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Investigation on Self-Healing Concrete Using Bacillus Subtilis Bacteria

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Abstract. Cracking is a common occurrence in concrete, primarily attributed to its relatively low tensile strength due to External loads which induce high tensile stresses. Immediate and proper treatment is essential to prevent the expansion of cracks, as their unchecked growth may lead to higher repair costs. Bacterially induced calcium carbonate precipitation emerges as an eco-friendly alternative for crack repair. This technique involves the metabolic activities of specific bacteria in concrete, resulting in microbial mineral precipitation. In this study an attempt has been made to define bacterial concrete and its behavior such as self-healing by minor cracks induced in the samples. Concrete cubes of M20, M25 and M30 have been casted with three dosages of bacterial solution (Bascillus Subtilis) as 60 ml, 75 ml & 90 ml per cube (150 mm size). It has been observed that the compressive strength of bacterial concrete has increased slightly as compared to conventional concrete for each dose. The best performance in compressive strength enhancement has been observed for 75 ml dose and best self-healing has been observed for 90 ml dose of bacterial solution (per cube) in bacterial concrete. Ultrasonic pulse velocity test shows excellent quality for all samples of bacterial concrete.

Keywords: Self-healing, Concrete, Bascillus Subtilis, Bacteria

1 Introduction

Concrete is the construction material that is most widely utilized across the globe. Nevertheless, the occurrence of cracking in concrete structures is an inherent phenomenon resulting from various factors such as drying shrinkage, thermal contraction/expansion, and applied loads. These cracks serve as a convenient pathway for the infiltration of moisture, gases, chlorides, and other chemicals, which can ultimately result in the corrosion of reinforcement and the deterioration of the structure [1]. Hence, it is of utmost importance to develop repair techniques for cracks that are capable of autonomously sealing the cracks and restoring the concrete. Self-healing concrete is a groundbreaking technology that endows concrete with the inherent capability to autonomously repair cracks. The fundamental principle revolves around incorporating specialized healing agents within the concrete matrix that can be activated when cracks form in order to initiate the healing process [2]. Various methods have been investigated, such as encapsulating healing agents (parasitic bacteria, chemical admixtures, epoxy resins, etc.) in carriers such as glass tubes/capsules, employing shape-memory alloys that contract when cracks appear, utilizing engineered cementitious composites (ECC) for intrinsic self-healing, and employing microbial approaches that involve bacteria [2, 3, 4, 5]. Among the various mechanisms for self-healing, bacterial approaches have demonstrated significant potential and have emerged as an environmentally friendly and sustainable technique. Certain bacteria possess the inherent ability to induce the formation of calcium carbonate (CaCO3) through the metabolic conversion of organic substrates. [6, 7]. Ureolytic bacteria commonly utilized for this purpose include Bacillus sphaericus, Bacillus subtilis, Bacillus pasteurii, and Sporosarcina pasteurii, which enzymatically hydrolyze urea to produce carbonate and ammonia, ultimately resulting in the precipitation of CaCO3 in the presence of calcium [8, 9].

Ramachandran et al. initially investigated the concept of self-healing concrete using bacteria [10]. They observed the formation of CaCO3 deposits in cement mortar cubes when B. subtilis and B. pasteurii were introduced along with a nutrient medium containing calcium sources such as calcium acetate/nitrate. This resulted in an enhancement of the concrete's compressive strength and the sealing of cracks up to a width of 0.46 mm achieved successful crack sealing in bacteria-based self-healing concrete, regardless of whether the concrete was exposed to air or water [11]. Wang et al. conducted a study on concrete beams using B. subtilis/B. sphaericus spores and calcium lactate encapsulated in expanded clay particles. They observed a recovery of 27-73% in strength after the self-healing of cracks [12]. Gupta et al. reported an enhancement in the durability and compressive strength of concrete when Bacillus megaterium and Bacillus cereus, along with calcium sources, were incorporated. This enhancement was attributed to the deposition of biomineral CaCO3 [13]. Preliminary studies indicate that the incorporation of bacterial solutions generally enhances the compressive strength of concrete by approximately 5-25%, which can be attributed to the precipitation of the biomineral CaCO3 [7, 8, 11].

In addition to various Bacillus species, other genera such as Sporosarcina pasteurii and Lysinibacillus sphaericus, which possess the ability of ureolysis, have been subjected to investigation [12, 14]. Furthermore, bacteria that form biofilms, such as Shewanella, exhibit promise due to their strong adherence to concrete surfaces [15]. Studies have also examined the synergistic combinations of bacteria capable of ureolysis and biofilm formation in order to facilitate more efficient sealing of cracks [16]. By exploring a diverse range of bacteria sourced from extreme environments, including alkaliphiles and thermophiles, which are well-suited to the highly alkaline pH and temperature variations of concrete, it is possible to identify the most optimal microbial species [17].

Concrete specimens were fabricated by directly incorporating varying quantities of B. subtilis bacterial solution and subjected to assessments of compressive strength, ultrasonic pulse velocity (UPV), and self-repair ability. The outcomes furnish valuable insights into the optimal dosage of bacteria required to attain enhanced strength and sustainable self-repairing concrete, thus promoting the practical application of microbial self-healing techniques.

2 Experimental Programme

2.1 Materials

In this investigation concrete mixes M20, M25 and M30 were designed using OPC 43 grade cement. M20 mix was nominal mix having mix proportion ratio of 1:1.5:3 with 0.45 water-cement ratio. M25 & M30 mixes were designed as per the mix design code IS 10262: 2009. The mix proportion ratio of 1:1.495:3.825 & 1:1.490:2.690 were considered for M25 & M30 mixes respectively with 0.50 water-cement ratio. The maximum nominal size of the aggregate was 20mm, with a minimum cement content of 320 kg/m³. The workability was considered high and suitable for moderate exposure conditions. The concrete was placed manually under good supervision, utilizing crushed angular aggregates.

2.2 Bacteria Selection

There are various types of bacteria which produces Calcium Carbonate are used in concrete for self-healing purpose, in this study Bacillus Subtilis bacteria was selected due to ease of availability from microbiology department of our university (Fig 1). It is also formally known as Hay bacillus or grass bacillus, is a Gram-positive, catalane-positive bacterium, found in soil and the gastrointestinal tract of ruminants and humans. A member of the genus Bacillus, B. subtilis is rod-shaped, and can form a tough, protective endo -spores, allowing it to tolerate extreme environmental conditions. B. subtilis has historically been classified as an obligate aerobe, though evidence exists that it is a facultative aerobe. B. subtilis is considered the best studied Gram-positive bacterium and a model organism to study bacterial chromosome replication and cell differentiation. It is one of the bacterial champions in secreted enzyme production and used on an industrial scale by biotechnology companies.

Fig. 1. Bacterial Solution (Bacillus Subtilis)

2.3 Casting of concrete cubes & bacterial concrete, curing and testing

All concrete mixes M20, M25 and M30 of both conventional and bacterial concrete cubes (150 mm size) were casted (total 72 numbers) and kept under water for curing (Fig 2). Bacterial concrete cubes of M20, M25 and M30 were casted with three dosages of bacterial solution (Bascillus Subtilis) as 60 ml, 75 ml & 90 ml per cube (150 mm size). The direct mixing method was adopted for casting the bacterial concrete cubes. The bacterial solution was poured in the measuring jars from the flask and mixed with water properly for casting the bacterial concrete cubes.

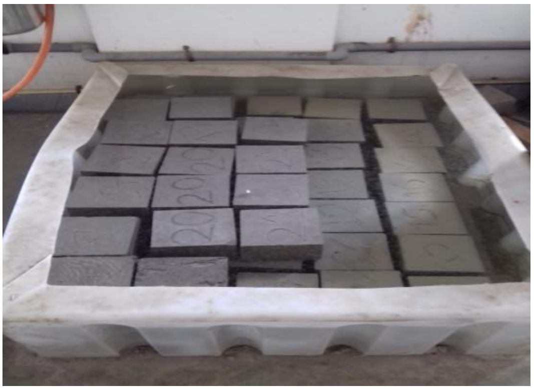

Fig. 2. Concrete cubes under curing

2.4 Compressive strength test

Compressive strength test was performed on all 72 samples of conventional concrete and bacterial concrete (150 mm size cubes) at 28 days under CTM as per IS 516-1959 (Fig 3). All samples were removed from water to get air dried 24 hours before the test done.

Fig. 3. Cubes under compression test

2.5 Ultra sonic pulse velocity Test

Ultrasonic pulse velocity test is generally carried out to determine the presence of voids in the internal structure of concrete by means of passing the ultrasonic rays through the body on concrete structure which establish the uniformity of and its acceptance criteria. The relation between pulse velocity and quality of concrete shown below in table 1. Ultra sonic pulse velocity test was performed on all samples and ultra sonic pulse velocity was calculated by recording the travel time of ultra sonic rays passing through the samples (Fig 4).

Table:1 Quality of concrete

Pulse velocity (m/s)	General condition
>4575	Excellent
3660 - 4575	Good
3050 - 3660	Questionable
2135 - 3050	Poor
2135	Very poor

Fig. 4. Ultrasonic pulse velocity test

3 Experimental results and discussions

Based on compressive strength test conducted on all cubes (conventional and bacterial) at 28 days, the compressive strength was compared. Ultrasonic pulse velocity test was performed on all samples and travel time of pulse velocity was recorded.

3.1 Compressive strength

The compressive strength tests were conducted on a total of 72 sample cubes measuring 150 mm each, following the guidelines outlined in IS 516:1959. After a curing period of 28 days, the compressive strength values for conventional mixes (M20, M25, and M30) were determined. These values were then juxtaposed against the 28 days compressive strength results of bacterial concrete mixes (M20, M25, and M30) for varying doses (60 ml, 75 ml, and 90 ml) of the bacterial solution. Fig. 5,6,7 illustrates the comparative analysis of these compressive strength outcomes.

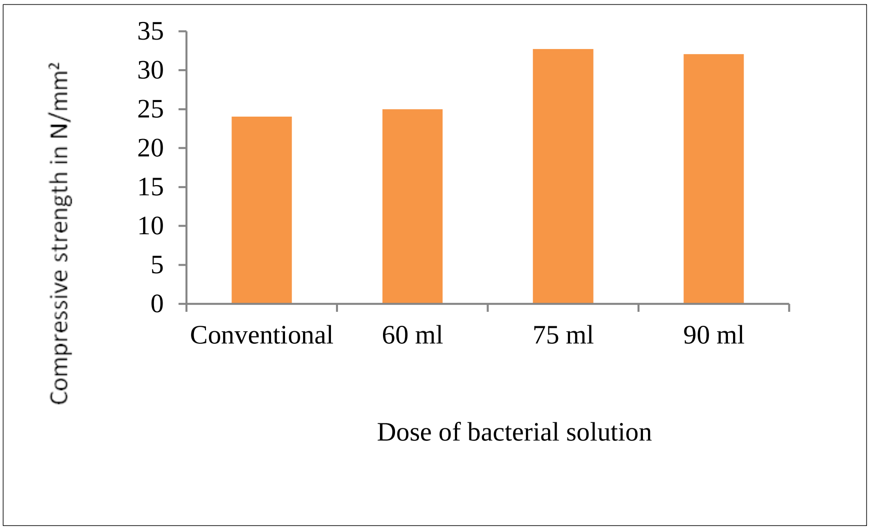

Fig. 5. Graphical representations of compressive strength (M20) at 28 days.

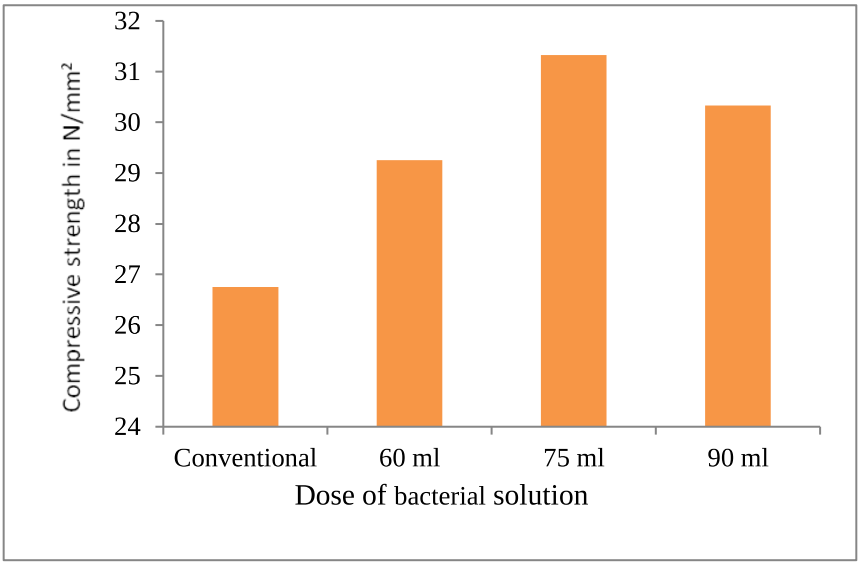

Fig. 6. Graphical representations of compressive strength (M25) at 28 days

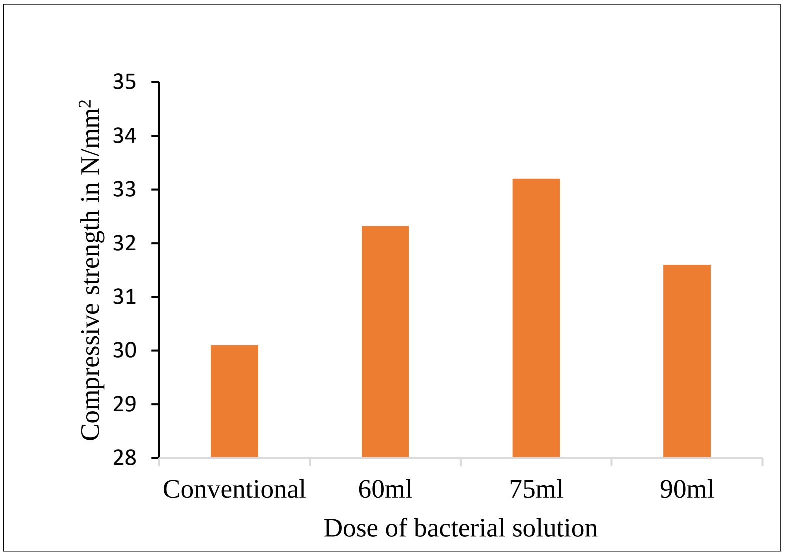

Fig. 7. Graphical representations of compressive strength (M30) at 28 days

As per the test results, the compressive strength of all mixes of bacterial concrete for all doses has increased compared to conventional concrete. The compressive strength of M20 conventional concrete is 24.03 N/mm^2, and for bacterial concrete, the compressive strengths are 25 N/mm^2 (60 ml), 32.73 N/mm2 (75 ml), and 32.05 N/mm^2 (90 ml), respectively. The result shows that compressive strength is 32.20% higher as compared to conventional concrete for a 75-ml dose of bacterial solution. The compressive strength of M25 conventional concrete is 26.4 N/mm^2, and that of bacterial concrete is 33.23 N/mm^2 (60 ml), 34.73 N/mm2 (75 ml), and 30.23 N/mm^2 (90 ml), respectively. The result shows that compressive strength is 31.55% higher as compared to conventional concrete for a 75-ml dose of bacterial solution. For M30 conventional concrete, the compressive strength is 30.1 N/mm^2, and for bacterial concrete, the compressive strengths are 32.32 N/mm^2 (60 ml), 33.2 N/mm^2 (75 ml), and 31.6 N/mm^2 (90 ml), respectively, which shows 10.29% more for a 75 ml dose of bacterial solution.

3.2 Ultrasonic Pulse Velocity Test

Ultrasonic Pulse Velocity Test was performed on both types of samples (conventional and bacterial concrete) of all mixes i.e. M20, M25 & M30 and it was found that all the samples are of very good quality because pulse velocity for all samples was greater than 4575 m/s.

3.3 Observation of self-healing

In a controlled loading environment using a CTM, minor cracks emerged in all bacterial concrete mixes across various bacterial solution doses (60 ml, 75 ml, and 90 ml). Subsequently, the samples were submerged in water for several days to monitor the self-healing process facilitated by bacteria. After a 14-day period, naked-eye observations revealed evident self-healing in the bacterial concrete. Furthermore, it was noted that samples with optimal bacterial concrete dosages exhibited a higher degree of self-healing compared to other samples. Notably, the maximum level of self-healing was observed in samples treated with a 90 ml bacterial solution. This observation underscores the dosage-dependent nature of the self-healing phenomenon in bacterial concrete, with higher concentrations of bacterial solution contributing to more pronounced and effective repair of cracks. The visual confirmation of self-healing for M25 Bacterial concrete has been shown in Fig-8,9,10 for all doses and similar pattern of healing has been observed for other mixes.

Fig. 8. Self-healing of bacterial concrete (60 ml solution) of M25

Fig. 9. Self-healing of bacterial concrete (75 ml solution) of M25

Fig. 10. Self-healing of bacterial concrete (90 ml solution) of M25

4 Conclusion

Based on the examination of test results and subsequent discussions, the following key conclusions have been established:

1) The compressive strength of bacterial concrete exhibits a notable improvement compared to conventional concrete, as evidenced by the test results.
2) The optimal dosage of bacterial solution for enhancing compressive strength is identified as 75 ml. For promoting self-healing properties, the most effective dose is determined to be 90 ml in all cases.
3) It is observed that self-healing is more on the side faces of the cubes as compared to top face of the cubes.
4) The quality assessment of bacterial concrete, as indicated by ultrasonic pulse velocity test results, affirms its good quality across all grades.
5) Bacterial concrete has capability of self-healing so it can be used as a repair technique to control the cracks developed in concrete.

These conclusions collectively emphasize the positive impact of bacterial concrete on both compressive strength and self-healing capabilities, underscoring its potential as a durable and resilient construction material. The identified optimal dosages provide valuable insights for practical applications, guiding the formulation of bacterial concrete mixtures for optimal performance in various construction scenarios.

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