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Experimental Investigation on Properties of Bacterial Concrete

Jeswin George[1], Neethu Joseph[2], Noby Mathew[3]

1(PG Student, Department of Civil Engineering, St. Joseph's College of Engineering and Technology, Palai)
2(Assistant Professor, Department of Civil Engineering, St. Joseph's College of Engineering and Technology, Palai)
3(Lecturer, Department of Microbiology, St. Thomas College, Palai)

Abstract:

Concrete is one of the most critical materials in public infrastructure. It is seen that Cracking is a common cause of failure in the case of concrete. Self-healing concrete offers a solution to prevent damage of concrete structures due to formation of cracks and its related problems. Some specific species of bacteria could be used for this purpose of self-healing and in this study microbiologically induced calcite precipitation was utilized to obtain the results using Consortium technique and Bacillus Subtilis bacteria. Compressive strength test, rate of water absorption, water absorption capacity and porosity test, self-healing analysis and SEM analysis were done to assess the enhancement in properties of bacterial concrete. A significant increase of compressive strength was observed in bacterial concrete, but the permeation properties showed a decrease due to denser structure of bacterial concrete. Crack healing ability was successfully observed through self-healing analysis, whereas the morphology of calcite crystals was evident through SEM analysis. Thus, it was seen that incorporation of bacteria in conventional concrete had resulted in better performing concrete.

Keywords **—Self-healing, Bacteria, Concrete, Bacillus Subtilis, Consortium technique .**

I. INTRODUCTION

A. General

Concrete is the most widely used material in construction industry. Concrete was once considered as an indestructible because of their longer service life compared to other material. However, concrete deteriorates due to multiple reasons like material limitations, design gaps and construction practices, as well as exposure conditions. One such problem is cracking of concrete. These cracks will affect the structural integrity over long periods of time gradually leaving the structure out of use. Also, concrete is porous in the microscopic scale. This inherent porosity of concrete allows moisture to seep in the concrete structure in time which causes cracks and thereby corrosion of steel reinforcements thus reducing the structural integrity and durability of the structure. Thus, an additive that seals the pores and cracks reduces the permeability and immensely improve the life of the structure.

B. Bacterial Concrete

There are lot of shortcomings with the conventional sealing agents. Thus materials with self-healing capabilities like bacteria could be used effectively. Bacteria grow under wide range of geo-chemical conditions and can act as geo-chemical agents resulting in concentration of materials. This induces the formation of special minerals known as bio-mineralization. The microbial mineral precipitation resulting from metabolic activities of favourable micro-organism can enhance the overall behaviour of concrete. Bacterial concrete consists of a concrete mix incorporated with bacterial and nutrient broth to support the bacteria when it becomes active. The bacteria feeds on the food provided resulting in healing of concrete due to calcite precipitation. This process is known as Microbiologically Induced Calcite Precipitation (MICP). Calcite forming bacterial species with spores which can endure extreme mechanical and chemical stresses are to be used. Bacteria of Bacillus genus were known to remain viable for up to 200 years which usually extends to the life span of the structure and thus ensuring the crack healing ability of concrete.

C. Chemical Process

When bacteria are exposed to the air and the food, the bacteria grow through the bio chemical process that causes them to harden and fuse which strengthens the structure of concrete. This process extends the lifespan the concrete. When the concrete is mixed with bacteria, the bacteria go into a dormant state. When any cracks or minor damage occurred to concrete, it provides space for water and air entry within concrete and then spores of the bacteria initiate calcite precipitation process. The basic principle of the process is that, the microbial urease hydrolyses urea to produce ammonia and carbon dioxide and the ammonia released in surrounding subsequently increases pH, leading to accumulation of insoluble Calcium Carbonate. The chemical reactions involved are shown below:

$$CO(NH_2)_2 + H_2O \longrightarrow NH_2COOH + NH_3$$
$$NH_2COOH + H_2O \longrightarrow NH_3 + H_2CO_3$$
$$H_2CO_3 \longrightarrow 2H^+ + 2CO_3^{2-}$$
$$NH_3 + H_2O \longrightarrow NH^{4+} + OH^-$$
$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3$$

These create calcium carbonate crystals that further expand and grow as the bacteria produce the calcium lactate food. The crystals expand until the entire gap is filled. This bio-chemical process helps to improve performance of concrete.

II. OBJECTIVES

To attain the bacterial action cultured bacteria needs to be embedded in the concrete. So, suitable bacteria need to be selected for the purpose followed by bacterial culturing which includes growing the bacteria in nutrient broth. The bacterial solution was then added to concrete while casting, cured and tested at required time. The main objectives are:

- Improving the properties of conventional concrete by the inclusion of bacteria.
- To create self-healing property in concrete.
- To reduce the permeability in concrete and thus prevent intrusion of chemicals, gases and water to attain a longer life.
- Improving the strength characteristics of concrete.
- Comparing conventional concrete and microbial concrete to assess the improvement.

III. MATERIALS AND METHODS

A. Cement

Ordinary Portland cement of 53 grade by Dalmia Cements confirming to IS: 12269-1987 specifications was used for all concrete mixes. Tests on cement was done and have a standard consistency of 34%, initial setting time of 60 min, final setting time of 150 min and a specific gravity of 3.1.

B. Coarse Agreggate

Crushed granite angular aggregate from a local source was used having a maximum size of 20 mm and down, with a specific gravity of 2.68 and water absorption of 1.015 %.

C. Fine Agreggate

The fine aggregate used for the experimental study was M-sand, which confirms to zone II of IS 383:1980. The specific gravity was found to be 2.422 and water absorption of 1.01%.

D. Microorganisms

Staphylococcus Aureus, Escherichia Coli, Pseudomonas Aeruginosa, Klebsiella sp and Bacillus Subtilis were used for the study. These strains were obtained and partially characterized at Dept. of Applied microbiology. One set of concrete specimen was made with addition of Bacillus Subtilis bacteria alone; whereas in the other set of specimen a Consortium of bacteria was used which consist of all the bacteria incuding Bacillus Subtilis.

Fig. 1 Bacterial solution prepared to be added in concrete

E. Mix Proportion

The mix proportions for standard grade of concrete (M40) was designed using IS10262:2009. The materials required for 1 cubic meter of concrete was 1: 1.29: 2.22 with water cement ratio of 0.4.

IV. RESULTS AND DISCUSSIONS

A. Compressive Strength

Compressive strength at 7 and 28days were obtained by applying load using compression testing machine. The test results of controlled concrete and bacterial concrete at 7 days and 28 days of curing are given in Table I and graphically represented in Fig. 2 and Fig. 3. It was observed that concrete with bacteria had an increase in compressive strength compared to controlled concrete. The improvement in compressive strength by bacterial concrete is probably due to deposition of $CaCO_3$ on the microorganism cell surfaces and within the pores, which plug the pores within the binder matrix. Thus, the results from the study showed that due to inclusion of bacteria in controlled concrete, compressive strength was improved which would in-turn increase the overall durability performance of the concrete.

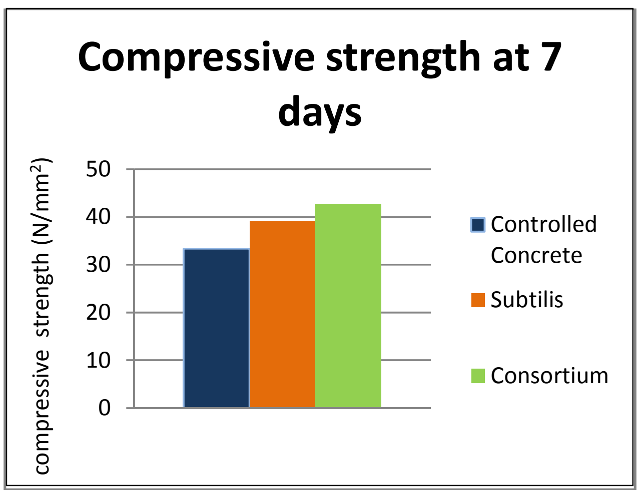

Fig. 2 Compressive strength at 7 days of curing

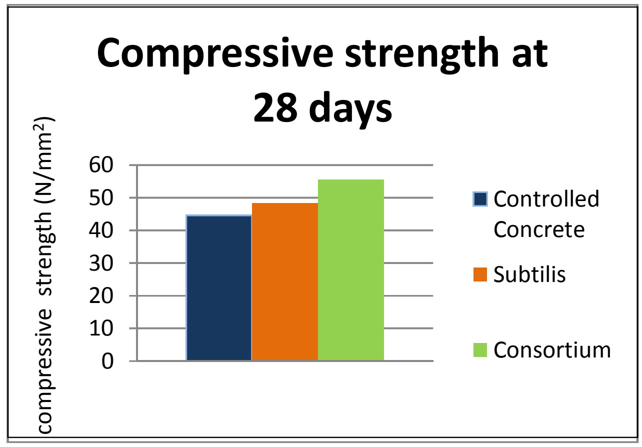

Fig. 3 Compressive strength at 28days of curing

Table I Compressive Strength Values at 7 and 28 Days

Type of concrete	Compressive strength at 7 days (N/mm^2)	Compressive strength at 28 days (N/mm^2)
Controlled mix	33.33	44.67
Bacillus Subtilis	39.11	48.29
Consortium technique	42.667	55.55

B. Water Absorption Capacity Test

Water absorption capacity test measures the water absorption rate and the maximum water absorption capacity. It is described as the standard test method for density, absorption, and voids in hardened concrete. The maximum quantity of water absorbed by a material at room temperature and pressure under conditions of saturation is expressed as a percentage of the dry mass of the sample. Water Absorption at different time intervals of controlled and bacterial concrete samples are given in Table II and percentage water absorption with time intervals of different samples are graphically represented in Fig. 4. It can be seen from the data that, with the inclusion of bacteria percentage water absorption in concrete have decreased. Thus the presence of bacteria resulted in a significant decrease in the water uptake compared to control specimens.

Table II Water Absorption at Different Time Intervals of Controlled and Bacterial Concrete

Time Interval, t(min)	Controlled Concrete m_o=8.17 Kg		Bacillus Subtitlis m_o= 8.23 Kg		Consortium m_o= 8.54 Kg	
	m_i	M_i %	m_i	M_i %	m_i	M_i %
0	8.17	0	8.23	0	8.54	0
15	8.21	0.489	8.27	0.486	8.58	0.468
30	8.22	0.612	8.27	0.486	8.58	0.468
60	8.22	0.612	8.28	0.607	8.59	0.585
90	8.22	0.612	8.28	0.607	8.59	0.585
180	8.23	0.734	8.29	0.729	8.6	0.703
1440	8.23	0.734	8.29	0.729	8.6	0.703
2880	8.23	0.734	8.29	0.729	8.6	0.703

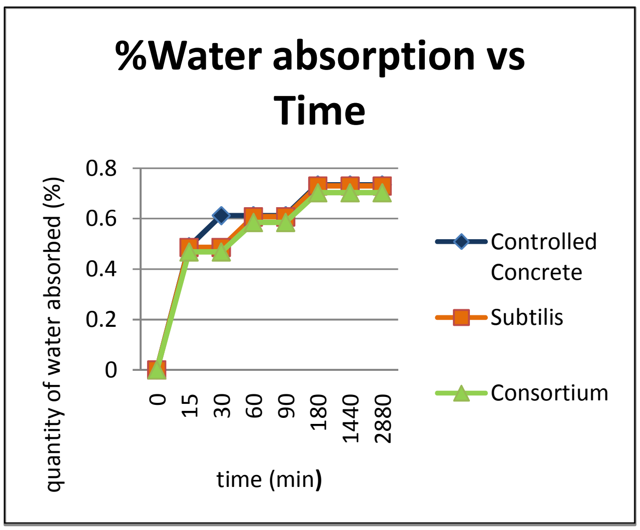

Fig. 4 Water absorption vs. time Graph

C. *Porosity Test*

Porosity test was conducted to estimate the percentage of voids present in concrete specimens. The test was conducted using cylinders of 100mm x 200mm size of controlled and bacterial concrete specimens at 28 and 60 days of curing. First of all, saturated weights W_{sat} of the specimens and also weight of specimen suspended W_{sub} in water were taken. Then bacterial specimens were dried in oven at about 105^0C until constant mass W_{dry} was obtained.

$$\text{Apparent porosity} = \frac{(Wsat - Wdry)}{(Wsat - Wsub)} X100$$

Volume of Permeable Voids,

$$VPV \% = (1 - \frac{SGb}{SGa}) X100$$

Where,

Concrete bulk dry specific gravity (SG_b) =

$$\frac{Wdry}{Wsat - Wsub}$$

Concrete apparent specific gravity (SG_a) =

$$\frac{Wdry}{Wdry - Wsub}$$

The Water Absorption Capacity, Apparent porosity and Volume of permeable voids (VPV) % for controlled concrete and bacterial concrete are given in Table III and graphically represented in Fig. 5, Fig. 6 and in Fig. 7. From the graphs and charts it is quite evident that introduction of bacteria in concrete resulted in reduced Water Absorption Capacity, Apparent porosity and a reduced amount of permeable voids.

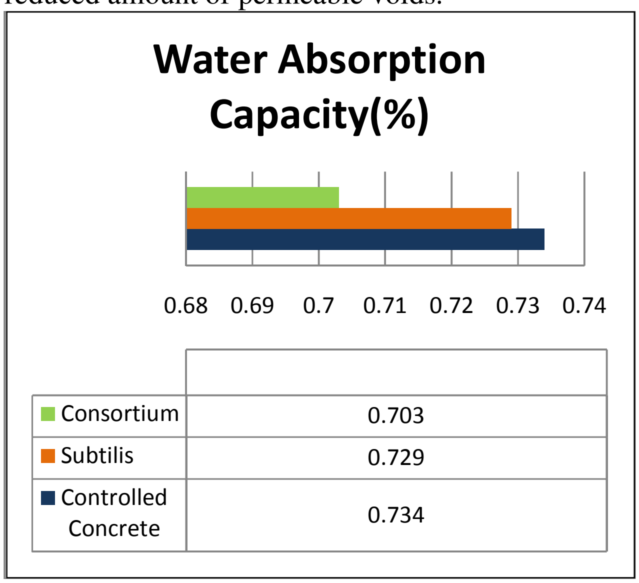

Fig. 5 Water Absorption Capacity in % for different concrete specimens

Table III Water Absorption Capacity (WAC) %, Apparent Porosity and Volume of Permeable Voids in Controlled and Bacterial Concrete

Concrete specimen	Water Absorption Capacity (WAC) %	Apparent porosity		Volume of permeable voids (VPV) %	
		28 days	60 days	28 days	60 days
Controlled concrete	0.734	8.28	7.74	8.2	7.73
Subtilis	0.729	7.7	7.3	7.85	7.2
Consortium	0.703	6.75	6.15	6.71	6.54

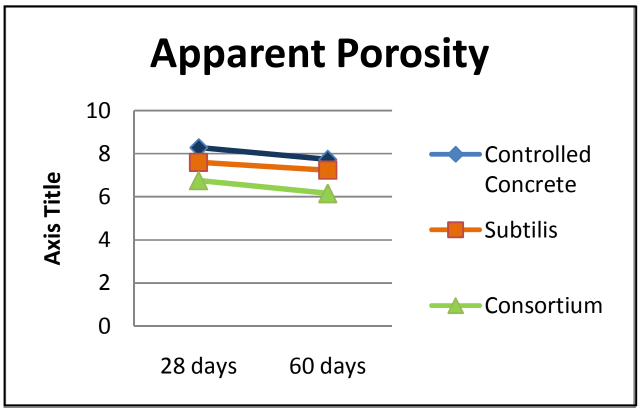

Fig. 6 Apparent Porosity of different concrete specimens

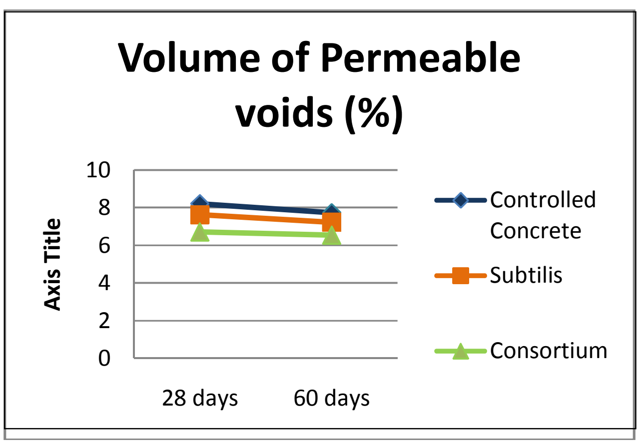

Fig. 7 Volume of Permeable voids in different concrete specimens

D. Self-Healing Analysis

Self-healing analysis is the visual inspection of crack remediation properties of bacterial concrete. This self-healing ability could be easily examined by forming hair cracks on concrete specimens and allow the cracks to heal over the period of time. Crack-healing was quantified by immersing the specimen at 25 ^{0}C in water. From Fig. 8 it can be seen that white precipitates of Calcium Carbonate seals the cracks. Thus, by precipitation of Calcium Carbonate by bacteria which are embedded in concrete at the time of casting, the cracks faces were bonded together.


Fig. 8 Crack healing by calcite precipitation

E. SEM Analysis

Through SEM analysis the evidence of microbial calcite precipitation in concrete samples could be discovered. These microscopic observations serve to confirm the mechanism of microbial calcite precipitation in concrete For SEM analysis concrete specimens of small size which are clean and dry were taken.

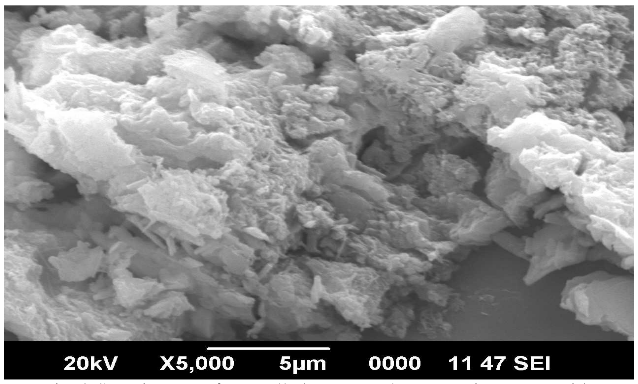

Fig. 9 SEM images of controlled concrete demonstrating more voids

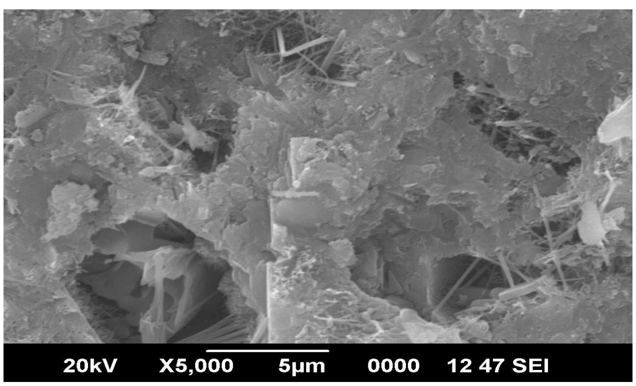

Fig. 10 SEM image of Bacterial concrete showing a denser microstructure

The above images are result of SEM analysis conducted. From Fig. 9 the voids in controlled concrete are very clear; whereas in Fig.10 much denser microstructures which imply calcite precipitation had occurred, which had led to the improved properties of bacterial concrete. SEM images of Concrete with Bacillus Subtilis were shown in Fig. 11 and calcite crystals were of clustered lamellar morphology. But the specimen with Consortium of bacteria shows distinct rhombohedral shaped calcite crystals as seen in Fig. 12. Thus it could be understood that improvement in properties of bacterial concrete was predominantly due to calcite precipitation which occurred at pores and micro cracks.

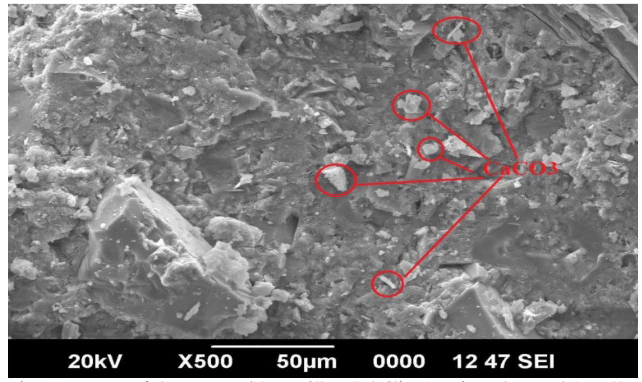

Fig. 11 Image of Concrete with Bacillus Subtilis showing clustered lamellar of $CaCO_3$

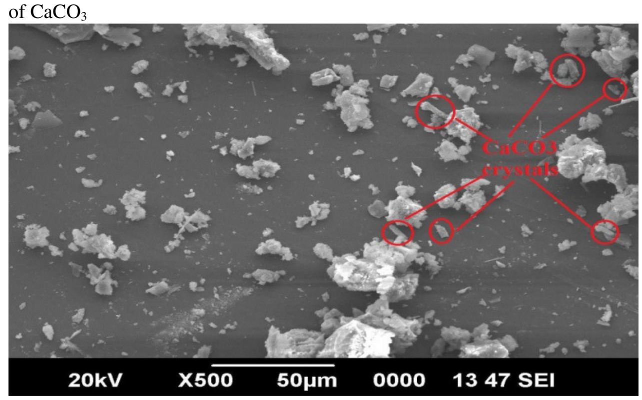

Fig. 12 Image of Concrete with consortium of bacteria showing CaCO3 crystals

V. CONCLUSION

Along with the self-healing ability of sealing the cracks, bacterial inclusion led to improved strength, microstructure, and reduced permeability. Consortium of bacteria had 8.34% strength increase at 7days and 13.1% strength increase at 28days when compared to concrete with Bacillus Subtilis alone, which makes the consortium technique more acceptable. The increase in compressive strength is mainly due to consolidation of pores inside the concrete with bacteria induced calcium carbonate precipitation. With induction of bacteria in concrete the Water Absorption characteristics of the concrete specimens decreased. Also, the Apparent Porosity values and Volume of Permeable Voids were much less when compared to controlled concrete. Self-healing analysis proved the crack healing in bacterial concrete and presence of calcite precipitation. SEM analysis showed an improved microstructure with lesser voids, and calcite present there had rhombohedral and lamellar morphology.

Thus, we can conclude that the produced calcium carbonate has filled some void volume thereby making the texture more compact and resistive to permeation. Microbial concrete technology has proved to be better than many conventional technologies due of its eco-friendly nature, self-healing abilities and convenience in usage. This novel technology could provide the basis of some high quality structures and an alternative to other existing technologies that will be cost effective and environmentally safe, but more work is required to improve the feasibility of this technology from both economical and practical viewpoints. The application of microbial concrete to construction may also simplify some of the existing construction processes and revolutionize the ways of new construction processes.

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