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A REVIEW ON SELF-HEALING CONCRETE USING BACTERIA

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ABSTRACT. *Recent interests in the field of Bio-technology and Civil Engineering have raised the topics on the precipitation of Calcium Carbonate by certain bacteria strains. The relationship between cracks and possible self-healing techniques; artificial and natural are considered. Importance has been laid on the bio-mineralization process and the mechanism of bacterial concrete. The methods of application of these artificial substances that aid the self-healing process in concrete and the effects of engineered self-healing in concrete are discussed in this review.*

Keywords: Concrete, Crack sealing, Self-healing, Bacteria, Autogenous healing, Permeability, Bio-mineralization

1. INTRODUCTION

Concrete is a material widely used for construction that can withstand compressive loads but needs steel in order to resist tensile stresses; its brittle nature makes it susceptible to cracks. Cracks pave way for the ingress of aggressive and potentially harmful fluids or substances such as sulfate, chlorides and carbonates. These aggressive fluids permeate inside the concrete, affecting the reinforcement by corrosion, thereby reducing the durability of the concrete structure. Cracks may not be regarded as failure of the concrete but the introduction of harmful substances create the need to seal these cracks by repairing the structure. The rising costs associated with repairs have led researchers to consider alternatives of crack sealing with growing interests in crack healing. Studies on the subject of self-healing have shown promise in the use of organic and inorganic materials for sealing cracks. The introduction of bacteria into the concrete mixture is one of such organic methods and works by precipitation of calcium carbonate to fill up cracks in concrete. This paper contains an extensive review detailing the different methods whereby bacteria can be applied to concrete in order to achieve self-healing.

2. CRACKS AND SELF-HEALING

Joshi et al [1] defines healing as “the phenomenon of restoration of concrete structure from a state of damage”. Gupta et al [2] describes self-healing as “an emerging concept of delivering high quality materials combined with the capability to heal damages and it has received much attention in past decade for application in building structures. Therefore, an effective self-healing mechanism may be able to reduce repair and maintenance works substantially and concomitant environmental and economic impacts”. Concrete has been found to repair itself over time when cracks have widths less than 0.2mm, when cracks exceed this width, man-made solutions can be applied [3, 4]. Man-made solutions have incorporated different means of self-healing with different levels of viability.

2.1Autogenous Healing

Different researches have been carried to find out how concrete heals itself and different results have been obtained. Huang et al [5] has identified three mechanisms of autogenous self- healing as continuous hydration of unhydrated cement, the recrystallization of calcium hydroxide, and the formation of calcium carbonate. Li et al [6] reports that a relationship exists between the cement composition and crack healing properties, and mixes having higher binder particles tend to have better crack healing properties and this occurrence is caused by delayed hydration of unhydrated cement when in contact with water that passes through cracks [7].

In the absence of stress and in the presence of water, calcite is formed which closes up the cracks that are present on the concrete surface. The rate at which the crack is healed dependent on the concentration of water and the rate at which calcium carbonate is formed.

2.2 Autonomous Healing

Different mechanisms have been proposed by different researchers detailing artificial solutions with their major advantages being that they can close up cracks in concrete with widths greater than 0.1mm. Huang et al. [5] categorizes autogenous mechanisms of healing concrete into:

- Use of mineral admixtures which reacts with water that penetrates the surface of the cracked concrete
- Use of adhesive agents that hardens and connects the cracked surfaces
- Use of bacteria which precipitates calcium carbonate to repair cracks.

These mechanisms can be applied to the concrete via different methods and have a wide range of applications with respect to natural self-healing.

3. BIO-MINERALIZATION

The use of bacterial spores as a method of self-healing follows the mechanism of formation of calcite from autogenous healing. The process by which living organisms produce minerals through metabolic activities from their interaction with the environment is Bio-mineralization. Joshi et al [1] defines Microbially Induced Calcium Carbonate Precipitation (MICCP) as "the capability of microbes to form calcium carbonate extracellularly through a metabolic activity".

Zhang et al [8] noted that the factors affecting the rate of calcium carbonate precipitation are: the amount of calcium present in the concrete matrix and the external environment, the pH of the concrete matrix, the presence of dissolved carbon and the availability of (nucleation) sites where the precipitation can occur via bacterial metabolism (usually the bacterial cell walls). The formation of calcium carbonate can be mediated through different metabolic pathways

3.1 Autotrophic-mediated Pathways

In autotrophic pathways (non-methylotrophic methanogenesis, oxygenic photosynthesis and anoxygenic photosynthesis) precipitation of calcium carbonate is done by the dissolution of carbon dioxide in the presence of calcium ions from the environment. Castanier et al [9] noted that the bacterial spores "induce CO2 depletion of the medium or of the immediate environment of the bacteria. When calcium ions are present in the medium, such depletion favors calcium-carbonate precipitation". Table-1 shows the different metabolic pathways by which Calcium Carbonate formation can occur

Table -1: Different pathways of Bio-mineralization for MICP [10]

Autotrophic bacteria	**Heterotrophic bacteria**				
non-methylotrophic methanogenesis	Assimilatory pathways	Dissimilatory pathways			
	Urea decomposition	Oxidation of organic carbon			
an oxygenic photosynthesis		Aerobic		Anaerobic	
		Process	e–acceptor	Process	e–acceptor
oxygenic photosynthesis	Ammonification of amino acids	Respiration	O_2	NO_x reduction	NO_3^-/NO_2^-
		Methane oxidation	CH_4/O_2	Sulfate reduction	SO_4^2

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3.2 Heterotrophic-mediated Pathways

Castanier et al [9] defines two processes that could possibly occur simultaneously, which are passive precipitation and active precipitation. These processes involve two metabolic cycles: Sulfur cycle which occurs when Sulfur Reducing Bacteria (SRB) is used in an anoxic where organic matter is sufficient and the Nitrogen cycle which involves the conversion of amino acids in the presence of dissolved oxygen, organic matter and calcium into ammonia, the denitrification of nitrogen in the absence or low amounts of oxygen or the decomposition of urea or uric acid in the presence of oxygen and organic matter; all three pathways produce carbonates ions while ammonia is the metabolic end product. The production of ammonia increases the pH of the environment creating an alkaline environment which conforms to the pH of the concrete microstructure.

4. METHODS OF APPLICATION

Different modes of incorporation of the bacterial agents into the concrete have been researched and while some are not feasible, some have shown promise. Gupta et al [2] in their report highlighted two major methods of application: directly to the concrete and by means of encapsulation (in polymeric capsules, in additives, in lightweight concrete aggregate, and in special mineral compounds). Muhammad et al [12] depicted a table showing bacteria could be sprayed or injected into the concrete material or the concrete could be cured in bacterial culture to prevent or heal early age cracking. In addition to the above mentioned methods, Huang et al [5] also reported the use of vascular systems which are embedded inside the structure.

4.1 Direct Application

Jonkers et al [1] and Luo et al [11] studied the effect of direct application of bacterial spores to the concrete mix and determined that while it is a viable option (the spores precipitated calcite when examined within the 7 days of placement but the precipitate could not be found after 28 days), it could not be sustainable because the spores would die off due to the increased pH and the reduced pore size in the concrete microstructure. The repair rates at different cracking ages were also studied with respect of crack width (range 0.1mm to 0.5mm). An 85% healing rate was recorded with curing by water and the use of wet-dry cycles reporting the best restorative performance. Luo et al [11] also concluded that early age cracks were healed efficiently in contrast to late age cracks which they attributed to lack of protective shell for the spores and the distance to the nutrients which caused a low survival rate of the spores.

4.2 Encapsulation

Spores can be encapsulated physically or chemically. Experience and applications from self-healing in polymers, the food industry and the pharmaceutical industry have been useful for the process of encapsulation of spores. This is an efficient method of supplying spores within the concrete matrix with long term effects.

4.2.1 Polymeric Capsules

Report by Wang et al [13] where polymeric microcapsules were used to encapsulate the spores with precursors (nutrients such as calcium nitrate, urea and yeast extracts) and showed 48%-80% healing ratio compared to a 50% healing ratio via autogenous healing. Gupta et al [14] defined the optimum dosage of the capsule application as 3% because higher doses of 5% could result in increase in permeability and reduction of the compressive strength of the structure.

4.2.2 Special Cement Additive

Hydrogel encapsulation of bacteria by Wang et al. [15] resulted in a 40%-90% increase in the healing efficiency of the spores, provides water for bacterial growth while decreasing the water permeability of the concrete by about 68%. The addition of spores does not affect the workability of the concrete but reduces compressive and tensile strengths due to the formation of voids from the capsules.

4.2.3 Light Weight Aggregate

Jonkers [16] experimented with Expended perlite and expanded clay to immobilize and encapsulate spores with precursor compounds. Soft aggregates such as clay aggregates when ruptured, exposes the bacteria to air which triggers the precipitation process. Crack healing of widths of 0.46mm were recorded and while the soft plane of the aggregates might draw crack towards them, the spores were still viable after 6 months. The use of soft aggregates however was found to reduce the strength of the structure making them unfeasible for structural applications. [17]

4.2.4 Application of Mineral Compounds

Gupta et al, [14] defines “Diatomaceous earth (DE) is a type of mineral compound rich in silica and formed from shell of microorganisms called diatoms”. Wang et al. [18] immobilized bacteria in DE and when it cracks and the spores are exposed to air or water, urea is hydrolyzed and calcium carbonate is formed from the precursor (Calcium Nitrate).

The width of healing is dependent on the medium used for the immersion – water based or nutrient based medium nonetheless smaller crack widths were almost or completely healed. Usage of DE in large quantities leads to the mortar drying up due to the fine particles of the DE leading to a higher water absorption rate. Table 2 shows a summary of bacteria species and encapsulation materials that have been tested with respect to self-healing and its application and the findings associated with the research for each specie.

Table -2: Summary of capsule materials, bacterial species and their self-healing properties [2]

Species of bacteria used	Encapsulated (Capsule material)	Directly added	Mechanism	Major findings	Reference
Spore forming bacteria (species not mentioned)		X	Not mentioned in the study	a) High early healing was observed by water curing b) Higher the cracking age, lower is the extent of healing	[11]
Bacillus		X	Decomposition of calcium source to precipitate carbonate	a) Calcium source affects healing ratio- calcium glutamate performs better than lactate b) Bacteria remained viable for 4 months	[19]
Bacillus cohnii	X (Clay aggregates)		Metabolic conversion of calcium lactate	a) Crack width of 0.15 mm with length 8 cm completely sealed b) No loss of viability up to 6 months	[16]
Bacillus Sphaericus	X (immobilized in PU and silica gel inside glass)		Ureolytic decomposition of calcium nitrate	a) PU immobilized bacteria specimens showed lowest permeability b) Higher bacteria activity in silica sol c) Higher strength recovery in case of PU immobilization	[15]
Bacillus Sphaericus	X (Diatomaceous earth)		Ureolytic decomposition of calcium nitrate	a) Highest reduction of water absorption was observed in bacteria containing specimen b) Dosage of DE must be carefully adjusted because it causes loss in concrete workability	[20]
Bacillus Sphaericus	X (Melamine based capsules)		Ureolytic decomposition of calcium nitrate	a) Crack healing ratio of 48% to 80%; highest crack width healed is 970 µm b) Permeability recorded for bacteria specimen is about 10 times compared to control c) highest reduction in crack area in case of wet-dry cycle	[21]
Bacillus Sphaericus	√ (hydrogel) – one component (only bacteria) and two component (bacteria and nutrient) system		Ureolytic decomposition of calcium nitrate	a)Maximum crack sealing of 500 µm under wet-dry cycles b) Permeability decrease of 68% for specimens containing hydrogel encapsulating both bacteria and nutrients together	[12]
Bacillus Sphaericus	√ (Sodium alginate based hydrogel)		Ureolytic decomposition of calcium nitrate	Bacterial activity was observed only for encapsulated samples at crack face measured by oxygen consumption	[15]
Bacillus Subtilis	√(Lightweight aggregates and graphite nano-platelets)		Decomposition of calcium lactate	a) Bacteria can be distributed uniformly in concrete when immobilized in graphite nano-platelets (GNP) due to fine particle size and uniform dispersion of GNP b) Bacteria immobilized in GNP showed high self-healing when samples were pre-cracked at early stages (3 day and 7 day) c) Lightweight aggregates are more effective when samples are pre-damaged at later stage (14 day and 28 day)	[22]

4.3Vascular Method

A vascular network can be built in the structure by pre embedding smooth glass tube bars into the concrete and removing them later, leaving spaces in the structures where the bacterial spores can be injected or pumped into the canals if cracks intersect these spaces [23-25]. In this case, to the holes or tunnels created in the structure, the healing agent can be applied over long periods of time leading to higher healing rate and greater efficiency of the healing process. The fig-1 shows a modified version of the vascular system proposed by C. M. Dry [26].

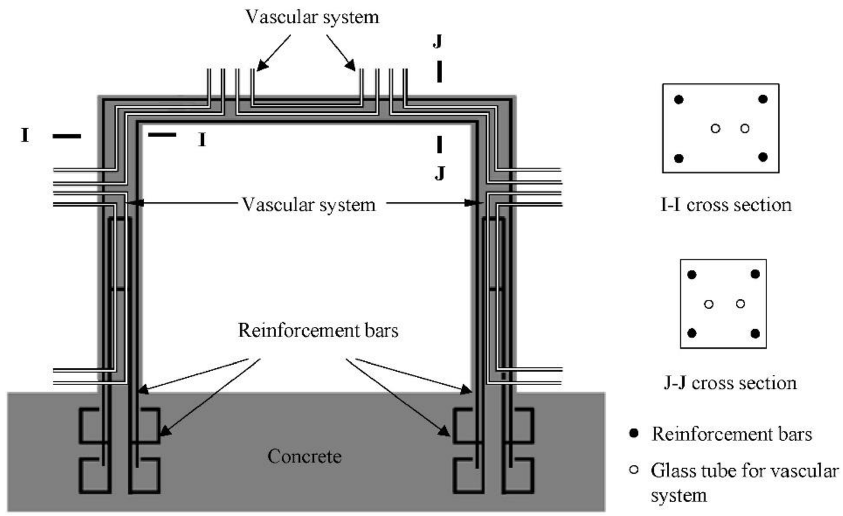

Fig-1: Modified Vascular System for self-healing [5]

5. EFFECT OF BACTERIA ON CONCRETE PROPERTIES

5.1 Precursors and Setting Time

The effect of the addition of precursors into the concrete mix resulted in mixed results. Depending on the type of nutrient use for bacterial spores in concrete, the setting time can be accelerated or retarded. Calcium Lactate delays setting time whereas Calcium Formate and Calcium Nitrate quickens the setting time. [27, 28]

5.2 Compressive Strength

Using bio concrete could increase or decrease the compressive strengths of the concrete depending on the bacterial species used, the percent of cement replaced with pozzolans, the use of admixtures such as Rice Husk Ash and Fly Ash and the mode of supply of bacteria to the concrete structure.[29, 10, 30-33]. Tables 3 points out bacteria types, their compressive strength increase with respect to control concrete and the concentration of cells per milliliter of concrete.

Table -3: Bacteria types and their compressive strengths with respect to normal concrete [10]

S.NO	Bacteria used	Best results	Bacterial concentration	Reference
1	Bacillus sp. CT-5	Compressive strength 40% more than the control concrete	5×10^7 cells/mm^3	[28]
2	Bacillus megaterium	Maximum rate of strength development was 24% achieved in highest grade of concrete 50 Mpa	30×10^5 cfu/ml	[31]
3	Bacillus subtilis	Improvement of 12% in compressive strength as compared to controlled concrete specimens with light weight aggregates	2.8×10^8 cells/ml	[22]
4	Bacillus aerius	Increase in compressive strength by 11.8% in bacterial concrete compared to control with 10% dosage of RHA	10^5 cells/ml	[34]
5	Sporosarcina pasteurii	Compressive strength 35% more than the control concrete	10^5 cells/ml	[35]
6	AKKR5	10% increase in compressive strength as compared to control concrete	10^5 cells/ml	[36]
7	Shewanella Species	25% increase in compressive strength of cement mortar compared with the control mortar	100,000 cells/ml	[37]

5.3 Permeability (Water and Chloride ions)

Ingress of harmful fluids is directly related to permeability. The activity of bacteria in the concrete reduces the permeability because the pores are filled with Calcium Carbonate from precipitation. Some spores (Pasteurii spp.), reduces the absorption rate of water and reduces the rate of chloride penetration [33, 39]. Aerius spp. decreases water absorption and porosity which increases durability and also reduces the amount of charges passing through the concrete [35]. Ingress of Chloride ions is dependent on the internal pore and capillary structure of the concrete and the pore and capillary structure is determined by factors such as mix design, degree of hydration, curing, etc. Comparing control concrete to bio-concrete, Bio-crete enhances the resistance of concrete to Chloride penetration [36, 32]

5.4 Microstructure

Research carried out using Scanning Electron Microscopy (SEM) showed that rod shaped bacteria which carry out calcite precipitation improved the micro structure of concrete. The addition of additives further enhances the micro structure by filling up voids in the concrete micro structure. [39, 32, 40, 41].

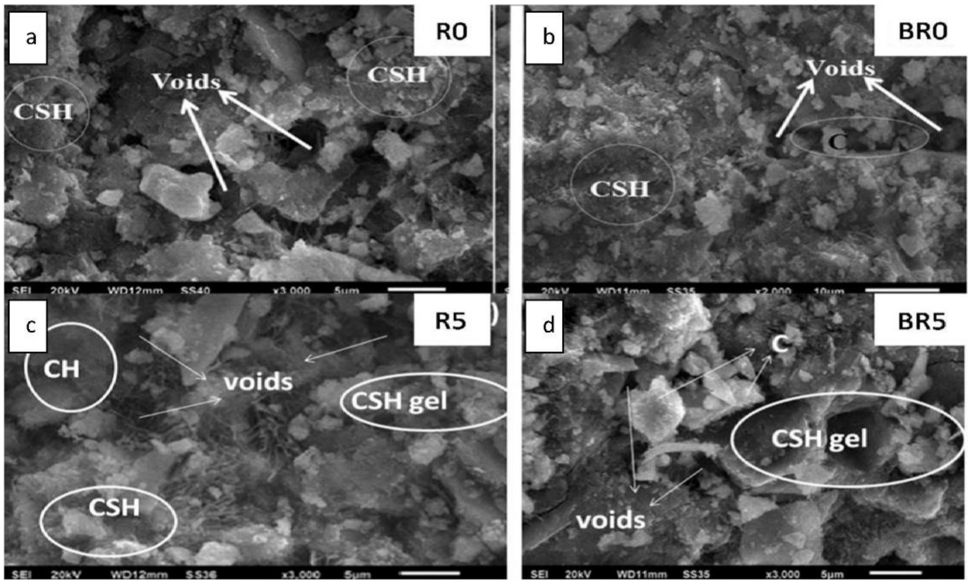

Fig -2: Scanning electron microscope (SEM) Images showing a. Normal Concrete b. Bacterial Concrete c. 5% RHA Concrete d. Bacterial concrete with 5% RHA [10]

6. CONCLUSION

While, the study of bacterial concrete is still far off from being cost efficient or general feasible for use in all conditions, it shows promising interest and can be used in controlled environments. Gupta et al [2] suggested that to make bacterial concrete commercially viable the cost of production should be reduced or by making the design more viable for long life applications so that it would work under continuous cycle of loading and extreme conditions.

Bacteria induced self- healing has drawn much attention due to its ability to be applied or long term constructions, eco-friendly and being well-matched with the concrete mix. It can be applied to virtually any structure (under-ground structures, bridges, pavements, etc.) as its application is versatile due to the different modes of application.

While more research is needed to consolidate its shortcomings such as the time it takes to heal cracks which usually take longer for larger widths of cracks; a more sustainable approach needs to be found to make it a more viable option in the industry. The ability of bacterial concrete to heal cracks deeper in the concrete should also be studied. The nutrients required for use by the bacteria should also be considered and the cost of obtaining them could be reduced. The cost and efficiency of the bacterial concrete with respect to conventional repairs should also be looked into to make it cheaper and accessible. Bio-concrete can be the future of sustainable engineering but research needs to assess the life cycle and means to further improve the current life cycle of the system.

Over the past few years, the interest in bacterial concrete has been astounding and the research and studies conducting have been quite progressive which leads us to believe that its implementation in the industry isn't far.

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