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Self-Repairing Concrete for Sustainable Solutions

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Abstract- **The aim of this research project is the development of a new type of concrete in which integrated bacteria promote self-healing of cracks. Traditional concrete does usually show some self-healing capacity what is due to excess non-hydrated cement particles present in the material matrix. These particles can undergo secondary hydration by crack ingress water resulting in formation of fresh hydration products which can seal or heal smaller cracks. However, the integration of excess cement in concrete is unwanted from both an economical and environmental viewpoint. Cement is expensive and, moreover, its production contributes significantly to global atmospheric CO_2 emissions. In this study we developed a two-component self-healing system which is composed of bacteria which catalyze the metabolic conversion of organic compounds to calcite. Both components are mixed with the fresh cement paste, thus becoming an integral part of the concrete. Experimental results show that ingress water channeled through freshly formed cracks activates present bacteria which through metabolic conversion of organic mineral-precursor compounds produce copious amounts of calcite. This new bio-based two-component system may represent a new class of self-healing mechanisms which can be applied to cement- based systems. The self-healing capacity of this system is currently being quantified what should result in an estimate of the materials durability increase. A self-healing concrete may be beneficial for both economic and environmental reasons. The bacteria based concrete proposed here could substantially reduce maintenance, repair and premature structure degradation what not only saves money but also reduces atmospheric CO_2 emissions considerably as less cement is needed for this type of self-healing concrete. The recent research shows that specific species of bacteria can actually be useful as a tool to repair cracks in early stage of already existing concrete structures. A highly impermeable calcite layer formed over the surface of an already existing concrete layer, due to microbial activities of the bacteria (Bacillus subtilus) seals the cracks in the concrete structure and also has excellent resistance to corrosion.**

Index terms- **Self-Healing, Bacterial Concrete, Calcite, Bacillus Subtilus, Calcium Carbonate**

INTRODUCTION

Concrete can be considered as a kind of artificial rocks with the properties similar to that of some kinds of rocks. As it is strong, durable and relatively cheap, concrete is since, almost two centuries, the most used construction materials worldwide, which can easily be recognized as it has changed the physiognomy of rural areas. Normally the concrete as we all know is good in compression but week in tension. The most of the crack which forms initially is due to tension. Cracks can form at any stage of its life and mostly begin internally where they cannot be seen for years until major repairs are needed. Damage is caused by freeze/thaw cycles, corrosion, extreme loads, chemical attacks and other environmental conditions. Consequently, maintenance to concrete structures is frequent and costly. Billions of dollars are spent every year on buildings, bridges and highways for maintenance, making materials requiring less frequent repairs very appealing. The production of concrete is an energy pensive process when mining, transportation and processing is considered. Its production level lies more than 2.35 billion metric tons per year and contributes an astonishing 10% of CO_2 emissions into the atmosphere. Here the self-healing would enables the fewer repairs works or even failure of a structure through which the production level can even be decreased along with the reduced CO_2 emission.

Tiny cracks on the surface of the concrete make the whole structure vulnerable because water seeps in to the cracks and degrade the concrete and corrode the steel reinforcement, greatly reducing the lifespan of a structure. Repairs can be particularly time consuming and expensive because it is often very difficult to gain access to the structure to make repairs, especially if they are underground or at a great height. High figures of CO_2 emission, energy and materials consumption, structural failures and huge indirect costs are anything but a sign of sustainability. From an environmental viewpoint, the latter concrete types are preferred as less cement per concrete volume is used contributing to lower CO_2 emissions. Although high strength concrete allows building of more slender structures than ordinary concrete and thus need less concrete volume, the total amount of cement used is still significantly higher due to the inherent high percentage of non- or partially hydrated cement particles in the material matrix. The development of a self-healing mechanism in concrete that is based on a potentially cheaper and more sustainable material then cement could thus be beneficial for both economy and environment. The main goal is to develop a type of self –

BIOMINERALISATION IN SETTING TIME

Healing concrete using a sustainable self-healing agent, i.e. limestone-producing bacteria. Although bacteria, and particularly acid-producing bacteria, have been traditionally considered as harmful organisms for concrete, recent research has shown that specific species such as ureolytic and other bacteria can actually be useful as a tool to repair cracks or clean the surface of concrete. Self-repairing concrete biologically produces calcium carbonate crystals to seal cracks that appear on the surface of the concrete structures. Specific spore forming alkalliphillic bacteria genus Bacillus, supplied with a calcium-based nutrient are incorporated in to the concrete suspended in mixing water. These bacteria based self-healing agent is believed to remain hibernated within the concrete for up to 200 years. When cracks appear in a concrete structure and water starts to seep in through, the spores of the bacteria starts microbial activities on contact with the water and oxygen. In the process of precipitating calcite crystals through nitrogen cycle the soluble nutrients are is converted to insoluble $CaCO_3$. The $CaCO_3$ solidifies on the cracked surface, thereby sealing it up. It mimics the process by which bone fractures in the human body are naturally healed by osteoplastic cells that mineralize to reform the bone. The consumption of oxygen during the metabolic biochemical reactions to form $CaCO_3$ helps in arresting corrosion of steel because the oxygen is responsible to initiate the process of corrosion thereby increasing the durability of steel reinforced concrete structures.

USING BACTERIA TO SELF-HEAL CRACKS IN CONCRETE

Bacteria added to concrete mix in suspension state must meet certain criteria. Concrete is a highly alkaline building material , so bacteria used as self-healing agent should be able to survive in this high alkaline environment for long durations and be able to form spores (highly resistant structures) withstanding mechanical forces during concrete mixing. In the concrete technology laboratory, a bacterial concrete mix is prepared using alkali-resistant soil bacteria Bacillus subtilus along with nutrients from which the bacteria could potentially produce calcite based bio-minerals. It was found that strains of the bacteria genus Bacillus were found to thrive in this high-alkaline environment. Such gram positive bacteria have extremely thick outer cell membrane that enables them to remain viable until a suitable environment is available to grow. They would become lively when the cracks form on concrete surface allowing water to ingress into the structure. This phenomenon will reduce the pH of the concrete environment where the bacteria incorporated become activated.

A peptone based broth medium supplied along with bacteria in suspension helps in producing calcite crystals. It is found that this biomineralisation process will not interfere with the setting time of the concrete. The most expensive ingredient in developing bacterial concrete is nutrients. So any inexpensive alternative for laboratory growth media would potentially bring down the cost of the bacteria based self-healing sustainable concrete. Only factor need to be checked is the effect of nutrients media on the setting time of cement. So this needs proper study while using suitable medium.

MECHANISM OF SELF-HEALING USING BACTERIA

The microorganism used for manufacturing of microbial concrete should able to possess long-term effective crack sealing mechanism during its lifetime serviceability. The principle behind bacterial crack healing mechanism is that the bacteria should able to transform soluble organic nutrients into insoluble inorganic calcite crystals which seals the cracks. For effective crack healing, both bacteria and nutrients incorporated into concrete should not disturb the integrity of cement sand matrix and also should not negatively affect other important fresh and hardened properties of concrete. Only spore-forming gram positive strain bacteria can survive in high pH environment of concrete sustaining various stresses. It was reported that when bacteria is added directly to the concrete mix in suspension, their life-time is limited due to two reasons; one is continuing cement hydration resulting in reduction of cement sand matrix pore -diameter and other is due to insufficient nutrients to precipitate calcite crystals. However, a novel method of protecting the bacterial spores by immobilization before addition to the concrete mixture appeared to substantially prolong their life-time

BACILLUS SUBTILIS

This strain isolated from soil has characteristics of high level urease activity, incessant precipitation of dense insoluble calcite crystals and has high negative zeta- potential. Potential applications of biological mineral precipitation are wide such as in sand consolidation and stabilization, remediation of cracks in concrete, preservation and restoration of historic heritage structures, areas where it is not possible to shut down the plant or hazardous for human beings to reach for repair work such as nuclear power plants, repair of waste water sewage pipes etc. These are the most bacteria to use for self-healing purposes since these are alkalliphillic spore forming bacteria. The bacteria, from this genus Bacillus subtilus is adopted for present study. The bacteria are cultured in the broth medium of artificial broth extract.

PRINCIPLE OF SELF-HEALING PROCESS

Specially selected types of the genus Bacillus, along with a calcium based nutrient and nitrogen and phosphorus in presence of oxygen, the soluble calcium source is converted to insoluble calcium carbonate by ureolytic activity. The calcium carbonate solidifies on the cracked surface, thereby sealing it up. It mimics the process by which bone fractures in the human body are naturally healed by osteoblastic cells that mineralize to reform the bone. MICP occurs via far more complicated processes than chemically induced precipitation. The bacterial cell surface with a variety of ions can non-specifically induce mineral deposition by providing a nucleation site. Ca_2+ is not likely utilized by microbial metabolic processes; rather it accumulates outside the cell. In medium, it is possible that individual microorganisms produce ammonia as a result of enzymatic urea hydrolysis to create an alkaline micro environment around the cell. The high pH of these localized areas, without an initial increase in pH in the entire medium, commences the growth of $CaCO_3$ crystals around the cell. Possible biochemical reactions (vide Eq. a, b & c) in Urea-CaCl2 medium to precipitate $CaCO_3$ at the cell surface can be summarized as follows

[a] : $Ca_2+ + Cell \quad Cell\text{-}Ca_2+$

[b] : $Cl- + HCO_3 - + NH_3 \quad NH4Cl + CO_2-$

[c] : $Cell\text{-}Ca_2+ + CO\ _2- \quad Cell\text{-}CaCO \downarrow$

The study of M V Seshagiri Rao (15) showed that using SEM analysis it was proved that the rhombohedra shape to calcite crystals is due to the presence of chloride ions whereas spherical shape to crystals is due to the presence of acetate ions.

EXPERIMENTAL PROGARM

The main aim of the present experimental program is to obtain the specific details of the crack healing of the concrete incorporated with the bacterial species of specific kind. This experimental program involves

Phase 1: Culture and growth of Bacillus subtilus.

Phase 2: Evaluation of the compressive strength of the concrete incorporated with the bacteria.

Phase 3: Healing mechanism of the self-repairing concrete.

MATERIALS USED

Following are the details of the materials used in this investigation:

Cement OPC of 53 grade locally available is used in this investigation. The Cement is tested for various properties as per the IS : 4031 – 1988 and found to be confirming to various specifications of IS: 12269 – 1987 having specific gravity 3.0.

Fine aggregate locally available clean, well graded, natural river sand having fineness modulus of 2.89 conforming IS: 383 – 1970 was used as the fine aggregate.

VIABILITY OF BACTERIA IN CONCRETE

Growth of bacteria in concrete is a most questionable factor because of concrete s high alkalinity which is a restricting aspect for the survival of the bacteria. Only specific alkalliphillic bacteria can survive in such hostile environment of concrete. Therefore, it is necessary to immobilize the bacterial cells and to protect them from the high pH in concrete. Polyurethane (PU) has been widely for immobilization of nutrients and bacterial cells even silica gel was used to protect the bacteria against the high pH in concrete. Several studies show that the bacteria can survive for several hundred years if spores remained unaffected.

MORPHOLOGY OF NATURALLY PRECIPITATED CALCIUM CARBONATE CRYSTALS

$CaCO_3$ is available in three different crystal structures but with same chemical formula in the form of Calcite, aragonite and vaterite. Most stable form of $CaCO_3$, Calcite is rhombohedra in shape. It is formed due to the presence of magnesium, manganese and orthophosphate ions. Aragonite is a orthorhombic shaped crystal form of $CaCO_3$ and geologically changes into calcite over time at high temperature or low temperature in the presence of magnesium ions and pH less than 11. Vaterite mineral is rarely found in nature. It is produced in the pH range from 8.5 to 10, low Ca_2+ concentration or low temperature and high Ca_2+ concentration. The morphology of vaterite depends on the pH value and temperature. It was morphology of the crystals does not depend on calcium source only.

Coarse Aggregate crushed angular aggregate of size 20 mm nominal size from the local source with specific gravity of 2.7 was used as coarse aggregate.
Water locally available potable water conforming to IS 456 is used.

Microorganisms Bacillus subtilus, a model laboratory soil bacterium which is cultured and grown at Biotech Laboratory was used at a total cell concentration of 105 cells per ml by serial dilution.
Mix Design The mix proportion for the ordinary grade concrete and standard grade concrete are designed using IS 10262 – 1982. Materials required for 1 cubic metre of concrete in ordinary grade concrete (M 20) is

Ordinary Grade Concrete (M 20)	Mix proportion 1: 2.43: 3.31: 0.55

RESULTS AND DISCUSSION

The strength characteristics of the standard cubes (100mm x 100mm x 100mm) with and without the bacteria were casted and tested as per the Is code. The several cubes were tested for the compressive strength and remaining for the healing phenomenon analysis i.e. the self-repairing phenomenon by calcite precipitate formation. The standard results of the compressive strength are tabulated in Table 1. The increased in the compressive strength in bacteria induced specimen is nearly 19.4% as in table 2 than the controlled specimens. For the crack healing study the bacteria induced concrete is allowed to develop the first crack by loading and then the crack healing phenomenon is studied by allowing the ingress water and atmospheric air to pass through the developed crack. The study reveals that the crack is healed to some extent by means of the calcite layer formation, i.e. microbiologically induced calcite precipitation. The table 1& 2 shows the compressive strengths of concrete cube and percentage increase with the days.
Figures depict the comparative results of compression strengths of concrete.
Table 1: Effect of bacillus Subtillus bacteria addition on Compressive strength:

Nature of concrete	Compressive Strength of Concrete Cube (MPa)		
	7 days	14 days	28 days

Controlled concrete	14.18	21.61	28.18
Self-Healing Concrete	17.01	24.11	32.86

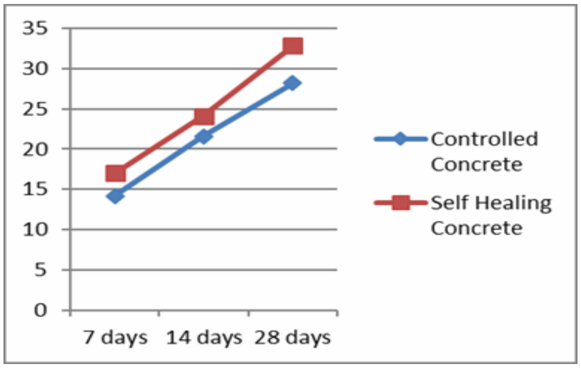

Figure 1: comparison of compressive strength of Controlled and Self-healing concrete

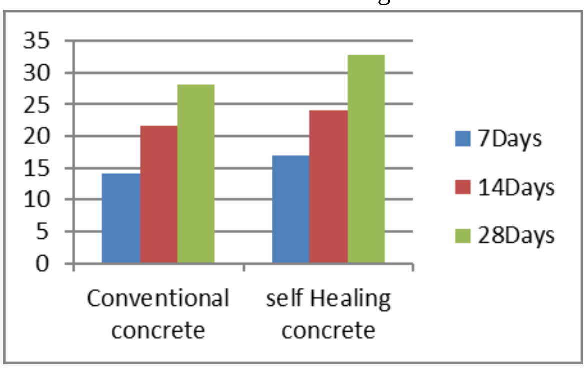

Figure 2: Effect of bacillus Subtillus bacteria on compressive strength

Table 2: Effect of bacillus Subtillus bacteria addition on Compressive strength:

% Increase of Compressive Strength of Concrete Cube (MPa)		
7 days	14 days	28 days
19.95 %	11.57 %	16.61 %

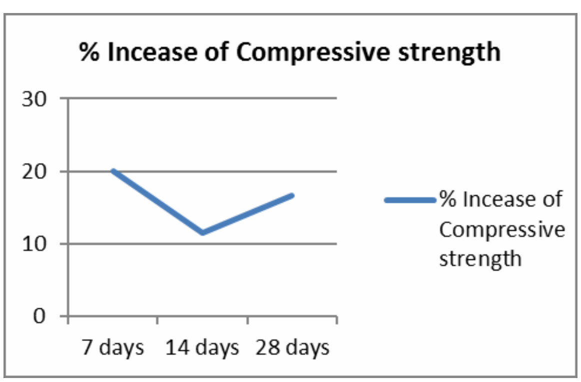

Figure 3: % Increase in Compressive strength of self-healing concrete with ages

Figure 4: Crack healed concrete specimen with crack (left) & Healed Specimen (right)

CONCLUSION

Microbial mineral precipitation resulting from metabolic activities of some specific microorganisms in concrete to improve the overall behavior of concrete has become an important area of research. The following are the summary of research outcomes done at the final project

The alkalliphillic aerobic microorganism bacillus subtilus is induced into cement mortar samples at cell concentration of 105 cells per ml in suspension along with the mixing water. The greatest improvement in compressive strength occurs at cell concentrations of 105 cells/ml for all ages.

The study showed that a 16.61 % increase in 28 day compressive strength of cement mortar was achieved. The strength improvement is due to growth of filler material within the pores of the cement–sand matrix. Different cell concentrations were derived from the bacterial growth culture by serial dilution method.

SCOPE OF FUTURE RESEARCH

Bacterial concrete has improved microstructure and permeation properties than controlled concrete. Studies showed that bacterial concrete has better acid resistance in aggressive environments. So, this study can be extended to evaluate the durability performance of the bacterial concrete in terms of acid attack, chloride penetration, porosity, elevated temperature studies and corrosion resistance studies.

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