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RESEARCH ARTICLE

REVIEW ON BACTERIAL CONCRETE

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ABSTRACT

Cracks in concrete are inevitable and are one of the inherent weaknesses of concrete. Water and other salts seep through these cracks, corrosion initiates, and thus reduces the life of concrete. Bacterial concrete is a material, which can successfully remediate cracks in concrete. This technique is highly desirable because the mineral precipitation induced as a result of bacterial activities is pollution free and natural. As the cell wall of bacteria is anionic, metal accumulation (calcite) on the surface of the wall is substantial, thus the entire cell becomes crystalline and they eventually plug the pores and cracks in concrete. This phenomenon is known as microbiologically induced calcite precipitation. Not only the cracks are healed it will also increase the strength and durability of concrete.

INTRODUCTION

Concrete forms major component in the construction industry as it is cheap, easily available and convenient to cast. But a drawback of these materials is that, it is weak in tension and so it cracks under sustained loading and due to aggressive environmental agents which ultimately reduce the life of the structure which are built using these materials. This process of damage occurs in the early life of the building structure and also during its life time. Synthetic materials like epoxies are used for remediation. But they are not compatible, costly, reduce aesthetic appearance and need constant maintenance. Therefore bacterial induced calcium carbonate (Calcite) precipitation has been proposed as an alternative and environment friendly crack remediation and hence improvement of strength of building materials. A novel technique is adopted in remediating cracks and fissures in concrete by utilizing microbiologically induced calcite or calcium carbonate ($CaCO_3$) precipitation (MICP) is a technique that comes under a broader category of science called bio-mineralization. MICP is highly desirable because the Calcite precipitation induced as a result of bacterial activities is pollution free and natural. This technique can be used to improve the compressive strength and stiffness of cracked concrete specimens. Research leading to bacterial calcium carbonate precipitation and its ability to heal cracks of construction materials has led to many applications like crack remediation of concrete, sand consolidation, restoration of historical monuments and other such applications.

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MATERIALS AND METHODS

Need for bacterial concrete

Concrete has a large load bearing capacity for compressive load, but the material is weak in tension.That is why steel reinforcement bars are embedded in the material to build structures. The steel bars take over the load when the concrete cracks in tension. The concrete on other hand protects the steel bars from the environmental attacks and prevent corrosion. However, the cracks in the concrete form a problem.Here the ingress of water and ions take place and deterioration of the structure starts with the corrosion of steel. To increase the durability of the structure either the cracks that are formed are repaired later, or in the design phase, extra reinforcement is placed in the structure to ensure that the crack width stay within a desirable limit. This extra reinforcement is needed only for durability reasons (to keep the crack width small) and not for structural capacity. Especially with current steel prices, this extra steel is not desirable. Durability is one reason toprevent cracks or limit cracks widths. Repair of conventional concrete structures usually involves applying a concrete mortar which is bonded to the damaged surfaces. Sometimes, the mortar needs to be keyed into the existing structure with metal pins to ensure that it does not fall away. Repairs can be particularly time consuming and expensive because it is often very difficult to gain access to the structure to perform repair works especially if they are underground or at a great height. Other reasons are water tightness of structure, loss of stiffness and aesthetic reasons. If in some way, a reliable method could be developed that repairs cracks in concrete automatically, this would increase and ensure durability and functionality. On the other hand it would save a lot of money. Of course repair costs of cracks that develop in concrete structures would go down.

Fig.1. Corrosion due to ingress water

Finding the right bacteria

Cement and water have a pH value of up to 13 when mixed together, usuallyhostile environment for life. Most organisms die in an environment with a pH value of 10 and above. So, it is essential to find bacteria capable of surviving an extreme alkaline environment. Also the bacteria selected should be thermophilic, because during hydration process of cement large amount of heat is developed. The search concentrated on microbes that thrive in alkaline environments which can be found in natural environments, such as alkali lakes in Russia, carbonaterich soils in desert areas of Spain and soda lakes in Egypt. Samples of endolithic bacteria (Bacteria that can live inside stones) were collected along with bacteria found in sediments in the lakes. Strains of the bacteria genus Bacillus were found to thrive in this high alkaline environment. Different types of bacteria’s are incorporated into a small blocks of concrete. Each concretes block would be lefts to two month to set hard. Then the block would be pulverized and the remains tested to see whether the bacteria had survived. It was found that the only group of bacteria that were able to survive were the ones that produced spores comparable to plant seeds. Such spores have extremely thick cell walls that enable them to remain intact for up to 200 years while waiting for a better environment to germinate. Further it would become activated at the time of cracking, food is available and water seeps into the structure. This induces low pH value of highly alkaline concrete of the range (pH 10 to 11.5). Bacillus is the only group of bacteria's that are able to survive this high alkaline environment.Finding a suitable food source for the bacteria that could survive in the concrete took a long time and many different nutrients were tried until it was discovered that calcium lactate was a carbon source that provides biomass. If it starts to dissolve during the mixing process, calcium lactate does not interfere with the setting time of the concrete.

Some of the bacteria which come under Bacillus genus are:-

- Bacillus subtilis
- Bacillus Spharecius
- Bacillus Pasteuri
- Bacillus Pseudofirmus etc.

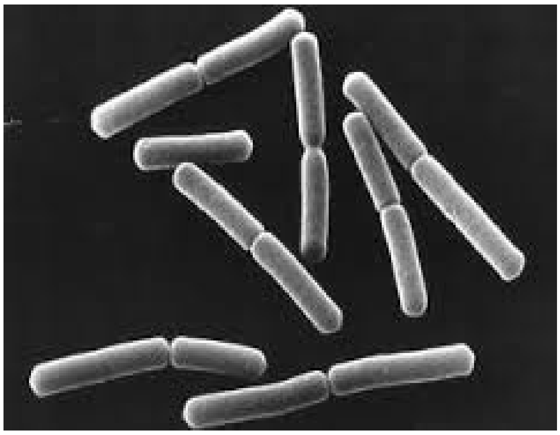

Fig.2. Bacillus Subtilis

Fig.3. Bacillus Spharecius

Fig.4. Bacillus Pasteruii

Fig.5. Bacillus Pseudofirmus

Working of bacterial concrete

Self-healing concrete (bacterial concrete) is a product that will biologically produce limestone to heal cracks that appear on the surface of concrete structures.Specially selected types of the bacteria along with a calcium based nutrient known as calcium lactate, nitrogen and phosphorus are added to the ingredients of the concrete when it is being mixed. These self-healing agents can lie dormant within the concrete for up to 200 years. However, 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. Under favourable conditions, Bacillus bacteria in concrete continuously precipitate a new highly impermeable calcite layer over the surface of the already existing concrete layer. Calcite has a coarse crystalline structure that readily adheres to surfaces in the form of scales. In addition to the ability to continuously grow upon itself,it is highly insoluble in water. Due to its inherent ability to precipitate calcite continuously, bacterial concrete can be called as a "Smart Bio Material". Cracks in concrete significantly influence the durability characteristics of the structure. The bacterial remediation technique can be used for repairing structures of historical importance to preserve the aesthetics value.

Mechanism of Production of Calcite ($CaCO_3$)

In natural environments, chemical $CaCO_3$ precipitation (Ca^{2+}+ $CO_3^{2-} \rightarrow CaCO_3\downarrow$) is accompanied by biological processes, both of which often occur simultaneously or sequentially. This microbiologically induced calcium carbonate precipitation (MICP) comprises of a series of complex biochemical reactions. As part of metabolism, bacteria produce urease, which catalyses urea tocarbonate and ammonium, resulting in an increase of pH and carbonate concentration in bacterial environment.These compounds further hydrolyses to ammonia and carbonic acid that leads to the formation of bicarbonate. Finally calcite is precipitated over the cell surface.

$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3$
$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$
$NH_3 + 2H_2O \rightarrow 2NH^{4+} + 2OH^-$
$2OH^- + H_2CO_3 \leftrightarrow CO_3^{2-} + H_2O$
$Ca^{2+} + cell \rightarrow cell\text{-}Ca^{2+}$
$Cell\text{-}Ca^{2+} + CO_3^{2-} \rightarrow cell\text{-}CaCO_3\downarrow$

Schematic of Self-Healing Process in Bacterial Concrete

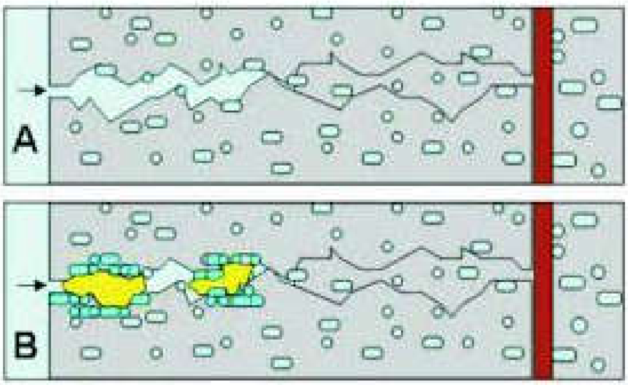

Fig.6. Self-healing process

- In A, water enters from the left into a micro crack activating the embedded bacterial spores.
- In B, the active bacteria seal the cracks with the production of limestone, protecting the embedded steel reinforcement from attack and erosion.

EXPERIMENTAL STUDY

Bacillus Subtilis and Bacillus Spharecius are the two major calcite producing microbes. Experiments were conducted by using those bacteria's and the results were compared with conventional concrete.

Case Study-1

Materials used

The following are the details of the materials used for concrete making.

Cement

Ordinary Portland cement of 53 grade available in local market is used in the investigation. The cement used has been tested for various properties as per IS: 4031-1988 and found to be confirming various specifications of IS: 12269-1987 having specific gravity of 3.0.

Ennore Sand

Ennore sand was used to find the compressive strength of cement mortar cubes.

Coarse Aggregate

Crushed granite angular aggregate of size 20 mm nominal size from local source was used as coarse aggregate having specific gravity of 2.71.

Fine Aggregate

Natural river sand confirming to IS-383 zone II having specific gravity of 2.60.

Water
Locally available portable water confirming to IS 456 is used.

Microorganisms

Bacillus Subtilis, a model laboratory bacterium is used.

Test on Concrete

Sand and cement was mixed properly. Distilled water and the required amount of microorganisms with media were mixed and added to the cement-sand mix to make cement sand paste. Standard cubes of size 70mm × 70mm × 70mm were casted and compacted using vibration machine. All the specimens were cured in water. The compressive strength of the mortar cubes at 3 days, 7 days and 28 days was determined and Scanning Electron Microscopy (SEM) analysis was made on the broken sample of 28 days cube specimen. Micrographs were obtained with a RUSKA3,500 Scanning Electron

Microscope. The mixing process is carried out in electrically operated concrete mixer. The materials were laid in uniform layers, one over the other in the order-coarse aggregate, fine aggregate and cementitious material. Dry mixing is done to obtain a uniform colour. Distilled water and the required amount of microorganisms (i.e. 10^5/ml cell concentration were used) with media were mixed. Standard cubes 100mm x 100mm x 100mm were casted and compacted. All the specimens were cured in water. The compressive strength of the concrete cubes at 7 days, 14 days, 28 days, 60 days, 90 days, 180 days, 270 days and 365 days was determined. Standard cylindrical moulds of size 150 mm diameter and 300mm height were casted and compacted. Split tensile strength tests were carried out on cylinders using a compression testing machine of 1000kN capacity as per IS 516:1959. Concrete cubes with and without addition of bacteria were casted. After 28 days of casting, each cube was tested for weight and dimensions.

Fig.7. Test of Compressive Strength

RESULTS

Case Study -2

Bacillus sphareciusLMG 225 57 (BCCM, Gent) was used for this study. The compressive strength of the remediated cubes was found to increase considerably after they were appliedwith the bio-concrete formed with Bacillus sapharecius. The readings increased for the cracked specimen whencompared with the control specimen.

Materials Used

Bacillus Sphaericus

Bacillus Sphaericus is strictly aerobic gram positive rod shaped bacterium. It is an insecticide against certain strains of diseased mosquitoes. Bacillus Sphaericus are pore forming bacterium, dormant for several years and would be able to withstand extreme temperature.

Cement

Portland Pozzolana Cement (PPC) was used in casting the specimens. PPC is manufactured by the inter grinding of OPC clinker with 10 to 25 percent of Pozzolanic material.

Coarse Aggregate

Hard granite broken stones of less than 20mm size were used as coarse aggregate. The specific gravity, fineness modulus, water absorption and bulk density of the coarse aggregate were tested.

Fine Aggregate

River sand size less than 4.75 mm size were used as fine aggregate. The specific gravity, fineness modulus, water absorption and bulk density of the fine aggregate were tested.

Water

Portable water in laboratory with pH value of not less than 6 and the requirement of IS 456-2000 was used for mixing concrete and curing the specimen.

Mix Design

The process of selecting suitable ingredients of concrete and determining their relative proportion with the object of producing concrete of certain minimum strength as economically as possible is known as Mix Design. The mix design of grades M20, M25 and M30 is carried out to achieve specified age, workability of fresh concrete and durability requirements by using IS 10262-2009.

Water-cement ratio

Corresponding to target mean strength, the water cement ratio is read from the appropriate curve in IS10262. Hence a water-cement ratio of 0.44 is accepted.

Water cement ratio= 0.375
For mild exposure, w/c=0.55
The water content is = 188.80 litres/m^3
The cement content works out to be 188.8/0.375 = 503.00 kg/m^3

Tests on Fresh Concrete

Fresh concrete or plastic concrete is a freely mixed material which can be moulded into any shapes. The relative quantities of cement, aggregates and water mixed together, to control the properties of cement in wet and the hardened state.

Slump Test

Slump test is the most commonly used method of measuring workability of concrete. The apparatus for conducting the slump test consists of a metallic mould in the form of a frustum of a cone having the internal dimensions as follows

Bottom Diameter = 200 mm
Top Diameter = 100 mm
Height = 300 mm

Compaction Factor test

The sample of concrete to be tested is placed on the top hopper upto the brim. The trap door is opened so that the concrete falls into the lower hopper. Then the trap door of the bottom hopper is opened and the concrete is allowed to fall into the cylinder

$$\text{Compaction Factor} = \frac{\text{weight of partially compacted concrete}}{\text{weight of fully compacted concrete}}$$

Tests on Hardened Concrete

Compressive Strength

Compressive strength test are made at recognized ages of the test specimens. Minimum of three specimens, preferably from different batches shall be made for testing at each selected age. The load is applied at the rate of 140 $kg/cm^2/min$ (approximately) until the failure of the specimen.

Compressive strength, F_c=P/Aeq 5.2
Where, F_c =Compressive Strength (N/mm^2)
P = Ultimate Load (N) and
A = Loaded Area (150mm × 150mm)
Split Tensile Strength Test

Tensile strength of concrete is determined by splitting the cylinder across the vertical diameter. Split tensile strength is an indirect method of finding out the tensile strength of concrete. The splited tensile strength is calculated using the formula,

F=2P/πdLeq 5.3
Where P = applied load
D = diameter of the specimen
L = length of the specimen
Flexural Strength Test

The standard size of the specimens 10×10 × 50 cm is used. The mould should be made of metal or cast iron, with sufficient plate thickness to prevent spreading or warping. The testing machine may be of sufficient capacity for the testing and rate of loading as specified. The load is applied through the roller placed at middle(central point load).The flexural strength of specimen is expressed as modulus of rupture, f_b.

Flexural strength, f_b= P×l/(bd^2) eq 5.4
Where, P = Applied load
l = Length of specimen
b,d = Cross section dimensions of specimen.

RESULTS AND DISCUSSION

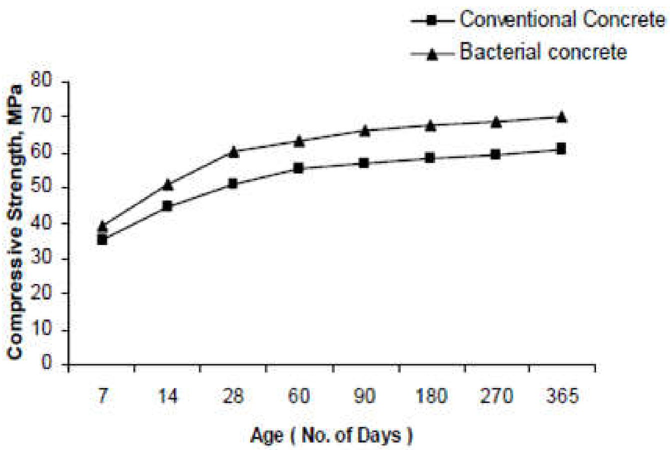

Fig.8. Variation of compressive strength with age

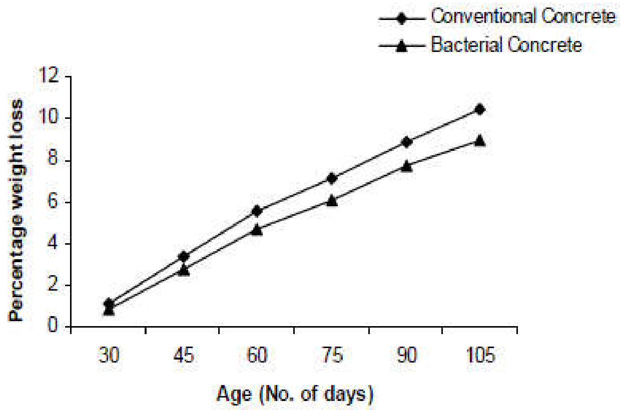

Fig.9. Variation of percentage weight loss with age

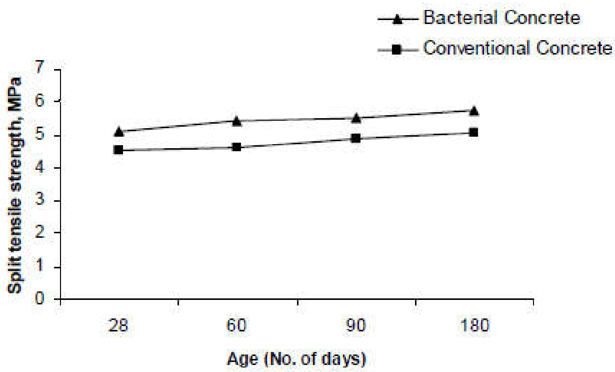

Fig.10. Variation of split tensile strength with age

Case Study -1

Compressive strength of concrete

The compressive strength of concrete at 7 days, 28 days, 60 days, 90 days, 180 days, 270 days, and 365 days were found out. It was observed that with the addition of bacteria the compressive strength of concrete showed significant increase by 14.92% at 28 days.

Split tensile strength

The split tensile strength on standard cylindrical specimens at 28 days , 60 days , 90 days, and 180 days were found out. It is observed that with the addition of bacteria there is a significant increase in split tensile strength.

Loss in weight and loss in compressive strength

The loss in weight and loss in compressive strength at different ages were found out. With the addition of bacteria it is observed that there is less percentage of loss in weight and compressive strength.

Case Study -2

The examinations of the control concrete and bacterial concrete cubes are done to determine the mechanical properties. The results reveal that the bacteria incorporated concrete specimens shows better compressive strength after 7th and 28th days of curing than control concrete. The percentage increase in compressive strength at 7 days of curing is obtained as 6.22%, 4.23% and 4.85% for M20, M25 and M30 grade of concrete respectively. Similarly, at 28 days of curing, it was found to be 7.62%, 5.02%, 6.92% for M20, M25 and M30 grade of concrete respectively. The split tensile strength of cylindrical specimens at the end of 7 days and the percentage increase was obtained as 9.04%, 13.62%, 10.73% for M20, M25 and M30 grade of concrete respectively. Similarly, for 28 days of curing it was 3.07%, 1.41%, 1.82% for M20, M25 and M30 grade of concrete respectively. The percentage increase of flexural strength of prismatic beam specimens at the end of 7 days is 12.12%, 15.29%, 6.89% and for 28 days was 4.58%, 2.09%, 1.91% for M20, M25 and M30 grade of concrete respectively. From the above results, due to the incorporation of bacteria the compressive strength of concrete increases remarkably.

CONCLUSION

Self-healing concrete could solve the problem of concrete structures deteriorating well before the end of their service life. The development of a new type of bacteria-based self-healing concrete appears promising. That concrete-incorporated bacterium can produce copious amounts of minerals which can potentially seal freshly formed cracks. The crack-sealing capacity and concomitant reduced material permeability enhances the properties of concrete structures. Durability of concrete structures is increased considerably with the use of bacterial concrete. The cost of bacterial concrete is also little bit more, but if produced on an industrial scale the self-healing concrete could come down in cost considerably. If the life of the structure can be extended, the increase in the cost of the concrete would still save a lot of money in the longer term.

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