium carbonate by *Vibrio* spp. from an inland saltern. *FEMS Microbial. Ecol*. **13(3)**: 197–204.

Vahabi A, Noghabi KA, and Ramezanianpour A. A (2012) Application of Biotechnology-Based Method for Enhancing Concrete Properties. *J Med Bioeng*. **1**: 36-38.

Wang, JY, Tittelboom KT, Belie ND and Verstraete W (2010) Potential of Appyling Bacteria to heal cracks in concrete. *2nd international Conference on sustainable construction material and technologies*. Universita Politecnica delle Marche, Ancona, Italy.

Worrell E, Price L, Martin N, Hendriks C and Ozawa ML (2001) Carbon dioxide emissions from the global cement industry. *Annual Review Energy Environ.* **26**: 303-329.