Bacterial Concrete- A Novel Biotechnical Application in Construction Sector

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Abstract**—** Concrete is a very essential component of construction materials which is widely used in infrastructure. Despite of its vital usage in construction, it is still known to have several limitations. It is estimated that cement production alone contributes to about 7% of global anthropogenic carbon dioxide emissions which is responsible for green house effect resulting in global warming.

A novel eco friendly self healing technique called Bio-calcification is one such approach to investigate the crack healing mechanism in enhancing properties of concrete. Microbiologically induced calcite precipitation (MICP), a highly impermeable calcite layer formed over the surface of an already existing concrete layer, due to microbial activities of the bacteria seals the cracks in the concrete structure.

This paper outlines the basic mechanism of bacterial concrete on which studies were carried out to investigate the causes involved in enhancing the strength and durability of concrete. It possesses certain self healing properties which are potentially enormous for lengthening in service-life of infrastructure, increases the performance, excellent resistance to corrosion, substantially reducing the maintenance costs and considerably increases the safety of structures.

Keywords**—** *self-healing, Bio-calcification, Calcium Carbonate, bacterial concrete, repairing, calcite precipitation, sustainable, durable, economic, MICP*

I. INTRODUCTION

Concrete is the most critical element applied in public infrastructure/buildings and is often difficult to service, yet requires lengthy service periods. It is weak in tension, has limited ductility and little resistance to cracking. Also, failure like corrosion can lead to structural failures with potentially serious long term operational consequences. Based on the continuous research carried out across the world; various modifications have been made timely to overcome the shortcomings in cement concrete.

Recent research has shown that biotechnology can actually be useful as a tool to repair cracks in and already existing concrete structures by using specific species of bacteria in concrete. This new concrete, that is prepared to repair itself, presents a potentially enormous lengthening in service-life of public infrastructure/buildings and also considerably reduces the maintenance costs, therefore lowers carbondioxide emissions.

II. MICROBIOLOGICALLY INDUCED CALCITE PRECIPITATION

A. The Biological Self Healing Process

It is important to know and understand, what kind of bacteria will live in the concrete, how they work to improve the longevity of public infrastructure, what the catalyst will be that causes the chemical reaction in the bacteria, what happens to the specific kinds of specialized bacteria when exposed to the catalyst, and how they work together to not only heal cracks before they form, but also strengthen the overall structure into which they are incorporated.

When the bacteria are exposed to the air and the "food," the bacteria go through a chemical process that causes them to harden and fuse, filling in the crack that has formed, strengthening the structure of the concrete, and adhering to the sides of the crack to seal the damage site. This process extends the lifespan of the structure while also fixing the damage caused. The process of healing a crack can take a few days.

The basic concept behind this specific version of self-healing concrete is utilizing certain types of bacteria and how they function to seal microscopic cracks in the concrete before they grow into larger cracks. During the biocalcification process the enzymatic hydrolysis of urea takes place forming ammonia and carbon dioxide. Urease, which is provided by bacteria deposits $CaCO_3$, a highly impermeable calcite layer, over the surface of an already existing concrete layer which is relatively dense and can block cracks and thus hamper ingress of water efficiently increasing corrosion resistance and consequently increasing the strength and durability of concrete structures. MICP is a complex mechanism and is a function of cell concentration, ionic strength, nutrient and pH of the medium. Modern techniques such as X-ray diffraction tests and SEM analysis can be used to quantify the study of stages of calcite deposition on the surface and in cracks.[6]

B. How Does Bacteria Remidiate Cracks

When the concrete is mixed with bacteria, the bacteria go into a dormant state. All that the bacteria need there is exposure to the air to activate their functions. Any cracks that should occur provide the necessary exposure. When the cracks form, bacteria in very close proximity to the crack, starts precipitating calcite crystals. When a concrete structure is damaged and water starts to seep through the cracks that appear in the concrete, the spores of the bacteria germinate on contact with the water and nutrients. The bacteria get activated and start feeding on the calcium lactate nutrient. As the bacteria feeds oxygen is consumed and the soluble calcium lactate is converted to insoluble limestone. The limestone solidifies on the cracked surface, thereby sealing it up. Oxygen is an essential element in the process of corrosion of steel and when the bacterial activity has consumed it all it increases the durability of steel reinforced concrete constructions.

C. Chemistry Of The Process.

Table 1: Steps involved in MICP Process

STEP 1	CO $(NH_2)_2$ + H_2O → $NH_2COOH + NH_3$	Urea hydrolyzed
STEP 2	$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$	Ammonia released
STEP 3	$H_2CO_3 \rightarrow 2\,H^+ + 2CO_3^{2-}$	Bicarbonate formed
STEP 4	$NH_3 + H_2O \rightarrow NH_4^- + OH^-$	Ammonium and hydroxide ion giving rise to pH.
STEP 5	$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$	Precipitate formed

Bacterial concrete is a new approach to an old idea that a microbial mineral deposit constantly occurs in natural environment and causes healing.

This concrete makes use of calcite precipitation by favorable bacteria; hence it is called Microbial or Bacterial concrete. It can be prepared by adding spore forming bacteria in the concrete that are able to continuously precipitate calcite, this process of production of calcite precipitation is called Microbiologically Induced Calcite Precipitation (MICP).

In MICP process, Microorganisms (cell surface charge is negative) draw cations including Ca^{2+} from the environment to deposit on the cell surface. The bacteria can thus act as a nucleation site which facilitates in the precipitation of calcite which can eventually plug the pores and cracks in the concrete. The MICP process comprises of a series of complex biochemical reactions. As part of metabolism, Bacteria produces urease, which catalyzes urea to produce CO_2 and ammonia, resulting in an increase of pH in the surroundings where ions Ca^{2+} and CO_3^{2-} precipitate as $CaCO_3$. These create calcium carbonate crystals that further expand and grow as the bacteria devour the calcium lactate food. The crystals expand until the entire gap is filled. [6]

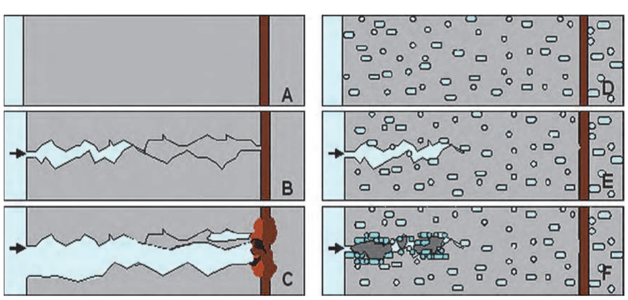

Fig 1: Ingress of moisture restricted by Calcite precipitation

It is found that microbial calcite precipitation (Fig. 1) resulting from metabolic activities by bacterial cultures in concrete improves the properties of concrete like the compressive strength and durability of concrete and also reduces permeability resulting in lesser corrosion, thus, improves the overall strength of concrete structures.

D. Types of Bacteria

There are various types of Bacteria which are used for making bacterial concrete and help to improve the concrete strength and durability. According to the literature review, following are varieties of the bacteria which can be utilized in the concrete:

APPILCATIONS	TYPES OF BACTERIA
As crack healer	B. pasteurii
	Deleya halophila
	Halomonas eurihalina
	Myxococcus xanthus
	B. megaterium
For surface treatment	B. sphaericus
As water purifier	B. subtilis
	B. sphaericus
	Thiobacillus

Fig 2: Various Bacteria Species

III. EXPERIMENTAL PROCEDURE

The main aim of the present experimental program is to obtain specific experimental data, which helps to understand the crack healing ability of Bacterial concrete and its characteristics (Strength and Durability).

A. Steps Involved

This experimental program is categorized into four phases:
Phase 1: Culture and Growth of Bacteria
Phase 2: Evaluation of compressive strength enhancement in Bacterial concrete specimens
Phase 3: Evaluation of Durability enhancement in Bacterial concrete specimens
Phase 4: Microscopic analysis of $CaCO_3$ precipitation in Bacterial concrete specimens. [6]

B. Characterization Studies

The calcite precipitation by means of bio-mineralization can be analyzed by using various characterization methods and techniques. These techniques are specialized and involve different types of microbial analysis like diffraction, imaging and spectroscopy which includes light, X-rays, neutron or electron as primary radiation.

i. *Compressive Strength and Tensile Strength*: Compressive strength of cement paste, mortar and concrete having bacteria is performed using automatic compression testing machine. Split tensile strength concrete with bacteria is performed by making cylinders and testing using compression testing machine.

ii. *X-ray diffraction*: This test is conducted to indicate the presence of calcite in bacterial concrete. Higher the peak values obtained shows; higher is the presence of calcite precipitate. Hence it can be said that microbial precipitated calcite improves the performance of cement composites.

iii. *Scanning Electron Microscopy (SEM):* The calcite deposition inside the micro cracks of concrete by bacteria is scanned and analyzed under this Electronic Microscope. The increase in compressive strength of concrete can be examined by doing SEM analysis. To determine whether the increase in compressive strength of the specimens having bacteria could be attributed to the microbial calcite precipitation, the crack samples with the highest strength values are examined under SEM.

iv. *Ultrasonic Pulse Velocity*: The principle of UPV equipment is dependent on time taken for the pulse to pass through the concrete when measured by electronic measuring circuits. Thus, the cracks and deformations in the cubes indicate higher velocity value. [2]

IV. ADVANTAGES OF BACTERIAL CONCRETE OVER CONVENTIONAL CONCRETE

A. *Sustainable Green Building Material*

Concrete is a strong and relatively cheap construction material and is therefore presently the most used construction material worldwide. Though concrete has a massive production, yet it exerts a negative effect on the environment. In the past two decades the building industry became faced with a number of serious problems related to scarcity of raw materials and energy along with the emission of hazardous products into the environment. The yearly world-wide demand for concrete has reached 0.5 to 1.0 m^3 per capita. It is estimated that cement production alone contributes to about 7% of global anthropogenic carbon-dioxide emissions.

Mitigation of the ecological footprint can no longer be considered as something extra but as an inherent component of technological and industrial achievements. For a sustainable building industry, focus should be on minimizing resource consumption, preference on renewable materials and energy, closed cycles of non-renewable resources, optimize the life span of a structure by using more reliable and easily repairable materials and reduction of maintenance costs by extending the service life of structures.

A possible way to achieve these sustainable factors is by using self-healing materials like bacterial concrete that will increase the life span of structures, reduce consumption of resources resulting in reduction of the maintenance costs. Apart from the lower consumption of resources, a longer life span of structures also impacts in the reduction of indirect costs like need for construction-related transport of materials and people. Therefore, the development of a self-healing mechanism in concrete that is based on a potentially cheaper and more sustainable material in cement could thus be beneficial for both economy and environment and thus can be rated as a green building material as well.[2]

B. *Reduction in Permeability and Resistance to Corrosion*

Permeability of concrete is another significant characteristic of concrete that affects its durability. Concrete with low permeability has been recorded to last much longer. Once the moisture or gases get into concrete structure, the structure no longer maintains its structural integrity; the life span is reduced, and the general safety of the public is severely in danger. Many conventional techniques like application of chemical admixtures, plasticizers, water reducing agents etc. are known to improve the workability of concrete by reducing the inter-granular friction which affects porosity. However, they come along with various disadvantages:

a) Incompatibility of protective layer and base layer due to difference in thermal expansion coefficient

b) Disintegration of protective layer over a period of time

c) Need for constant and periodic maintenance

Due to these shortcomings, effect of microbial concrete on permeability properties was studied by different researchers.

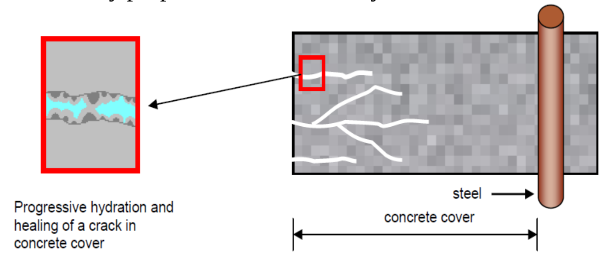

Fig 3: Self - Healing of micro cracks in concrete cover

Self-healing of micro cracks is the reason for densification of the concrete cover, thus reducing the rate of entry of chloride ions into the concrete (Fig 3). Thus, calcite precipitation in concrete results in a decrease of chloride ingress into concrete.

Corrosion of steel in concrete structures is one of the major reasons in failure of structures. Corrosion initiates due to ingress of chloride ions, moisture and carbon dioxide through the cover of concrete onto the steel surface. Corrosion and permeability are somehow related to each other. The cracks lead to ingress of moisture and chlorides which is responsible for early leakages and corrosion of steel. Corrosion products such as iron oxides and hydroxides lead to induced stresses in concrete that crack the concrete cover which in turn exposes reinforcement to direct environmental attack that results in progressive deterioration of the structure. Thus, application of bacteria producing microbial calcite in concrete may help in sealing the cracks of ingress and improve the life of reinforced concrete. [1]

C. *Economic Considerations and Payback Period*

Another matter of concern is the huge maintenance costs for structures built in the past. The total amount of money involved in repair and upgrading is estimated to around 140 billion US dollars. In The Netherlands 50% of about thousand inspected bridges, viaducts and tunnels required further detailed inspection of their load bearing structure and one third of the annual budget for large civil engineering works is spent on inspection, monitoring, maintenance, upgrading and repair. In the United Kingdom the costs for repair and maintenance accounts for almost 45% of UK's activity in construction and building industry. In India, total construction structures including industrial and commercial projects and public properties were estimated as Rs 35,000 billion, which is equal to 20% of the income generated every year. It was also estimated that Rs 3,200 billion was required to rebuild India's damaged concrete structures. Housing sector alone has assets of worth more than Rs 500 billion and would require more than Rs 170 billion for repair and maintenance every year. There is no doubt that the lack of quality and premature failure our aging infrastructure is a major issue to be dealt. [1]

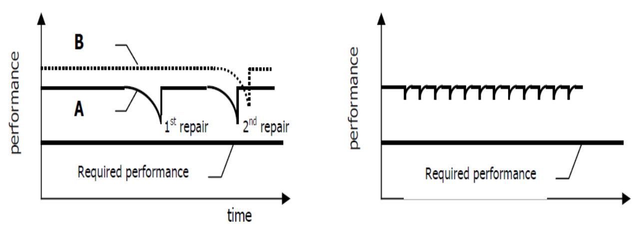

Fig 4 (a), (b): Damage Prevention Paradigm

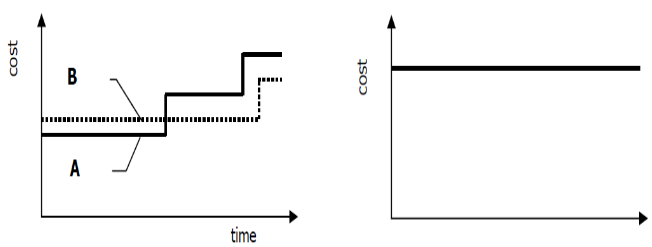

Fig 5 (a), (b): Damage Control Paradigm

The design philosophy that focuses on prevention of damage by using high strength materials has been termed as Damage Prevention Paradigm. It states that improving the strength of a material will certainly increase the load bearing capacity and postpone the moment first damage occurs. However, there is still an incremental improvement of existing technology within the damage prevention paradigm which is otherwise referred with the Damage Control Paradigm, where even a certain degree of damage is not considered acceptable, but even supposed to initiate an inherent mechanism of self-healing.

The production cost of self-healing materials will most often exceed from traditional materials' cost.

But the extra initial cost of self healing materials is justified by the reduction of the costs for inspection, repair and maintenance due to a longer service live. In Figure 4 (a,b) the performance and costs for a low quality (Fig 4a) and a high quality (Fig 4b) structure are compared, both designed according to the DPP. Figure 5 (a,b) shows similar curves for a system designed according to the DCP.

A cost comparison system designed according to the DPP and the DCP illustrates that, depending on the required life time of the structure, higher initial costs will finally pay off. If the indirect costs due to repair are not considered in Figure 4b and 5b would have been taken into account as well, higher initial costs are almost always justified.

In Figure 5a, an ideal self-healing material performance has been proposed. Unlike ideal conditions, the self-healing and repairing potential of a material will be limited. This means that it is not practical to expect that the use of self-healing materials will make inspections, monitoring, repair and maintenance completely unessential. However, the construction sector can already be benefited from incremental improvements of the self-healing capacity of a material. If the maintenance-free period can be extended and the moment of repair can be postponed, high savings are feasible. In this respect, it is important to realize the large scale usage of concrete in which minor improvements of the material performance can result in huge savings of repair and maintenance costs. Therefore, if the usage of self-healing materials is the only rational solution, the superficial costs of the material will be no restraining factor. [1]

V. CONCLUSION

Use of biotechnology in development of new type of concrete named Bacterial concrete, will prove to be superior to many conventional technologies due to its eco-friendly nature and self-healing abilities leading to increase in strength and durability. This technique will result in increase in compressive strength, reduction in permeability and water absorption resulting in reduction of reinforcement corrosion in the concrete. With this process, money can be saved, structures will last much longer, and the concrete industry as a whole will turn out a far more sustainable product, effectively reducing its CO_2 contribution and therefore it will soon provide the basis for high quality structures that will be cost effective, sustainable and environmentally safe, but more research work is required to improve the feasibility of this technology from both an economical and practical viewpoints.

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