

Self Healing Concrete for Sustainable and Economical Constructions – A Review

Hritik Arora¹, Emil Saji¹, Mridul Umesh²

¹ Department of Life Sciences, CHRIST (Deemed to be University), Bangalore, India

² Assistant Professor, Department of Life Sciences, CHRIST (Deemed to be University), Bangalore, India

Abstract

The rapid growth in engineering and technology has paved way for searching of innovative methods and sustainable material for construction. The economic aspects associated with deterioration of concretes accelerated the search for sustainable bacterial concretes with self-healing application. Biomineralization approach could be successfully used for tackling out the problems associated with synthetic concretes and could be exploited commercially in manufacturing industries. In spite of its immense potential this technique still remains in its ground state and need more focus for its commercialization. This work summarizes the underlying principles behind self-healing microbial concretes and their application for sustainable constructions.

Key Words: Biomineralization, concrete, encapsulation, embedment.

I. INTRODUCTION:

At present, technology has taken the standards and efficiencies of construction to a new height. Different types of processes, methods and materials are used to attain very good, sustainable and economic concrete construction. But due to human errors, incorrect handling and unskilled labour, an absolutely perfect building is impossible to make. Many problems like weathering, cracks, leaks, and bending arises after the construction. The most common problem, that is the crack may arise due to many reasons. Some reasons are: (1) Concrete expands and shrinks with temperature.(2) Due to heavy load on the building.(3) Loss of water from concrete surface encourages shrinkage.(4) Insufficient vibration at the time of laying the concrete.(5)Improper cover provided during concreting.(6)The high water-cement ratio.(7)Due to corrosion of the reinforcement steel.(8)Many mixtures with rapid setting and strength gain performance have an increased shrinkage potential.

To minimize the formation of cracks and leaks many preventive measures are followed. Some of them are: (a)Reducing water content in concrete. (b)Using the proper mixtures and quality materials.(c) Using proper finishing techniques. (d)Proper curing, placement, and vibration of concrete.

But what about the buildings that already have cracks in them. Repairing methods like stitching, sealing, muting, vacuum impregnation, and dry packing are all very expensive and provide only a brief fix until the eventual weathering and weakening of the building. Furthermore, It is estimated that cement (Portland clinker) production alone contributes 7% to global anthropogenic CO₂ emissions, what is particularly due to the sintering of limestone and clay at a temperature of 1500°C, as during this process calcium carbonate (CaCO₃) is converted to calcium oxide (CaO) while releasing CO₂ (Worrell et al., 2001). Therefore, from an environmental viewpoint, concrete does not appear to be a sustainable material for construction at all (Gerilla et al., 2007). Thus, it is more environmentally friendly to fix the pre-existing concrete and to make new types of concrete that are able to resist wear and tear by being able to fix itself

To this mean, plenty of research has been done in the past two decades on the use of bacteria, a promising new model of sustainable repair methodology, to fix and heal the concrete when cracks develop on them. The method focuses on the bacteria that precipitate Calcium Carbonate (CaCO₃) to heal the cracks if they form on the concrete. This review tries to illuminate the various techniques and methods scientists have devised in the past two decades.

II. METHODOLOGY:

The Various Methods that were tried this past two decades are:-

1. Incorporation of Bacteria into the Concrete during its mixing
2. Incorporation of Bacterial Spores into the Concrete during its mixing
3. Applying a liquid consisting of the Bacteria or its spores in a nutrient medium directly on the cracks of a Cracked Cement Sample

All these methods use different bacteria which use different mechanisms to precipitate Calcite into the concrete. These methods are all based on Biomineralization. Biomineralization refers to the process of mineral formation by living organisms which is a widespread phenomenon in nature (Tebo et al. 2005). Biologically induced mineralization usually occurs in an open environment as an uncontrolled consequence of microbial metabolic activity (Rivadeneira 1994).

III. CALCITE PRECIPITATION:

Calcite precipitation or Microbiologically Induced Calcite Precipitation (MICP) is a type of Biomineralization that induces the precipitation of calcium carbonate within the matrix where the microbe is located. It can be traced back to the Precambrian period, and in this precipitation three polymorphic forms of calcium carbonate may be precipitated: Aragonite, Calcite, or Vaterite. For the process of Bioremediation of concrete, researchers have tried to make sure that the Calcite form of Calcium Carbonate; the most stable form of the mineral is precipitated.

The main groups of Bacteria found to be able to precipitate calcium carbonate are cyanobacteria, and Sulphate-reducing Bacteria. Two different pathways through which Calcium Carbonate is precipitated have been identified. They are

- 1) Autotrophic Pathway: There are three kinds of Autotrophic pathways and each of lead to the production carbonate autotrophically from carbon from gases or dissolved carbon dioxide.
- 2) Heterotrophic Pathway: In this pathway, there is crystal precipitation due to heterotrophic growth. Based on the nutrients and ions available in the matrix that these heterotrophic microbes live in, they produce crystals that are precipitated out. With the proper nutrient medium, Calcium Carbonate crystals are precipitated

There are several mechanisms which explain the process of carbonate precipitation, but three of them: Ureolysis, Denitrification, and metabolic conversion of organic acids have been exploited for bioremediation of concrete.

A) The Autotrophic Pathway:

This pathway takes place in autotrophic microbes who convert atmospheric or dissolved Carbon Dioxide (CO₂) into carbonate. There are 3 possible ways which this can be accomplished. They are-

a) Methanogenesis:

Done by Methanogenic Archaea. This autotrophic pathway converts CO₂ and H₂ to Methane (CH₄)

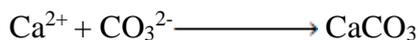
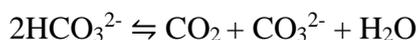
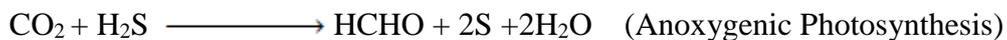
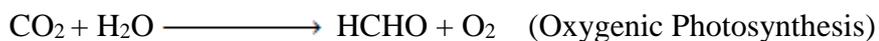


The Equations show the anaerobic oxidation of methane by electron acceptors such as Sulphate ion (as in Sulphur Bacteria) and production of bicarbonate (Castaner et. al 2000). The produced bicarbonate ions form calcium carbonate ions if calcium ions are present in the matrix where the bacteria is present.

b) Oxygenic and Anoxygenic Photosynthesis:

Photosynthesis is also a pathway which can give rise to the precipitation of calcium carbonate in presence of calcium ions. There are two types of photosynthetic bacteria, Oxygenic photosynthetic bacteria whose examples are Cyanobacteria, and Anoxygenic photosynthetic bacteria whose examples are purple bacteria. Both oxygenic and anoxygenic photosynthesizing microbes utilize different mechanisms to produce

Methanal (HCHO). Carbon dioxide (CO₂) is removed from bicarbonate solutions during microbial photosynthesis forming Carbonate (CO₃²⁻). This leads to the increase of local pH and finally Calcium carbonate precipitation in the presence of Calcium ions (Hammes and Verstraete 2002).



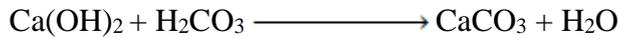
From these reactions we can see that this pathway is only possible when the bacteria are exposed to sunlight and carbon dioxide in the surrounding environment, this pathway is not suited for the bioremediation of concrete even though it may help to reduce CO₂ levels and help combat Global Warming.

B) The Heterotrophic Pathway:

Microbial communities precipitate crystals of different carbonates in different nutrient media consisting of different metal ions. For example of the media contains Calcium ions then the crystal precipitated will be Calcium carbonate, similarly of the media contains magnesium ions, the crystals precipitated will be Magnesium Carbonate. The bacteria form Carbonate ions by using various organic acids (acetate, Lactate, citrate, succinate, oxalate, malate, etc.) as sources of energy and these carbonate ions react with the metal ions in solution to form the corresponding carbonate. Calcium carbonate precipitation through use of organic acid has been widely documented in different substrate environments, including caves, marine environment, lakes and soil. It was found that heterotrophic bacterial communities (*Arthrobacter* and *Rhodococcus*) isolated from stalactites in the cave could produce calcium carbonate in the presence of calcium acetate (Rusznayk et al. 2011; Groth et al. 2001). Cacchio et al. (2003) also found that *Bacillus* and *Arthrobacter* species are capable of precipitating calcium carbonate under alkaline carbonate medium.

The main advantages of this pathway are that Organic acids act as the sole energy source for these microbes and the proteins and Extra polymeric Substances (EPS) on their cell wall act as nucleation sites. With each type of cell wall, different polymorphs or Calcium Carbonate may be precipitated, from Aragonite (Needle-like crystals) to Calcite (Rhombic Crystals). Thus with this pathway, specific strains of bacteria can be chosen to precipitate a specific type of Calcium Carbonate.

The Sulphur and Nitrogen cycle are the two other methods that can be used for calcium carbonate precipitation. Sulphur cycle follows by dissimilatory reduction of sulphate. In this process, calcium carbonate is produced if calcium source, organic matter and sulphate are present in the medium. The increase in pH as a result of degasification of hydrogen sulphide shifts the reaction towards precipitation of calcium carbonate (Castainer et al.1999). One of the ways sulphur bacteria produce calcium carbonate is,

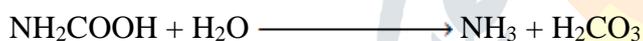


Using the Nitrogen Cycle, there are 3 main pathways for Calcium Carbonate Precipitation. They are (1) Ureolysis (2) Ammonification of amino acids and (3) Nitrate reduction. As a result of the nitrogen cycle, calcium carbonate is precipitated upon the presence of sufficient calcium ion in the medium (Castainer et al. 1999).

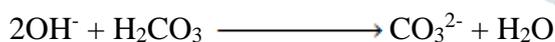
(a) Ureolysis:

Microorganisms such as *Bacillus sphaericus* and *Bacillus pasteurii* are able to produce biominerals through metabolic reaction in the presence of calcium source (Wang et al., 2012b).

In Ureolysis, Urease positive bacteria convert Urea into Carbamic Acid which in turn converts into Ammonia by reacting with H_2O .



The H_2CO_3 formed can dissociate into carbonate ions (CO_3^{2-}).



These carbonate ions can react with the Calcium ions if present in the environment to precipitate as Calcium carbonate.



For the last reaction the calcium ion can be provided either by internal sources that are available in the cement structure or by adding chemicals such as calcium chloride, calcium nitrate or calcium lactate externally (Stuckrath et al. 2014). However calcium chloride as a calcium source may cause chloride ion attack and thus may degrade the reinforcement bars. Thus, application of calcium nitrate or calcium lactate is recommended.

The disadvantages, however of this method is that the ammonium ions (NH_4^+) produced through ureolysis results in the emission of NO. It is also found that remediation of 1 m^2 of concrete needs 10 g/L of urea which produces 4.7g of nitrogen. This amount is about one-third of the nitrogen that is produced by each person everyday (De Muynck et al. 2010). Also, the presence of excessive ammonium in the concrete matrix leads to degradation of the reinforcement bars.

(b) Metabolic conversion of organic acid salts to carbonate

Another pathway to precipitate is the metabolic conversion of organic acid salts to carbonate. This carbonate then reacts with the calcium ions in the cement matrix to give calcium carbonate (Jonkers et al. 2010; Wiktor and Jonkers 2011; Sierra-Beltran et al. 2014; Jonkers 2011). Here aerobic oxidation of organic acids leads to the formation of CO_2 , which in alkaline environment converts to carbonate ions. The carbonate ions react with the calcium ions in the cement matrix to precipitate as calcium carbonate.

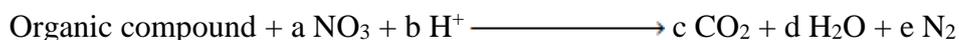
The reaction for calcium lactate to calcium carbonate is given below,

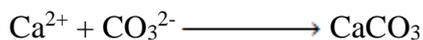


A reaction between the produced water and carbon dioxide and the available calcium oxide in the concrete matrix contributes to the increase of autogenous healing (Achal et al. 2011; Achal and Pan 2011; Van Tittelboom and De Belie 2013). Compared to the ureolysis pathway, this pathway is much more sustainable as no nitrogen compounds are being formed through this method, also since O_2 is being used in this reaction the reinforcement bars in the concrete are also protected from corrosion. Compatibility with concrete composition, protection of reinforcement bars and high calcium carbonate precipitation are among the main advantages of this method.

(c) Dissimilatory Nitrate reduction

Denitrification is the process through which Nitrate (NO_3^-) is reduced to nitrite (NO_2^-), nitric oxide (NO), and nitrogen (N_2). The most direct application of this pathway is that it can be applied to the anaerobic place. Denitrification is carried out by denitrifying bacteria. The microorganisms that are involved in the denitrification process are facultative anaerobes, mainly *Denitrobacillus*, *Thiobacillus*, *Alcaligenes*, *Pseudomonas*, *Spirillum*, *Achromobacter* and *Micrococcus* species (Karatat 2008). Due to organic denitrification CO_2 , H_2O and N_2 are produced. In the reaction, H^+ is consumed thus increasing the pH of the matrix. This increase in pH leads to the conversion of CO_2 to carbonate, which in turn reacts with the calcium ions in the matrix to precipitate as calcium carbonate.





This process, however, is slower compared to ureolysis. Urea hydrolysis occurs in a short period of time. Therefore, calcium carbonate precipitation through ureolysis pathway is the fastest approach among calcium carbonate biomineralization processes (De Muynck et al. 2010).

Since Biomineralization is a slow process, chemicals that hasten it are in high demand. Also, bacteria that are low-risk and precipitate a high amount of Calcium carbonate are in demand, however, care is to be taken that the selected bacteria does not form a biofilm which leads to uneven and undesirable patches on the concrete (Ghaz-Jahanian et al. 2013).

Table 1. Over view of microorganism and nutrients which have been used to produce calcium carbonate in concrete matrix

Mechanism of Precipitation	Microorganism	Nutrient	Embedment in Concrete	References
Bacterial Metabolic Conversion of Organic acid	<i>B. pseudofirmus</i>	Calcium lactate, calcium glutamate, yeast extract and peptone	Direct	Jonkers and Schlangen (2009)
	<i>B. pseudofirmus</i>	Calcium lactate, calcium acetate, yeast extract and peptone	Direct	Jonkers et. al (2010)
	<i>B. cohnii</i>	Calcium lactate, calcium acetate, yeast extract and peptone	Direct	Jonkers et.al (2010)
	<i>B. cohnii</i>	Calcium lactate and yeast extract	Immobilized	Sierra-Beltran et al. (2014)
	<i>B. alkalinitrilicus</i>	Calcium lactate and yeast extract	Immobilized	Wiktors and Jonkers (2011)
Ureolysis	<i>B. sphaericus</i>	Urea, calcium nitrate and yeast extract	Immobilized	Wang et. al (2014b)
	<i>B. sphaericus</i>	Urea and Calcium Chloride	Direct	Achal et al. (2013)
	<i>B. sphaericus</i>	Urea, calcium nitrate and yeast extract	Immobilized	Wang et al. (2012a)
	<i>B. sphaericus</i>	Urea and Calcium Chloride	Direct	Achal et al. (2011)
	<i>B. sphaericus</i>	Urea, calcium nitrate and yeast extract	Immobilized	Wang et al. (2010)

	<i>B.sphaericus</i>	Urea, Calcium chloride, calcium nitrate and yeast extract	Immobilized	Van Tittelboom et al. (2010)
	<i>B.sphaericus</i>	Urea, calcium nitrate and yeast extract	Immobilized	Wang et al. (2014c)
	<i>B.sphaericus</i>	Urea, Calcium Chloride and Calcium Acetate	-	De Muynck et al. (2008a)
	<i>B.sphaericus</i>	Urea, calcium nitrate and yeast extract	Direct	Wang et al. (2012b)
	<i>S.pasteruui</i>	Urea and Calcium Chloride	Direct	Ramachandran et al. (2001)
	<i>Pseudomonas aeruginosa</i>	Urea and Calcium acetate	Direct	Ramachandran et al. (2001)
	<i>B.sphaericus</i>	Urea and Calcium acetate	Direct	Kim et al (2013)
	<i>S.pasteruui</i>	Urea, calcium chloride	Direct	Kim et al (2013)
	<i>S.pasteruui</i>	Urea and Calcium Chloride	Immobilized	Bang et al (2001)
	<i>S.pasteruui</i>	Urea, calcium nitrate and calcium chloride	-	Qian et al (2010b)
	<i>S.pasteruui</i>	Urea, and Calcium nitrate	-	Chunxiang et al (2009)
	<i>S.pasteruui</i>	Urea, and calcium chloride	Immobilized	Bang et al. (2010)
	<i>S.pasteruui</i>	Urea, nutrient broth and calcium chloride	Direct	Maheswaran et al. (2014)
	<i>B.cereus</i>	Urea, nutrient broth and calcium chloride	Direct	Maheswaran et al. (2014)
	<i>B.amyloliquefaciens</i>	Urea, calcium acetate, yeast extract and glucose	-	Lee (2003)
	<i>Sporosarcina soli</i>	Urea and calcium chloride	Direct	Park et al. (2010)
	<i>B. massiliensis</i>	Urea and calcium chloride	Direct	Park et al (2010)
	<i>Arthrobacter crystallopoietes</i>	Urea and calcium chloride	Direct	Park et al (2010)
	<i>Lysinibacillus</i>	Urea and calcium	Direct	Park et al. (2010)

	<i>fusiformis</i>	chloride			
Denitrification	<i>Diaphorobacter nitroreducens</i>	Urea, calcium formate, nitrate and yeast extract	calcium calcium and yeast	Immobilized	Erşan et al (2015a)
	<i>B.sphaericus</i>	Urea, calcium formate, nitrate and yeast extract	calcium calcium and yeast	Immobilized	Erşan et al (2015a)

(Table credits bioconcrete: next generation of selfhealing concrete, Mostafa Seifan et al.)

IV. EMBEDMENT OF MICROBES IN CONCRETE MATRIX:

The microorganism or the healing agent can be inserted into the concrete by three methods-

(1) Vascular network method

This method is by the supplies of the healing agent from the outside of the structure through the pre-constructed vascular network during concrete preparation. The healing agent moves through the vascular network due to the pressure gradient created. This method seems to be quite impractical due to several short-comings like the healing agent must have constant viscosity throughout its life to maintain the easy flow of the healing agent. If the agent is more than the crack capacity it can cause aesthetic problems. It is difficult to distribute vessels throughout the structure. And the incorporation of the vascular network inside concrete could decrease the bond between the concrete composition which will lead to structural delamination.

(2) Direct Embedment

Bacteria directly are embedded into the concrete mixture during preparation. The healing agent is dissolved in water and then added to cement and sand. Alkaliphilic and spore-forming bacteria is the most suited due to their tolerance to extreme environment. The incorporation of the microorganism into concrete can influence the metabolic activity due to high pH condition and harsh environment where the cell is vulnerable to death due to the dry condition. Studies have also shown a decrease in the number of viable bacteria over time indicating that bacterial cell can be viable only for up to 4 months (135 days), (Jonkers et al. 2010). Therefore we need to use immobilized spore-forming bacteria to maintain the bacteria in concrete for a long period of time.

(3) Encapsulation

The bacteria are protected by a protective material such as diatomaceous earth, hydrogel and porous expanded clay particles. It can increase the viability of the bacteria for a long period of time inside the capsule which will mechanically break open when the cracks are formed. It is found that filling

by microcapsule will create large pores which are the space that appears after microcapsule rupture. (Van Tittelboom et al. 2011; Van Tittelboom and De Belie 2013). So encapsulation efficiency depends on capsule size and their distribution.

V. PREPARATION OF THE CONCRETE:

Encapsulation

- The concrete sample can be made by normal Portland cement CEM152.5N and CaCO₃ precipitating bacteria like *Bacillus sphaericus* with a purified strain of LMG 222 57 isolated from calcareous sludge from biocatalytic ureolytic calcification reactor. The bacteria were immobilized in silica gel to protect from extreme alkali condition. The bacterial treatment was done in ways as follows:

(1) *Bacillus sphaericus* in sol-gel with CaCl₂:

1.2g of NaCl added to 10ml demineralized water and the mixture was vortexed. 50ml of an overnight grown centrifuged culture at 7000rpm for 5min at 4°C. The pellet was suspended and vortexed after that 40ml levasil sol added and vortexed again. The obtained suspension was bought into the crack by a syringe and repeated until the entire crack was filled after hardening of sol into gel the sample was immersed in an equimolar solution of urea and CaCl₂. 2H₂O for 3 days.

(2) Sol-gel:

1.2g of NaCl added to 10ml demineralized water and the mixture was vortexed for 30 seconds. Then, 40ml of Levasil sol added and vortexed again by means of a syringe, the suspension was bought into filling the entire crack.

(3) *Bacillus sphaericus* with CaCl₂:

The sample immersed in *B. sphaericus* for 24h. The growth medium consists of 20g/L yeast extract and 20g/L urea. The surface of the sample is wiped with a paper towel to remove some bacteria from the surface so the ureolytic activity occurs inside the cracks. Then the sample was immersed in an equimolar solution of urea.

(4) *Bacillus sphaericus* with sol-gel and with CaCl₂:

Sample treated with sol-gel as mentioned above (2) and then when it hardened, the sample was subjected to *Bacillus sphaericus* + CaCl_2 treatment.[Kim Van Tittelboom, Nele De Belie, Willem De Muynck, Willy Verstraete].

Use of silica gel or polyurethane

Concrete, being an important construction material is bound to cracks due to many reasons which in turn reduce the life of it. Therefore, the use of bacterial as self-healing came up. But due to the extreme alkali condition of the environment ($\text{pH}>12$) reduce its bacterial activity. The bacterial might also get destroyed in the process of hydration. Therefore a suitable carrier is required for the survival and immobilization of the bacteria. So, silica gel or polyurethane was used as a carrier. Silica gel is a popular carrier as it has good properties of mechanical, thermal and photochemical stability. The silica sol and bacteria suspension were injected into the crack by syringe. When gel formation takes place it is repeated until the cracks are filled. The specimen is immersed in a medium of urea and Ca^{+} then CaCO_3 precipitation occurs. The encapsulation is in the glass tube which is incorporated during casting when cracks occur the glass capsule break and bacterial flow into the crack the silica gel form in situ when silica sol meets Ca^{+} . at the same time bacterial cells meet with urea and Ca^{+} , CaCO_3 precipitates. Polyurethane (PU) is used as a waterproof material. The PU foam with the bacterial cell was cut into equal size pieces then the PU foam strips were placed into the cracks of mortar specimen. The specimen was incubated in a Urea- CaCl_2 medium at room temperature. As a result, CaCO_3 precipitation occurs and the compressive strength of the crack was higher than the control specimen [Jianyun Wang, Kim Van Tittelboom, Nele De Belie, Willy Verstraete].

Direct Embedment

- The sample can be made with IS 12269-1987 with local natural river sand conforming to IS 383-1970. with *Bacillus* sp. Of CT-5 isolate which is commercially available cement isolated from an enrichment culture technique of nutrient broth and nutrient broth-urea medium for the isolate. This *Bacillus* sp. CT-5 grown in nutrient broth-urea(NBU) was used in the cement mortar with a cement to sand ratio of 1:3(by weight) and bacterial culture or water to cement at 0.47. after demolding its cured in NBU medium at room temperature. Then a compression test is done by automatic compression-testing machine(COMPTTEST 3000 at AIML Ltd, New Delhi) [Varenyam Achal; Abhijit Mukherjee; and M. Sudhakara Reddy]
- A mixture of calcium lactate and bacterial spore embedded in clay particle. Spores that were isolated from alkaline lake soil (Wadi Nature, Egypt) were used as the self-healing agent and sequence analysis of 16S rRNA gene of the bacteria show a 98.7% homology to *Bacillus alkalinitrilicus* as alkali-resistant bacteria. This culture was washed by repeated centrifugation and resuspension to

harvest the vegetative cells and spore. Then it is heated to inactivate the vegetative cells for 30min at 80°C. The mortar was prepared from Portland cement (CEMI 42.5N, ENCI,) fine sand and LWA with bacterial spore (bacterial specimen) or without spore (control specimen). After 56 days the specimen was stretched with a computer controlled application for crack formation. Two crack specimens were prepared with a high number of cracks was immersed in water. Later, on exposure to the atmosphere for diffusion of gases over air-water interface for the bacterial spore to activate and precipitate the required CaCO₃ based material for the healing of cracks. [Virginie Wiktor, Henk M. Jonkers].

Vascular network

This method is inspired by the nature of bones and the complexity of its healing mechanism. To create network concrete porous concrete cylinder were used as core based on work by (Yang 2002, Mahboub 2009), the material was gravel(1513 kg/m³), Portland cement CEM I 42.5,(355 kg/m³), Pulverized Fly Ash (22kg/m³) and super-plasticizer (1.4 l/m³) with 0.28 water-cement ratio. Porous concrete cylinders of 35mm diameter and 130 mm height were cast in PVC then all samples were covered with plastic. Demoulded after 24h the cured in curing chamber for 7 days. The taken out it was allowed to achieve saturation surface dry condition for 24h. one sample was covered in PVA water-soluble plastic and one sample was not covered. Then the porous cylinder was put into a 56 diameter PVC mould then cast around the cylinder core. After 7 days the porous network was taken out and dried in an oven at 35°C for 24h and tensile stress applied to create a crack. The healing agent was injected into the sample using syringe through the top end. Epoxy was the healing agent to seal the crack consisting of epoxy resin Conpox Harpiks BY 158(liquid) and hardener Haerder HY 2996 with a weight ratio of 0.3 with a fluorescent dye.

VI. PERFORMANCE OF SELF HEALING CONCRETE:

Self-healing concrete is significant for its high compressive strength and durability through biomineralization. The durability of concrete can be improved by reducing absorption, permeability and diffusion of fluids and gases. The permeability of the specimen with polyurethane immobilized bacteria decreased by six times compared to the control and water absorption has decreased due to its bio-based agent, in both microencapsulated bacteria and non encapsulated one too. The encapsulated ones had a healing ratio ranging from 48%- 80%, on the other hand, non encapsulated ones had a ratio of 18%- 50% by the means of Bacillus sphaericus LMG 22557(J.Y. Wang, H. Soens, W.Verstraete, N. De Belie)

Table 2. Performance effect of self healing concrete

Microbe	Effect on compression strength		Effect on durability		Reference
	Effect	Time (day)	Permeability	Water absorption	
<i>Bacillus Sphaericus</i>	-	28	+	Nil	Wang et al (2014c)
	-	90			
	+	3	Nil	P	
	+	7			Achal et al (2011)
	+	21			
	Nil	Nil	Nil	P	Wang et al (2012b)
	+	7	+	Nil	
	+	28			Achal et al (2013)
	Nil	Nil	+	Nil	
Nil	Nil	+	Nil	Wang et al (2014b)	
				Wang et al (2012a)	
<i>S. pasteurii</i>	+	7	Nil	Nil	Bang et al (2010)
	+	28			Chahal et al (2012)
	+	28	Nil	+	
<i>Bacillus cohnii</i>	+	7	Nil	Nil	Sierra-Beltran et al (2014)
	+	28			
	+	56			
<i>B. pseudofirmus</i>	-	3	Nil	Nil	Jonkers et al (2010)
	-	7			
	-	28			
<i>Diaphrobactor nitroreducens</i>	-	7	Nil	Nil	Erşan et al. (2015a)
	-	28			

+ positive effect, - negative effect

The water absorption test to demonstrate the absorption rate for mortar cubes showed that over a period of 168h, the cubes treated with *Bacillus* sp. Nearly absorbed six times less water compared to the control mortar specimen. The deposition of CaCO_3 resulted in a decrease in the sorptivity as a result reduced intake of a harmful substance that could reduce the life of the concrete

However, there are contradicting results where the use of bio-based healing agent through the process of encapsulation of *B. sphaericus* in mortar resulted in a decrease in the compression strength by 15%- 34% (Wang et al. 2014b) whereas the cube mortar of *B. sphaericus* the compressive strength (Achal et al.2013). There was a positive influence on compressive strength for less concentration of cells at 5×10^6 cells/ mm^3 and a reduction compressive strength in the mortar with 5×10^8 cells/ mm^3 . There are other studies showing that by *Sporosarcina pasteurii* as healing agent increased the compressive strength of the mortar as the higher the concentration of immobilized bacteria increased the compressive strength by 24%. There was improved compressive strength with improved cell concentration from 6.1×10^7 cells/ cm^3 compared to 3.1×10^7 cells/ cm^3

109 cells/cm³(Bang et al. 2010). There are studies indicate that *B. sphaericus* that were immobilized, ureolytic and denitrifying bacteria in concrete decreased compressive strength. But the use of *Diaphorobacter nitroreducens* in clay activated carbon marginally enhanced compressive strength. However, immobilization of *B. sphaericus* in metakaolin and zeolite has an adverse effect on compressive strength. All this contradiction in the results of different researches is mainly due to the different culture media and nutrient source as well as environment condition. The biomineralization can plug the porosities and void inside the concrete too. Therefore the application of microbes that can produce small bio-minerals for the healing of cracks.

VII. CONCLUSION:

Application of self-healing approach over the existing method of construction is capable to fill microcracks and restrict crack development, which can reduce labor and maintenance cost. (Jonkers et al 2010). It can reduce CO₂ emission for cement industries due to decreased cement production(De Muynck et al., 2008; Berenjjan et al.2016). Reduction in porosity, rendering concrete watertight, compatibility between CaCO₃ and concrete composition and favorable thermal expansion are the other advantages of using self-healing concrete

VII. REFERENCES-

- [1] E. Worrell, L. Price, N. Martin, C. Hendriks and L. Meida. Carbon dioxide emissions from the global cement industry. In Annual Review of Energy and the Environment. 26 (1): 03-329; 2001.
- [2] Gerilla G., Teknomo K., & Hokao K. An environmental assessment of wood and steel reinforced concrete housing construction. In Building And Environment. 42(7): 2778-2784; 2007
- [3] B. Tebo, H. Johnson, J. McCarthy and A. Templeton. Geomicrobiology of manganese(II) oxidation. In Trends in Microbiology. 13(9):421-428; 2005
- [4] M. Rivadeneyra. Precipitation of calcium carbonate by *Vibrio* spp. from an inland saltern. In FEMS Microbiology Ecology. 13(3): 197-204; 1994.
- [5] S. Casteiner, Métayer-Levrel G.L, J. Perthuisot. "Bacterial roles in precipitation of carbonate minerals". In: Riding RE, Awramik SM(eds) Microbial sediments. Springer: Berlin Heidelberg : 32–39; 2000.
- [6] F. Hammes and W. Verstraete. Key roles of pH and calcium metabolism in microbial carbonate precipitation. In Reviews in Environmental Science and Bio/Technology. 1(1): 3-7; 2002

- [7] A. Ruzsnyák, Akob D.M., Nietzsche S, et al., Calcite Biomineralization by Bacterial Isolates from the Recently Discovered Pristine Karstic Herrenberg Cave. In *Applied and Environmental Microbiology*. 78(4): 1157-1167; 2011.
- [8] I. Groth, P. Schumann, L. Laiz, S. San. Geomicrobiological Study of the Grotta dei Cervi, Porto Badisco Italy. In *Geomicrobiology Journal*.18(3): 241-258; 2001.
- [9] P. Cacchio, C. Ercole, G. Cappuccio and A. Lepidi. Calcium Carbonate Precipitation by Bacterial Strains Isolated from a Limestone Cave and from a Loamy Soil. In *Geomicrobiology Journal*. 20(2) : 85-98; 2003.
- [10] S. Castanier, G. Le Métayer-Levrel and J. Perthuisot. Ca-carbonates precipitation and limestone genesis — the microbiogeologist point of view. In *Sedimentary Geology*. 126(1-4):19-23; 1999
- [11] J. Wang, N. De Belie and W. Verstraete. Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete. In *Journal of Industrial Microbiology & Biotechnology*. 39(4): 567-577; 2012b
- [12] C. Stuckrath, R. Serpell, L. Valenzuela and M. Lopez. Quantification of chemical and biological calcium carbonate precipitation: Performance of self-healing in reinforced mortar containing chemical admixtures. In *Cement and Concrete Composites*. 50: 10-15; 2014
- [13] W. De Muynck, N. De Belie and W. Verstraete. Microbial carbonate precipitation in construction materials: A review. In *Ecological Engineering*. 36(2):118-136; 2010.
- [14] H. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu and E. Schlangen. Application of bacteria as self-healing agent for the development of sustainable concrete. In *Ecological Engineering*. 36(2): 230-235; 2010
- [15] V. Wiktor and H. Jonkers. Quantification of crack-healing in novel bacteria-based self-healing concrete. In *Cement and Concrete Composites*. 33(7): 763-770; 2011.
- [16] M. Sierra-Beltran, H. Jonkers and E. Schlangen. Characterization of sustainable bio-based mortar for concrete repair. In *Construction and Building Materials*. 67: 344-352; 2014
- [17] V. Achal, A. Mukherjee and M. Reddy. Microbial Concrete: Way to Enhance the Durability of Building Structures. *Journal of Materials in Civil Engineering*. 23(6): 730-734; 2011.
- [18] V. Achal and X. Pan. Characterization of Urease and Carbonic Anhydrase Producing Bacteria and Their Role in Calcite Precipitation. *Current Microbiology*. 62(3): 894-902; 2011.
- [19] K. Van Tittelboom and N. De Belie. Self-Healing in Cementitious Materials—A Review. In *Materials*. 6(6): 2182-2217; 2013.

- [20] M. Ghaz-Jahanian, F. Khodaparastan, A. Berenjian and H. Jafarizadeh-Malmiri. Influence of Small RNAs on Biofilm Formation Process in Bacteria. In *Molecular Biotechnology*. 55(3): 288-297; 2013.
- [21] H. Jonkers and H. Schlangen, Selbstheilen des Betons mit Hilfe von Bakterien . Bacteria-based Self-healing Concrete. In *Restoration of Buildings and Monuments*. 15(4): 255-265; 2009.
- [22] J. Wang, D. Snoeck, S. Van Vlierberghe, W. Verstraete and N. De Belie. Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete. In *Construction and Building Materials*. 68: 110-119; 2014
- [23] V. Achal, A. Mukerjee and M. Sudhakara Reddy. Biogenic treatment improves the durability and remediates the cracks of concrete structures. In *Construction and Building Materials*. 48:1-5; 2013
- [24] J. Wang, K. Van Tittelboom, N. De Belie and W. Verstraete. Use of silica gel or polyurethane immobilized bacteria for self-healing concrete. In *Construction and Building Materials*. 26(1): 532-540; 2012a.
- [25] Wang JY, Van Tittelboom K, De Belie N, Verstraete W. Potential of applying bacteria to heal cracks in concrete. 2nd International Conference on Sustainable Construction Materials and Technologies Proceedings no.3: 1807-1818
- [26] J. Wang, H. Soens, W. Verstraete and N. De Belie. Self-healing concrete by use of microencapsulated bacterial spores. In *Cement and Concrete Research*. 56: 39-152; 2014c
- [27] W. De Muynck, D. Debrouwer, N. De Belie and W. Verstraete. Bacterial carbonate precipitation improves the durability of cementitious materials. In *Cement and Concrete Research*. 38(7): 1005-1014; 2008.
- [28] S. Ramachandran, V. Ramakrishnan and S. Bang. Remediation of Concrete Using Microorganisms. In *ACI Materials Journal*. 98(1): 3-9; 2001
- [29] H. Kim, S. Park, J. Han and H. Lee. Microbially mediated calcium carbonate precipitation on normal and lightweight concrete. In *Construction and Building Materials*. 38:1073-1082; 2013
- [30] S. Bang, J. Galinat and V. Ramakrishnan. Calcite precipitation induced by polyurethane-immobilized *Bacillus pasteurii*. In *Enzyme and Microbial Technology*. 28: 4-5; 2001
- [31] Qian SZ, Zhou J, Schlangen E. Influence of curing condition and precracking time on the self-healing behavior of engineered cementitious composites. In *Cement Concrete Composites*. 32: 686–693; 2010b.

- [32] Q. Chunxiang, W. Jianyun, W. Ruixing and C. Liang. Corrosion protection of cement-based building materials by surface deposition of CaCO₃ by *Bacillus pasteurii*. In Materials Science and Engineering: C. 29(4): 1273-1280; 2009
- [33] S. Bang, J. Lippert, U. Yerra, S. Mulukutla and V. Ramakrishnan. Microbial calcite, a bio-based smart nanomaterial in concrete remediation. In International Journal of Smart and Nano Materials. 1(1): 28-39; 2010.
- [34] S. Maheswaran, S.S. Dasuru, A. Rama Chandra Murthy, B. Bhuvaneshwari, et. al. Strength improvement studies using new type wild strain *Bacillus cereus* on cement mortar. In Curr Sci India. 106(1): 50-57; 2014
- [35] Y. Lee. Calcite production by *Bacillus amyloliquefaciens*. In J Microbiol. 41(4): 345-348; 2003.
- [36] S. Park, Y. Park, W. Chun, W. Kim and S. Ghim. Calcite-forming bacteria for compressive strength improvement in mortar. In J Microbiol Biotechn. 20 (4): 782-788; 2010
- [37] Y. Erşan, F. Da Silva, N. Boon, W. Verstraete and N. De Belie. Screening of bacteria and concrete compatible protection materials. In Construction and Building Materials. 88 :196-203; 2015.
- [38] V. Tittelboom, K., De Belie, N., Van Loo, D., & Jacobs, P. Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. In Cement And Concrete Composites. 33(4): 497-505; 2011.
- [39] K. Mahboub, J. Canler, R. Rathbone, T. Robl and B. Davis. Pervious Concrete: Compaction and Aggregate Gradation. In ACI Materials Journal. 106(6): 523-528; 2009.
- [40] Chahal, N., Siddique, R., & Rajor, A. Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete. In Construction And Building Materials. 28(1): 351-356; 2012.
- [41] Seifan, M., Samani, A., & Berenjian, A. Bioconcrete: next generation of self-healing concrete. In Applied Microbiology And Biotechnology. 100(6): 2591-2602; 2016.
- [42] K. Van Tittelboom, N. De Belie, W. De Muynck and W. Verstraete. Use of bacteria to repair cracks in concrete. In Cement and Concrete Research. 40(1): 157-166; 2009
- [43] W. De Muynck, K. Cox, N. Belie and W. Verstraete, Bacterial carbonate precipitation as an alternative surface treatment for concrete. In Construction and Building Materials. 22(5): 875-885; 2008
- [44] Lesley A. Warren, Patricia A. Mauri. Microbially Mediated Calcium Carbonate Precipitation: Implications for Interpreting Calcite Precipitation and for Solid-Phase Capture of Inorganic Contaminants. In Geomicrobiology Journal. 18(1): 93-115; 2010.

- [45] N. Aran. The effect of calcium and sodium lactates on growth from spores of *Bacillus cereus* and *Clostridium perfringens* in a 'sous-vide' beef goulash under temperature abuse. In *International Journal of Food Microbiology*. 63(1-2): 117-123; 2001
- [46] K. Bachmeier, A. Williams, J. Warmington and S. Bang. Urease activity in microbiologically-induced calcite precipitation. In *Journal of Biotechnology*. 93(2): 171-181; 2002
- [47] R. Berner. The role of magnesium in the crystal growth of calcite and aragonite from sea water. In *Geochimica et Cosmochimica Acta*. 39(4): 489-494; 1975.
- [48] O. Ogah. Effect of Curing Methods on the Compressive Strength of Concrete. *International Journal Of Engineering And Computer Science*. 2016.
- [49] J. DeJong, M. Fritzes and K. Nüsslein. Microbially Induced Cementation to Control Sand Response to Undrained Shear. In *Journal of Geotechnical and Geoenvironmental Engineering*. 132(11): 1381-1392; 2006
- [50] J. Dick et al.. Bio-deposition of a calcium carbonate layer on degraded limestone by *Bacillus* species. In *Biodegradation*. 17(4): 357-367; 2006
- [51] W. Ghiorse, *Biology of Iron- and Manganese-Depositing Bacteria*, *Annual Review of Microbiology*, vol. 38, no. 1, 1984.
- [52] P. Ghosh, S. Mandal, B. Chattopadhyay and S. Pal. Use of microorganism to improve the strength of cement mortar. In *Cement and Concrete Research*. 35(10):1980-1983; 2005
- [53] E. Gruyaert, N. Robeyst and N. De Belie. Study of the hydration of Portland cement blended with blast-furnace slag by calorimetry and thermogravimetry. In *Journal of Thermal Analysis and Calorimetry*. 102(3): 941-951; 2010
- [54] S. Jacobsen, E. Sellevold and S. Matala. Frost durability of high strength concrete: Effect of internal cracking on ice formation. In *Cement and Concrete Research*. 26(6): 919-931; 1996
- [55] S. Jacobsen and E. Sellevold. Self healing of high strength concrete after deterioration by freeze/thaw. In *Cement and Concrete Research*. 26(1): 55-62; 1996
- [56] A. Kalfon, I. Larget-Thierry, J. Charles and H. Barjac. Growth, sporulation and larvicidal activity of *Bacillus sphaericus*. In *European Journal of Applied Microbiology and Biotechnology*. 18(3) :168-173; 1983
- [57] T. Kawaguchi and A. Decho. A laboratory investigation of cyanobacterial extracellular polymeric secretions (EPS) in influencing CaCO_3 polymorphism. In *Journal of Crystal Growth*. 240(1-2): 230-235; 2010

- [58] M. Keller and N. Sottos. Mechanical Properties of Microcapsules Used in a Self-Healing Polymer. In *Experimental Mechanics*. 46(6) :725-733; 2006
- [59] G. Kowalchuk. Community analysis of ammonia-oxidising bacteria, in relation to oxygen availability in soils and root-oxygenated sediments, using PCR, DGGE and oligonucleotide probe hybridisation. In *FEMS Microbiology Ecology*. 27(4):339-350; 1998
- [60] V. Li and E. Herbert. Robust Self-Healing Concrete for Sustainable Infrastructure. In *Journal of Advanced Concrete Technology*. 10: 207-218; 2012
- [61] M. Merz-Preiß and R. Riding. Cyanobacterial tufa calcification in two freshwater streams: ambient environment, chemical thresholds and biological processes. In *Sedimentary Geology*. 126(1-4): 103-124; 1999
- [62] H. Reinhardt and M. Jooss. Permeability and self-healing of cracked concrete as a function of temperature and crack width. In *Cement and Concrete Research*. 33(7): 981-985; 2003
- [63] M. Rivadeneyra, R. Delgado, E. Quesada and A. Ramos-Cormenzana. Precipitation of calcium carbonate by *Deleya halophila* in media containing NaCl as sole salt. In *Current Microbiology*. 22(3): 185-190; 1991.
- [64] C. Ruiz, M. Monteoliva-Sanchez, F. Huertas and A. Ramos-Cormenzana. Calcium carbonate precipitation by several species of *Myxococcus*. In *Chemosphere*. 17(4): 835-838; 1998
- [65] E. Schlangen and S. Sangadji. Addressing Infrastructure Durability and Sustainability by Self Healing Mechanisms - Recent Advances in Self Healing Concrete and Asphalt. In *Procedia Engineering*. 54:39-57; 2013
- [66] M. Seifan, A. Samani and A. Berenjian. Bioconcrete: next generation of self-healing concrete. In *Applied Microbiology and Biotechnology*. 100(6): 2591-2602; 2016
- [67] L. Velásquez and J. Dussan. Biosorption and bioaccumulation of heavy metals on dead and living biomass of *Bacillus sphaericus*. In *Journal of Hazardous Materials*. 167(1-3): 713-716; 2009
- [68] S. Stocks-Fischer, J. Galinat and S. Bang. Microbiological precipitation of CaCO₃. In *Soil Biology and Biochemistry*. 31(11): 1563-1571; 1999
- [69] S. Tsuneda, J. Jung, H. Hayashi, H. Aikawa, A. Hirata and H. Sasaki. Influence of extracellular polymers on electrokinetic properties of heterotrophic bacterial cells examined by soft particle electrophoresis theory. In *Colloids and Surfaces B: Biointerfaces*. 29(2-3): 181-188; 2003

- [70] M. Wu, B. Johannesson and M. Geiker. A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material. In *Construction and Building Materials*. 28(1): 571-583; 2012
- [71] K. Yates and L. Robbins. Radioisotope tracer studies of inorganic carbon and Ca in microbially derived CaCO₃. In *Geochimica et Cosmochimica Acta*. 63(1): 129-136; 1999
- [72] G. Ye, X. Liu, G. De Schutter, A. Poppe and L. Taerwe. Influence of limestone powder used as filler in SCC on hydration and microstructure of cement pastes. In *Cement and Concrete Composites*. 29(2): 94-102; 2007
- [73] W. Zhong and W. Yao. Influence of damage degree on self-healing of concrete. In *Construction and Building Materials*. 22(6):1137-1142; 2008
- [74] S. Mann. *Biomineralization*. New York: Oxford University Press, 2005.
- [75] V. Wiktor and H. Jonkers. Quantification of crack-healing in novel bacteria-based self-healing concrete. In *Cement and Concrete Composites*. 33(7): 763-770; 2011.
- [76] I. Karatas. *Microbiological improvement of the physical properties of soils*. 2008.

