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Strength And Durabilityassessment Of Bacteria Based Self-Healing Concrete

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Abstract: *In recent years, there is increasing interest in the phenomenon of mechanical property recovery in concrete construction using self-healing concrete. The study was motivated by the need to find a solution for the problem of cracking approaching the concept of self-healing concrete. The study was carried out on a bacteria based self-healing concrete using Bacillus Subtilis bacteria. The present paper describes the effect of this bacteria on the strength of concrete. An investigation on the strength assessment of the bacteria-based self-healing concrete by finding out the optimum amount of bacterial content to be added to obtain maximum strength is depicted in this.*

Keywords - *Bacillus Subtilis, Bacterial concrete, Self–healing*

I. Introduction

Concrete is a major material used in the construction field, from the foundation of buildings to the structures of bridges and dams. Several construction techniques without incorporating concrete have been developed but concrete still continues to be the most important building material for infrastructure. The major shortcoming of concrete is that it tends to crack when subjected to tension. Tiny cracks formed on the surface of the concrete make the whole structure vulnerable due to seepage of water into the concrete, promoting corrosion of the steel reinforcement, thus reducing the life span of the structure. Self-healing concrete is a solution to this problem of durability of concrete structures and has also received increasing attention as a smart material with interesting potential applications in civil infrastructure. Self-healing materials used in such type of concrete have the ability to heal the damage inflicted on the concrete partially or completely, thereby restoring the original functionality of the structure. Self-healing system can achieve a tremendous cost reduction in terms of health monitoring, damage detection and maintenance of concrete structures, assuring a safe service life of the structure.

II. Types of Self-Healing Mechanism

Autonomous self-healing is defined as a purposely designed self-healing mechanism. In this case a cementitious healing agent can be used in the presence of water as a prerequisite for the self-healing process to happen. A cementitious healing agent requires water in order to become effective. In absence of water healing will not occur. The water may penetrate into a crack from external sources. Alternatively water-saturated porous lightweight aggregate particles can be added to the concrete mixture. These particles may release water when a crack occurs and moisture gradients stimulate the flow of water[1].

2.1 Autogenous Self-healing Mechanism

Most of the traditional concrete mixes was left up with 20-30% unhydrated cement, when exposed to moisture through cracks hydrates, fill up and heal the cracks. The amount of unreacted cement was higher the coarser the cement and the lower the water/cement ratio of the mixture. If cracking of the concrete occurs, unreacted cement grains may become exposed to moisture penetrating the crack. In that case the hydration process may start again and hydration products may fill up and heal the crack. This inherent self-healing mechanism is known since long as autogenous healing[1]. This phenomena is termed to be the autogenous self-healing mechanism of concrete. The autogenous healing of cracks has been noticed by scientists in water retaining structures, culverts and pipes.

2.2 Autonomous Self-healing Mechanism

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lightweight aggregate particles can be added to the concrete mixture. These particles may release water when a crack occurs and moisture gradients stimulate the flow of water[1].

2.3 Hollow Glass Fibre System

In the hollow glass fibre system, fibers containing healing agents are completely embedded into the concrete. Hollow fibres filled with liquid healing agents are used in this system. Hollow Polypropylene fibers, with methylmethacrylate as healing agent as is one such system[2]. The hollow glass fibre system can itself be applied in two methods according to the delivery of the healing agents, as internal healing agent supply system and external healing agent supply system. When cracks appear due to loading on the structure, the fibre breaks and promotes the entry of liquid healing agent preserved in the fibre to the cracks and seal the cracks.

2.4 Microencapsulation System

Microencapsulation system is a system similar to hollow glass fibre system. This involves encapsulating healing agents within microcapsules and adding to the concrete. The main idea of this method is encapsulation, embedment, release and hardening of healing agents inside the host material matrix. Sodium silicate solution stored in polyurethane microcapsules is one such system. The healing liquid encapsulated in the host matrix is released when the capsules are ruptured by propagating cracks. It then reacts with the calcium hydroxide in cement and produces a C-S-H gel that partially heals the cracks. Compressive strength is unaffected by the presence of these capsules[3].

2.5 Shape Memory Alloy System

Shape memory alloy (SMA) system contain an equi-atomic composition of alloys that could exist in two stable and distinct phases which are reversible under certain temperature and stress conditions. Nicket-Titanium alloy is one such commonly used SMA in self-healing concrete. SMAs are characterized by two particular behaviors. One is the shape memory effect, which refers to the ability of SMAs to undergo reversible transformations between the two phases. In the martensite phase, SMAs are capable of regaining part of their residual strain after unloading. Once heated to enter into the austenite phase, all residual strain can be regained and the material could transform back to its original shape. Second is the super elasticity effect which refers to the ability of the SMAs to deform plastically after certain stress levels in the austenite phase and retrieve their original length and shape upon unloading with no residual strain. The shape memory effect and super elasticity effect of the SMAs endow them with great potential for applications in self-healing materials[4].

2.6 Bacteria Based System

Bacteria based system involves the use of ureolytic bacteria of genus Bacillus for the production of Calcium Carbonate minerals. The metabolism of this genus of bacteria involves the enzymatic hydrolysis of urea to ammonia and carbon dioxide. The reaction also causes an increase of pH from neutral to alkaline conditions forming bicarbonate and carbonate ions, which precipitate with the Calcium ions in the concrete to form Calcium Carbonate minerals. The further crystalisation of the Calcium Carbonate minerals heals the pores and cracks in the concrete[5].

III. Preparation of Bacterial Concrete

Bacteria are added to concrete mix in suspension state and it must meet certain criteria. Bacteria used as self-healing agent should be able to survive high alkaline environment of concrete for long durations and be able to form spores (highly resistant structures) withstanding mechanical forces during concrete mixing. A bacterial concrete mix prepared using alkali-resistant soil bacteria Bacillus subtilis JC3 along with nutrients from which the bacteria could potentially produce calcite based bio-minerals. The bacteria genus Bacillus has been found to thrive the high-alkaline environment of concrete due to its extremely thick outer cell membrane that enables them to remain viable until a suitable environment is available to grow. They would become active when the cracks form on concrete surface allowing water to enter into the structure. This phenomenon will reduce the pH of the concrete environment where the incorporated bacteria become activated. A peptone based nutrients supplied along with bacteria content in suspension helps in producing calcite crystals.

IV. Working Principle Of Self-Healing Process

In concrete structures, the micro cracks up to 0.2 mm wide are healed autogenously due to hydration of non-reacted cement particles present in the concrete matrix coming in contact with ingress water. The bacteria

based self-healing process has been found to heal cracks completely up to 0.5 mm width. On the surface of control concrete, Calcium Carbonate will be formed due to the reaction of CO_2 present with Calcium Hydroxide present in the concrete matrix according to the following reaction:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \ldots(1)$$

The Calcium Carbonate production in this case is rationed due to the limited amount of CO_2 present. As $Ca(OH)_2$ is a soluble mineral, it gets dissolved in entering water and diffuse out of the crack in the form of leaching. The self-healing process in bacteria incorporated concrete is much more efficient due to the active metabolic conversion of Calcium nutrients by the bacteria present in concrete:

$$Ca(C_3H_5O_2)_2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \ldots(2)$$

Here Calcium Carbonate is produced directly due to microbial metabolic process and also indirectly due to autogeneous healing. This process results in efficient bacteria-based crack sealing mechanism. Ureolytic bacteria, Bacillus Subtilis JC3 can precipitate $CaCO_3$ in the high alkaline environment by converting urea into Ammonium and Carbonate. The Ammonia degradation of urea increases the pH locally and promotes the microbial deposition of carbonate as calcite crystals in a calcium rich environment sealing the crack and maintains the pH of concrete.

V. Materials And Methods

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

5.1 Cement

Portland Pozzolana fly ash based cement is used in the investigation. The cement used has been tested for various properties as per IS:4031-1988 and found to be confirming to various specifications of IS:12269-1987. The cement has a specific gravity of 3.15, 38% of water content for standard consistency and 3% fineness.

5.2 Coarse Aggregate

The coarse aggregate of 20mm and down size, having a specific gravity of 2.83 and a fineness modulus of 4.12, tested as per IS:2386-1963 is used.

5.3 Fine Aggregate

Natural river sand with specific gravity of 2.63 and confirming to IS:383 zone II is used. The sand was tested as per IS:2386 (Part III) -1963. The sand is having percentage of water content at maximum bulking equal to 7%.

5.4 Water

Locally available portable water confirming to standards specified in IS:456-2000 is used.

5.5 Microorganisms

Bacillus Subtilis JC3, a laboratory cultured bacterium collected from Kerala Agricultural University Mannuthy, was used. Bacteria in suspension with a concentration of 10^8 cells/ml was collected and 10^3, 10^4, 10^5 and 10^6 cells/ml of bacterial concentration was made from the obtained sample

Table 1: Biochemical Characteristics Bacillus Subtilis Jc3

Characteristics	***Bacillus Subtilis* JC3**
Shape, size, gram stain	Long rods, 2.0 to 3.0 µm in length and 0.6-0.8 µm in width gram positive (refer fig.1)
Colony morphology (on nutrient agar plate)	Irregular, dry, white, opaque colonies (refer fig.2)
Fermentation: Lactose	No acid, no gas
Dextrose	No acid, no gas
Sucrose	Acid and gas
H2S production	-
Nitrate reduction	-
Indole production	-
Methyl Red test	-
Vogesproskauer test	-

Citrate utilization	-
Catalase activity	+
Gelatin liquefaction	+
Starch hydrolysis	+
Lipid hydrolysis	+

Note: "+" :- Present "-" :- Absent [Sunil et. al. 2010]

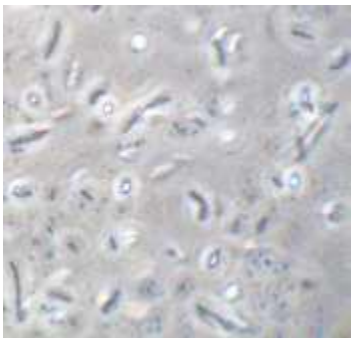

Figure 1: Phase contrast microphotograph of strain JC3 (Long rods, 0.6-0.8 µm in width and 2.0 to 3.0 µm in length, gram positive) [*Sunil et. al. 2010*]

Figure 2: Colony morphology of strain JC3 on nutrient agar plate (Irregular, dry, white, opaque colonies) [*Sunil et. al. 2010*]

VI. Culturing And Maintenance Of Bacteria

The pure culture was isolated from soil sample and was to be maintained constantly on nutrient agar slants. The bacteria, then forms irregular dry white colonies on the nutrient agar. Whenever requisite a single colony of the culture has to be inoculated into nutrient broth of 25 ml in 100 ml conical flask and the growth environment is maintained at 370°C temperature and placed in 125 rpm orbital shaker. The medium composition that is required for growth of the culture has been adopted as 5 g/lt Peptone, 5 g/lt NaCl and 3 g/lt Yeast extract. After 2 to 3 days of growth, slant cultures have to be preserved under refrigeration (4°C) until further use. Sub culturing was to be carried out for every 90 days. Contamination from other bacteria has to be checked periodically by streaking on nutrient agar plates.

VII. Tests On Concrete

7.1 Srength assessment

The cubes and cylinders were prepared for concrete mix of M20 grade with and without addition of microorganisms (*B. Subtilis*). The size of the cubes was 150mm x 150mm x150mm and cylinders was taken as 100mm diameter 200mm height respectively. Cubes were tested for compressive strength at 7 days and 28 days. Cylinders were tested for split tensile strength at 28 days.

7.2 Durability assessment

An experimental program was conducted on M20 grade concrete cubes of size 150mm x 150mm x150mm with and without addition of microorganisms (B. Subtilis). Specimens were immersed in 5% solution of H_2SO_4 for Acid Durability Tests, 5% solution of NaCl for Chloride Test and in distilled water for Water Absorption Test. The specimens were arranged in plastic tubs with a clearance around and above the specimen is not less than 30 mm. The response of the specimens to the solutions was evaluated through change in appearance, weight, compressive strength, thickness. Before testing, each specimen was removed from the baths, and brushed with a soft nylon brush and rinsed in tap water. This process removes loose surface material from the specimens[6].

VIII. Results And Discussion

The compressive strength of concrete for specimens with different bacterial concentration at 7 days and 28 days are given in Table 2. It was observed that the compressive strength of concrete showed significant increase by 42% for cell concentration of 10^5 of mixing water. The Split Tensile Strength on standard cylindrical specimens with different bacterial concentration at 28 days, are given in Table 3. It was observed that with the addition of bacteria there is a significant increase in the tensile strength by 63% for a bacteria concentration of 10^5 cells/ml at 28 days. As the results of strength tests on samples of various bacterial concentrations gave preeminent values for the samples with bacterial concentration 10^5 cells/ml, further investigations on the durability assessment was made on the bacterial concrete with the same concentration.

Investigations on the durability assessment were made as a comparative study of bacterial concrete with 10^5 cells/ml concentrations and the control mix concrete. The results of Acid Test of the loss in weight and compressive strength are given in Table 4. From the results it could be inferred that the addition of bacteria prevents the loss in weight during acid exposure to a certain limit proving the bacterial concrete to have higher Acid Attack Factor. Also, the relatively higher compressive strength by the bacterial when compared to control concrete proves it to have higher Acid Durability Factor on comparison with the conventional concrete. The results of Water Absorption Test, given in Table 5 shows lesser increase in weight of bacteria concrete sample than control, from which it could be reckoned that the concrete will become less porous due to the formation of Calcium Carbonate due to which it resulted in lesser water absorption rate. Chloride test results, as given in Table 6, shows that the addition of bacteria decreases weight loss due to Chloride exposure and enhances the Compressive Strength.

Table 2: Effect Of The Bacillus Subtilis Jc3 Bacteria Addition On Compressive Strength

Cell concentration/ml of mixing water	Average Compressive Strength of Concrete Cube in Mpa			
	7 days	% increase	28 days	% increase
10^0 (Control mix)	11.55	-	17.77	-
10^3	13.33	15.41	18.67	5.06
10^4	14.22	23.12	24.88	40.01
10^5	14.33	24.07	25.33	42.54
10^6	14.22	23.12	18.67	5.06

Table 3: Effect Of The Bacillus Subtilis Jc3 Bacteria Addition On Split Tensile Strength

Cell concentration/ml of mixing water	Average Split Tensile Strength of Concrete Cylinder in Mpa	
	28 days	% increase
10^0 (Control mix)	1.56	-
10^3	2.12	35.90
10^4	2.26	44.87
10^5	2.55	63.46
10^6	2.26	44.87

Table 4: Effect Of The Bacillus Subtilis Jc3 Bacteria Addition On Acid Test

Type of mix	Average Compressive Strength Cube (MPa)		Average % loss in weight	
	90 days	% increase	90 days	% decrease
Control mix	17.93	-	0.52	-
Bacterial concrete of 10^5 cells/ml concentration	18.67	4.13	0.36	44.44

Table 5: Effect Of The Bacillus Subtilis Jc3 Bacteria Addition On Water Absorption Test

Type of mix	Average increase in weight due to water absorption in %	% Decrease of water absorption rate
Control mix	0.443	-
Bacterial concrete of 10^5 cells/ml concentration	0.368	16.93

Table 6: Effect Of The Bacillus Subtilis Jc3 Bacteria Addition On Chloride Test

Type of mix	Average Compressive Strength Cube (MPa)		Average % loss in weight	
	90 days	% increase	90 days	% decrease
Control mix	32.88	-	0.86	-
Bacterial concrete of 10^5 cells/ml concentration	34.66	5.41	0.36	58.14

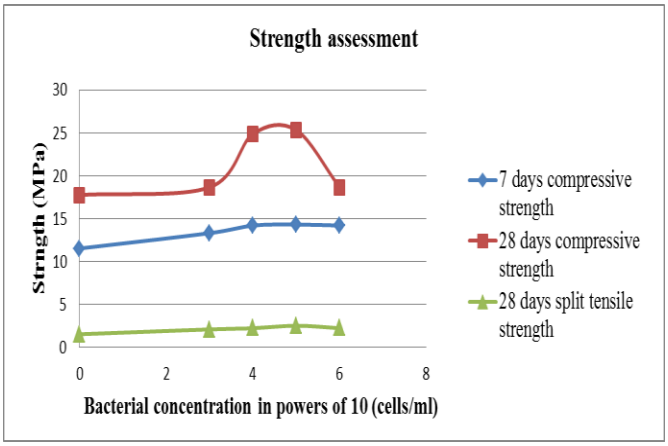

Figure 3: Variation of 7 days and 28 days compressive strength and split tensile strength of concrete samples according to bacterial concentration

IX. Conclusion

The experimental study shows that the addition of bacteria *Bacillus Subtilis* JC3 in concrete shows improvements in various properties of concrete in terms of compressive strength, split tensile strength, porosity, acid resistance and chloride resistance. As the bacteria can be produced in the laboratory, it could be proved to be safe and very cost effective. Bacterial concrete with a concentration of bacteria of 10^5cells/ml was found to give best results out of the samples used. Hence it could be concluded that this particular concentration give optimum results which is proven by 42% increase in compressive strength and 63% increase in split tensile strength when compared to conventional concrete. Durability tests relieved that bacterial concrete have higher Acid Durability Factor and higher Acid Attack Factor from Acid Tests results. Bacterial concrete exhibited lower rate of water absorption than conventional concrete. This is due to the bacteria induced formation of Calcium Carbonate in the pores present in concrete, leading to a lesser voids and hence a lesser permeability. Bacterial concrete is less vulnerable to Chloride Attack also. The study accomplishes that the use of bacteria (*Bacillus Subtilis*) in concrete enhances its strength and durability hence using this type of bacteria for self-healing mechanism in concrete can produce cost effective strong or durable structures.

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