Exploration and Examination of Properties of Bacterial Concrete

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Abstract

Concrete is vital in modern construction, contributing to carbon dioxide emissions and ozone layer depletion. Traditional concrete consists of cement, fine aggregate, coarse aggregate, chemical admixtures, and water. The hardening process can result in shrinkage fractures, leading to structural issues. To address this, bioconcrete is employed, incorporating microorganisms capable of precipitating calcium carbonate and facilitating crack sealing for self-healing. Microcracks in concrete can lead to structural failure due to corrosion. This paper explores the significance and efficacy of preparing bioconcrete using Bacillus megaterium. The bioconcrete created with Bacillus megaterium exhibited compressive strength, split tensile strength, flexural strength, elastic modulus, and impact resistance of 43.63, 4.01, 3.89, and 33750 N/mm², respectively.

1. Introduction

Concrete is an essential construction material renowned for its remarkable versatility and cost-effectiveness [1]. It is crafted through a carefully formulated blend of cement, coarse aggregates, fine aggregates, and water, resulting in a uniform substance. Cement, the central binding element, is produced in specialized cement plants. In contrast, water, along with fine and coarse aggregates, crucial components in concrete production, is readily obtained from local natural reserves.

Concrete strength heavily depends on the water-cement ratio (w/c). Optimal cement hydration requires a minimum water-cement ratio of approximately 0.38 [2, 3]. However, the pursuit of the desired workability of fresh concrete often leads to the inclusion of excess water, resulting in increased voids and a subsequent weakening of the concrete structure [4]. While concrete demonstrates significant compression strength, it is weak when subjected to tension forces [5-7]. To mitigate this weakness, reinforcements are strategically embedded within concrete members, allowing them to effectively withstand tension, flexural, torsional, and shear forces [8].

Concrete cracks can arise from tensile loads and factors such as excessive heat, non-uniform thermal expansion and contraction, and plastic shrinkage. Plastic shrinkage occurs when water loss from the concrete surface surpasses water migration from the interior to the surface [9].

Fresh concrete is highly alkaline, with a pH value of 12 to 13. Cracks in concrete structures serve as a primary pathway for reinforcement corrosion, enabling the infiltration of water and gases into the structure [10]. Concrete cracking can lead to carbonation, as atmospheric CO_2 penetrates through cracks, reacts with calcium hydroxide ($Ca(OH)_2$), and converts it into calcium carbonate, resulting in minor shrinkage. Additionally, in the presence of moisture, carbon dioxide transforms into dilute carbonic acid, diminishing the alkalinity of concrete. Consequently, the protective oxide film on the reinforcement is compromised, facilitating corrosion initiation [3]. To mitigate this issue, concrete should exhibit low permeability [11], and structural design must ensure that crack widths consistently adhere to codal provisions.

2. Consumption of Bacteria in Concrete

Recently, there has been a growing adoption of bacteria for diverse applications in concrete technology [12,13]. These applications encompass the self-healing of concrete, enhancement of compressive strength [14], and augmentation of concrete durability by reducing permeability [15]. In this research endeavor, the focus was on substituting cement in concrete with carefully selected bacteria, aiming to maximize the percentage of cement replacement.

Various types of bacteria are employed through diverse techniques to enhance concrete's strength and durability. The fundamental principle underpinning these methods involving bacterial applications centers on calcium carbonate precipitation. This process fills the concrete's pores, rendering it denser and less permeable, ultimately bolstering its strength and durability. The choice of bacteria hinges upon their capacity for calcium carbonate (CaCO3) precipitation and the application method. Importantly, the calcium carbonate precipitated by these bacteria is insoluble in water [16], thereby enhancing concrete property.

Microorganisms play a pivotal role in facilitating the precipitation of calcium carbonate ($CaCO_3$) through three primary mechanisms: i) Nitrogen cycle, ii) Sulfur cycle, and iii) Spontaneous mechanism, involving photosynthetic microorganisms. Gram-positive Bacillus bacteria are notably prevalent in bacterial concrete, with their cells serving as nucleation sites for $CaCO_3$ precipitation [17].

Bacteria are also used to repair ancient monuments' cracks by promoting calcium carbonate precipitation in suitable environments [18]. When introduced into concrete, bacteria utilize water and oxygen from fresh cracks to initiate calcium carbonate precipitation. This process leads to crack healing, resulting in what is known as self-healing concrete [19]. The incorporation of bacteria enhances both the strength and durability of concrete. The calcium carbonate precipitated by these microorganisms fills the minute pores within the concrete, resulting in a significant 25 to 30% increase in compressive strength when utilizing Bacillus megaterium for bacterial concrete production.

Experimental investigations conducted with pure and mixed bacteria cultures revealed that concrete specimens treated with pure cultures exhibited a more pronounced reduction in water absorption than those treated with mixed ureolytic cultures [21].

The goals of the current study are:

a) To identify a suitable bacterial species for the enhanced Microbial Induced Calcite (MIC) production.

b) To investigate the mechanical properties and microstructural characteristics of bacterial concrete.

3. Materials and Methods

3.1 Bacterial culture

The Bacillus megaterium bacterial culture was obtained from the IMTECH Microbial Type Culture Collection (MTCC) Gene Bank at the Institute of Microbial Technology in Chandigarh, India. After obtaining the culture, the microorganisms were expanded through sub-culturing onto a suitable medium and then incubated within the optimal temperature range of approximately 25–37°C.

3.2 Preparation of concrete

The concrete was formulated in M40 grade, utilizing OPC 53-grade cement and a bacterial culture. It incorporated 20-mm aggregates, maintaining as per mix design. The specific gravity of the cement was 3.15, and a water-cement ratio of 0.43 was employed. Various aggregates were employed, including sand, gravel, and crushed stones with a fine aggregate size of 4.75 mm and coarse aggregate size of 12.5 mm. Table 1 details the characteristics of the fine and coarse aggregates utilized.

To modify the plastic or hardened state of concrete, a chemical admixture, polycarboxylate ether, was introduced at a 7 kg/m^3 volume. All components were accurately weighed, thoroughly mixed, and cast into 150 × 150 × 150 mm cubic molds, which were manually compressed during the filling process. Casting was conducted in a moist environment to minimize moisture loss through evaporation, with demolding occurring after 24 hours. Table 2 outlines the mix ratio of the materials per unit volume of concrete. The workability of both control concrete and bacterial concrete mixes was assessed using a slump cone and maintained at 14 mm.

Table 1 Properties of fine and coarse aggregate

S.No.	Properties	Test Results	
		Fine aggregate	Coarse aggregate
1	Specific gravity	2.52	2.65
2	Fineness modulus	2.61	8.92
3	Water absorption	1%	0.5%
4	Zone	II	-

Table 2. Mix proportion of the ingredient per unit volume of concrete

S. No.	Ingredients	Mix Proportion
1.	Cement	325 kg/m³
2.	Water	140 litres
3.	Fine aggregate	844 kg/m³
4.	Coarse aggregate	1102 kg/m³
5.	Chemical admixture	7 kg/m³
6.	Water cement ratio	0.43

3.3. Curing of Concrete

Concrete curing was carried out before testing. Following demolding, the cubes were promptly transferred to the curing tank at a temperature of 27 to 30°C. Test specimens were prepared for both control and bacterial concrete with Bacillus megaterium.

4. TESTING OF SPECIMENS

The compression test was conducted to assess the strength of concrete using a 2000 kN capacity testing machine. Specimens with dimensions of 150x150x700 mm were cast for both conventional and bacterial concrete and subjected to appropriate curing for flexural strength testing. Additionally, specimens measuring 150x300 mm were cast and tested to determine the split and elastic modulus of concrete. Impact tests were carried out on concrete specimens with dimensions of 150 mm in diameter and 63.5 mm in thickness after curing for 28 days.

5. RESULTS AND DISCUSSIONS

5.1 Compressive Strength

The compressive strength of bacterial and conventional concrete cubes estimated at 7^{th} day, 14^{th} days, and 28^{th} day are tabulated in Table 3.

Table 3 Compressive strength of bacterial and conventional concrete cube

Description	Compressive Strength		
	7^{th} day	**14^{th} day**	**28^{th} day**
Conventional	28.52	38.77	44.37
Bacillus megaterium	18.98	36.27	43.63

5.2 Flexural Strength

The flexural strength of bacterial concrete and conventional concrete at 28th day are tabulated in Table 4.

Table 4 Flexural strength of bacterial and conventional concrete

Description	**Flexural Strength at 28 days, N/mm^2**
Conventional	4.75
Bacillus megaterium	4.01

5.3 Split Tensile Strength

Split tensile strength of concrete was obtained by casting 100 mm diameter and 200 mm long cylinders using the standard steel moulds and testing as per IS 5816-1999 after curing for 28 days. Table 5 gives the average split tensile strength of concrete.

Table 5 Split tensile strength of bacterial and conventional concrete

Type of concrete	**Average split tensile strength (N/mm^2) at 28 Days**
Conventional	3.20
Bacillus megaterium	3.89

5.4 Elastic Modulus

Elastic modulus of concrete is obtained by testing 150 mm diameter and 300 mm long cylinders using compressometer. The gauge length of the compressometer is 110 mm, and load were applied slowly in the compressive testing machine and strains were noted for every 5 kN intervals till it failed. The elastic modulus of 28 days control concrete and bacterial concretes are given in Table 6.

Table 6 Elastic modulus of concrete

Type of concrete	**Elastic modulus (N/mm^2)**
Conventional	33,600
Bacillus megaterium	33,750

5.5 Impact Test

An impact test was carried out on concrete specimens with dimensions of 150 mm in diameter and 63.5 mm in thickness. These specimens had been subjected to a curing period of 28 days. The test involved determining two critical parameters: the number of blows required to initiate the first crack and the number of blows needed to cause a portion of the specimen to separate. These values were then utilized to calculate the impact energy absorbed by the concrete at the points of initial crack and final crack. In order to ensure reliable results, a minimum of three samples were tested for each trial. The results, expressed in terms of energy (in Nm) absorbed by the concrete, have been compiled and are presented in Table 7.

Table 7 Impact energy absorbed by the concrete

Mix Proportions	**28 Days**	
	Initial crack (Nm)	**Final crack (Nm)**
Conventional	1831	1871
Bacillus megaterium	1688	1780

6. Conclusions

Based on the literature review, Bacillus megaterium were chosen to produce bacterial concrete and tests were made. Tests were conducted to find the growth time, quantity of calcium carbonate precipitation and mechanical properties of bacterial concrete. Mix design was made to produce M40 concrete, and control concrete was made as per mix design. Therefore, using bacteria-induced mineralization to repair cracks in mortar and concrete is a novel technique. Additional research is required to determine the long-term viability of the fracture healing process.

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