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Original Research Paper

Studies on the Development of Eco-friendly Self-healing Concrete - A Green Building Concept

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ABSTRACT

Cracks are the main cause for structural failure. One way to circumvent costly manual maintenance and repair is to incorporate an autonomous self-healing mechanism in concrete. This study exploited the potential to apply calcite-precipitating bacteria as a crack-healing agent in concrete. These bacteria were prepared in different cell concentrations and incorporated in the concrete mix. Compressive strength tests were performed at the stage of 28th day of curing. The effects of different cell concentrations of *Bacillus sphaericus* on concrete, reducing the crack, were studied. We used mortar cubes with 30mL of bacteria/mortar cube and sequentially increased up to 50mL (10, 20, 30, 40 and 50mL) in the ratio of mortar cubes in 1:6. The concrete grade used for the study was M25. At last, we had made concrete blocks of size 150×150×150 mm with concrete of grade M25. For those blocks, the compressive strength and non-destructive tests such as, rebound hammer and ultrasonic pulse velocity tests were performed. The results obtained in the work are that the compressive strength of blocks of size 150×150×150 mm is good when compared to control concrete. When load is applied to control concrete, the crack gets developed earlier and when bacterial concrete is used, the crack does not develop at an early stage.

INTRODUCTION

Concrete is a material, which is, by far the most used building material in the world. Concrete has a large load bearing capacity for compression load, but the material is weak in tension. That is why steel reinforcement bars are embedded in the material to be able to build structures. The steel bars take over the load when the concrete cracks in tension. The concrete on the other hand protects the steel bars from the attacks of the environment and prevent their corrosion. However, the cracks in the concrete are a serious problem. The "Bacterial Concrete" can be made by embedding bacteria in the concrete, that are able to constantly precipitate calcite. This phenomenon is called microbiologically induced calcite precipitation. Bacterial concrete refers to a new generation of concrete in which, selective cementation of porous media by microbiologically-induced $CaCO_3$ has been introduced for remediation of damaged structural formation or micro cracks. Recently, a novel concrete technology has been introduced, that is by incorporating biological approach in concrete (Henk 2007). Efficient sealing of surface cracks by mineral precipitation was observed when, bacteria-based solutions were externally applied by spraying onto damaged surfaces or by direct injection into cracks. These treatments resulted in regained material strength and reduction of surface permeability (Bang et al. 2001, De Muynck et al. 2008). An economical and practical perspective, autogenous self-healing is most attractive, the possibility to use viable bacteria as a matrix-embedded healing agent to obtain a truly self-healing system was explored (Jonkers 2007, Jonkers & Schlangen 2008). A major challenge in the latter approach was to identify bacteria, and their needed metabolic components, that are not only sustainable, but also do not negatively influence other concrete characteristics. This crossbreed between biology and engineering study of concrete is called bio-concrete, which involves the utilization of bacteria mineral precipitation to increase the strength and durability of the concrete (Ghosh et al. 2005). Bacterial induced calcium carbonate (calcite) precipitation has been proposed as an alternative and environmental friendly crack remediation, and hence the improvement of strength of building materials (De Belie et al. 2009).

The limited effectiveness appears to be largely due to the restricted expansive potential of exposed unhydrated cement particle surfaces as well as to the limited availability of CO_2 needed for the production of calcium carbonate-based minerals, which form the bulk of observed self-healing products (Li & Yang 2007, Nijland et al. 2007). Concrete is one of the most remarkable building materials of the modern age developed by humans. Concrete, in most of the structures is designed to crack in order to let embedded steel reinforcement take over the tensile stresses. Crack formation is also a typical phenomenon related to durability. Cracks in concrete allow water and chemicals to enter, a process that may lead eventually to the unwanted corrosion of the steel reinforcement and the deterioration of the concrete structure. The self-healing concrete is one that senses its crack formation and reacts to cure itself without human intervention, which can be defined as a healing process without human intervention.

The tinniest of cracks in an otherwise colossal slab can inevitably lead to structural degradation, leakages and costly repairs. Numerous research activities were conducted to make the concrete stronger, but yet there is a scope to make the concrete more durable; this study aims to focus on making the concrete durable by preventing its failure due to cracks. Microorganisms have been used for the self-healing process in the current project.

Concrete structures usually show some self-healing capacity, i.e. the ability to heal or seal freshly formed microcracks. This property is mainly due to the presence of non-hydrated excess cement particles in the material's matrix, which undergo delayed or secondary hydration upon reaction with ingressed water.

In this research, a new type of self-healing concrete is developed in which bacteria mediate the production of minerals which rapidly seal freshly formed cracks, a process that concomitantly decreases concrete permeability, and thus better protects embedded steel reinforcement from corrosion.

More and more concrete structures are affected by crack based failure which deteriorates the structure. If this technique of self healing is incorporated, it will improve the durability of concrete structures.

The research focuses on how the right condition be created for the bacteria not only to survive in the concrete but, to produce as much calcite as needed to repair the cracks. This study exploited the potential to apply calcite-precipitating bacteria as a crack-healing agent in concrete. These bacteria were prepared in different cell concentrations and incorporated in the concrete mix. Various tests were done to test the performance of the concrete.

MATERIALS AND METHODS

Steps involved in the process:

a. Preparation of bacterial inoculums.
b. Preparation of the concrete as per IS codal provision.
c. Mixing of the inoculums in different proportions in the specimens.
d. Curing the specimen under standard curing conditions.
e. NDT and strength test on cured specimen.

Types of Bacteria

***Bacillus sphaericus*:** *Bacillus* is a rod shaped, strictly aerobic, gram positive bacterium which is used as an insecticide against certain strains of disease-carrying or annoying. It is used as a mosquito larvicide (an insecticide toxic to insects only in the larva stage of life).

Preparation of Bacterial Species

Isolation of soil bacteria: *Required materials and reagents*: About 50-100 g of freshly collected soil, compost or decaying biomass samples (briefly air dried and sieved).

1. A small bucket and sterile sieve or metal grid
2. 4 Nutrient agar (NA) plates
3. 4 Carboxymethyl cellulose (CMC) agar plates
4. 2 Starch nutrient agar (SA) plates
5. 2 Skimmed milk nutrient agar (SMA) plates
6. 2 Tubes with Glucose-Nutrient broth plus Durham tube (aerobic, 5mL)
7. 2 Tubes with Glycerol-Nutrient broth plus Durham tube (aerobic, 5mL)
8. 100 mL sterile water (dH_2O) in 150 mL glass bottle with screw cap
9. 1 Sterile test tube (15mL) with screw cap
10. Sterile spatula or spoon
11. Incubator set at 35°C (for the whole class)
12. Table balance (plus sterile weighing boats)
13. 1 anaerobic cultivation pouch (BBL)
14. Sterile 10mL glass (or plastic) pipette (& pipette pump)
15. Sterile 1mL glass (or plastic) pipette

A freshly collected soil, compost or decaying biomass sample was suspended in sterile distilled water by shaking and then further diluted in distilled water. An aliquot of the undiluted and diluted sample was streaked onto the surface

Fig. 1: Inoculating the bacterial species under standard condition.

of four different agar plates. The plates were incubated in an incubator under aerobic conditions. After 3-7 days of incubation of the plates in an incubator at 35°C, individual colonies from the agar plates were taken from primary cultures for further analysis, characterization and bacterial identification (Fig. 1).

Preparation of bacterial inoculated M25 concrete specimens: As of now, not much research work is happening related to the mix proportions of the bacteria. Hence, a trial mix with M25 concrete is prepared as per the IS code, the aggregates were then tested for their quality and the water used is free from any chloride or sulphate traces (RO quality water). The mixing is done in two trials with both manual mixing and machine mixing to check the adaptability of the bacterial strain. The fully grown bacterial strain was inoculated in the lactose broth medium and it is directly added in the concrete rather than adding bacterial strain to avoid the tedious acclimatization process of bacteria with the environment. The bacterial strain was inoculated using a micro pipette (Borosil grade with 100 micro litre capacity). This bacterial liquid is directly added in the well mixed concrete and again the mixing is done for few minutes so that the bacterial species get mixed all over the concrete. Throughout the study a typical M25 concrete mix proportion with bacterial content varying from 1mL to 50mL is prepared and the specimens were casted in triplicate per mix ratio.

Chemical Reactions And Equations

Calcium hydroxide is a reaction product of the hydration of concrete. Calcium hydroxide can dissolve in water inside the crack and precipitate at the cracked surface (Fig. 2):

$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^-$$

To form calcium carbonate, the water in the crack has to contain dissolved carbon dioxide. The chemical reaction of the formation of calcium carbonate is as follow:

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$$

RESULTS AND DISCUSSION

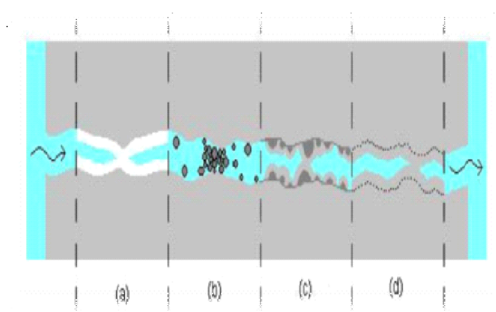

Fig. 2: Schematic representation of the cracking healing process.

Possible causes of self-healing:
(a) Formation of calcium carbonate or calcium hydroxide.
(b) Sedimentation of particles.
(c) Continued hydration.
(d) Swelling of the cement matrix.

Compressive Strength

The most important property of concrete is the compressive strength which is determined by loading the properly moulded and cured specimens as dictated by the standards. The testing machine may be of any type of sufficient capacity which will provide the required rate of loading. It shall be equipped with two steel bearing blocks with hardened faces. Fresh concrete is made by mixing the proper amounts of cement, water and aggregate as indicated by the mix design calculations, which is then placed in moulds, TS 500 and DIN designate 15×15×15 cm cubic moulds, whereas, ASTM specifies cylindrical moulds 6 inch (15cm) in diameter and 12 inch (30cm) in height. Three specimens should be prepared for each different mix or intended age. Cubes are filled in two equal portions whereas cylinders are filled in three. All possible measures should be taken during placing so that the specimen is prepared in a similar way to the actual placing conditions in the site. The specimens are left in moulds for two days and then cured in a moist environment such as curing room, water or a wet blank. At the end of 28 days, the cubic specimens are ready for the compression test. The cylindrical specimens should be capped with cement, gypsum or sulphur before testing and leaving enough time for hardening. This step is necessary because the two surfaces of the specimen coming in contact with the plates of the testing machine must be smooth and parallel to each other. Cubes provide this with capping, which is an advantage over the cylinders. The specimens are placed between the bearing blocks on the machine and loaded at a uniform rate of 2 $kg/cm^2/sec$ until failure. The maximum load carried by the specimen is recorded from the machine. The compressive strength of each individual specimen is calculated by dividing the maximum load at failure by the cross-sectional area of the specimen. The average of the three individual compressive strengths is accepted as the compressive strength of that batch of concrete (Fig. 3).

Rebound Hammer Test

a. Uniformity of the structure.
b. Corrosion is reduced in backrete due to the strong bonding of materials and closure of pores due to calcite formation.
c. NDT studies using rebound hammer show a considerable increase in the surface strength of the backrete than normal concrete (Fig. 4).

d. A crack width of 50 micrometer has been observed before failure, the bacterial effect is understudying on the closure of the pores.

Ultrasonic Pulse Velocity

a. Concrete specimens were casted with M25 designations using standard mix design procedures.

b. There was a considerable increase in the compressive and flexure strength which may be attributed to the microbial effect during the curing period.

c. Effect of pH on the bacterial species is yet to be studied, pH of concrete found to be in the range of 7.6-9.8 which is measured using standard pH probe.

d. Crack width of normal concrete and backrete varies, the successor has less crack depth and width which was analysed by using UPV UX4000 Instra make (Fig. 5).

Split Tension Test (ASTM C496-85 or BS 1881: Part 117: 1983)

For determining the modulus of rupture by a beam specimen, the upper part of the specimen is in compression while the lower part is under tension. In the split tension test all the specimen are under tension, therefore it gives a better idea about the tensile strength of concrete. Besides the conventional testing machine, supplementary bearing bar or plate and bearing strips made of plywood are necessary to perform the test. The specimens are exactly the same as the cylindrical ones used in compression tests. Diametrical lines are drawn on each of the specimen and the diameter is measured accurately. One of the plywood strips is centred along the centre of the lower bearing block (Fig. 6). The specimen

Fig. 3: Testing of compressive strength with various proportions (10mL, 20mL, 30mL, 40mL, 50 mL) of bacteria.

Fig. 4: Testing of rebound hammer with various proportions (10mL, 20mL, 30mL, 40mL, 50 mL) of bacteria.

Fig. 5: Testing of ultrasonic pulse velocity with various proportions (10mL, 20mL, 30mL, 40mL, 50 mL) of bacteria.

Fig. 6: Split tension test with various proportions (10mL, 20mL, 30mL, 40mL, 50 mL) of bacteria.

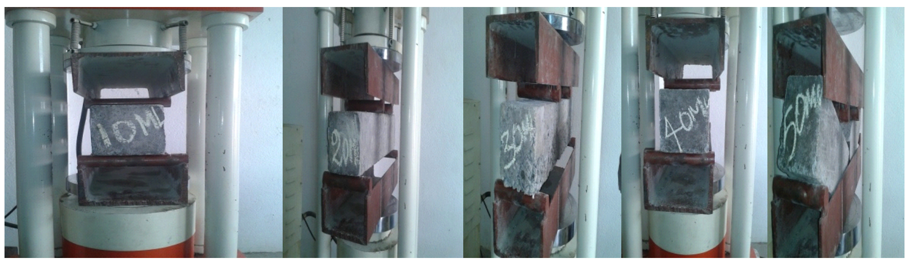

Fig. 7: Flexural strength test with various proportions (10mL, 20mL, 30mL, 40mL, 50 mL) of bacteria.

a b

Fig. 8: a. Newly formed cracks, b. Formation of calcium carbonate or calcium hydroxide and healing of the crack.

is placed on the plywood strip. A second plywood strip is placed lengthwise on the cylinder, centered on the lines marked on the ends of the cylinder. The load is applied continuously and without shock, at a constant rate within the range 100 to 200 psi/min, splitting tensile stress until failure of the specimen. The maximum applied load indicated by the machine at failure is recorded together with the type of failure and appearance of the concrete.

Flexural Strength (ASTMC39–96)

Flexural strength of concrete may be determined by using a simple beam with centre-point loading or third-point loading. In the centre-point loading the maximum tensile force is concentrated at a single point, whereas in third-point loading it is distributed to the length between the two loading points. The specimens and procedures of the two methods are very similar, therefore only the centre-point loading method will be discussed. A loading machine with sufficient capacity and bearing blocks (designed to insure that forces applied to the beam will be vertical only without eccentricity) are the necessary equipment to perform the test. 15×15×50 cm moulds are filled horizontally in two equal portions. Then they are cured as the cubic or cylindrical specimens (Fig. 7). The test specimen is centered on the supporting bearing blocks. The load-applying block is brought in contact with the upper surface at the centre line between the supports. If full contact is not obtained, capping is recommended. Span length is 60 cm, and the specimen is loaded in the direction of filling at a rate of 1000 kgf/min.

In the various specimens prepared and tested, the crack created by using the CTM machine and manually, it is observed that only fraction level minute cracks gets closed initially during a period of 3-4 days when the concrete is immersed in water level. During the initial period of curing, it is found that white coloured liquid emanates from the concrete specimen which is the bacterial growth outside the concrete and also the carbonation excreta. Once the cracking is done and the specimen is kept idle the bacterial species tend to close the gap by emanating the calcium carbonate in the liquid format and the micro-cracks are getting closed slowly.

NOVELTY

a. Self-healing of cracks in concrete using locally available non-pathogenic soil bacteria.

b. It was observed that with the addition of bacteria (*B. sphaericus*), the compressive strength of concrete showed significant increase by 14.92% at 28 days.

c. The cracks were developed after a long period of time when compared to the conventional concrete.

d. The tiny pores present in concrete were filled by the bacterial species which increases the durability of the concrete.

The bacterial species impregnated in concrete do not affect the behaviour of the normal concrete.

CONCLUSIONS

Based on the present experimental investigation, the conclusions drawn are:

a. The addition of *Bacillus spharecius* bacteria improves the hydration of cement.

b. The addition of *Bacillus spharecius* bacteria increases the compressive strength of concrete.

c. The crack formation is reduced in the bacterial concrete. Hence, it is efficient to use bacteria in concrete to reduce cracking.

d. The addition of bacteria improves the compressive strength of concrete up to the extent.

e. Based on the results obtained, the air-voids are very less in bacterial concrete compared to conventional concrete.

f. Thus, the conclusion drawn from our work is that the mechanical property of bacterial concrete is very good.

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