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Self Healing Concrete

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Abstract—*Long term performance of structures has become vital to the economics of all nations. Concrete has been the major instrument for providing stable and reliable infrastructures since the days of the Greek and Roman civilization. At present concrete infrastructure experience deterioration at a much faster rate than expected. This may be due to the fact that structures are subjected to aggressive chemical environments. Such structures include bridge decks, ocean piers, offshore platforms, pipes and structures for confinements of solid and liquid wastes containing hazards materials etc. The main objective of the present research investigation is to obtain the performance of the concrete by the microbiologically induced special growth/filler. Which led to the development of a very special concrete known as Bacterial Concrete where bacteria is induced in the concrete to heal up the faults / cracks by using the bacteria "Bacillus subtilis strain No.JC3". Calcite formation by Bacillus subtilis JC3 is a laboratory bacterium, which can produce calcite which precipitates on suitable media supplemented with a calcium source.. The culture of bacteria and pure culture was isolated from the soil sample at Microbiology and Biotechnology laboratories of Bangalore University and is maintained constantly on nutrient agar slants. A series of 150 mm cube specimen with design mix of M20 grade of concrete were casted by adding bacteria having 10^4, 10^5,10^6,10^7 cells/ml-media of concentration for the optimization.. The study showed a significant increase in the compressive strength due to the addition of bacteria for a cell concentration of 10^5 cells per ml .This is due to the bio-mineralization of calcium carbonate in the concrete. The test results revealed 16.51% increase in compressive strength using Bacteria Bacillus Subtilis JC3 over the Control Concrete. Also Characterization studies have been performed to confirm the calcite precipitation through different experimental techniques, viz. X-ray Diffraction and Scanning Electron Microscope.*

Keywords*: Bacterial Concrete, Bacteria Bacillus Subtilis JC3, Calcium carbonate precipitation, compressive strength, XRD Analysis ,SEM.*

1. INTRODUCTION

Concrete is today's material of choice for construction world-wide because of its strength and cost effectiveness. Concrete is a mixture of cement, water, sand and other aggregates in adequate proportions. It has high compressive strength and can withstand vast range of environmental changes quite effectively. where its system behaviour is influenced by the environment. Environmental influences can initiate cracking of the concrete due to changes and differences in temperature, changes in moisture content, and internal drying shrinkage. This natural initiation of cracks is a problem for the brittle concrete, where the cracks can easily propagate then material did not improve in ductility, which implies the cracking can decrease structure strength and so decrease safety.

Owing to research on concrete and consequently increased knowledge of this material, driven by desired decrease in use of natural resources, and driven by increased desires in extreme engineering, the strength of concrete has increased rapidly last decades.

To decrease the budget spent on maintenance and repairs, an advanced cement-based material should be developed. Instead of manual repairing the structures and filling the problem-causing cracks, it would be ideal to have a material doing the job itself as self healing.

Self-healing can be divided into two different fields based on different mechanisms. Autogenic self-healing and the other one is autonomic self-healing.

Autogenic self-healing means that the self-healing process only involves the original material components, and is initiated without human intervention. Autonomic self-healing happens under influence of engineered additions, inserted into the matrix, and is initiated by human intervention. Hence attempt has been made autogenic self healing aspect in concrete.

2. GENERAL CLASSIFICATION OF BACTERIA

2.1 Classification on the basis of shapes

Bacteria are usually classified on the basis of their shapes. Broadly, they can be divided into Rod-shaped bacteria (Bacilli), Sphere-shaped bacteria (Cocci) and Spiral-shaped bacteria (Spirilla).

2.2 Classification on the Basis of Gram Strain

This classification is based on the results of Gram Staining Method, in which an agent is used to bind to the cell wall of the bacteria, they are Gram-positive and Gram-negative.

2.3 Classification on the Basis of Oxygen Requirement

This classification is based on the requirement of oxygen for the survival of the bacterium. They are Aerobic (Use molecular oxygen as terminal electron acceptor) and

Anaerobic (Do not use molecular oxygen as terminal electron acceptor)

2.3.1 Bacillus subtilis strain JC3

Bacillus subtilis, known also as the hay bacillus or grass bacillus, is a Gram-positive, catalase-positive bacterium. A member of the genus Bacillus, subtilis is rod-shaped, and has the ability to form a tough, protective endospore, allowing the organism to tolerate extreme environmental conditions. subtilis has historically been classified as an obligate aerobe.

3. MECHANISM OF SELF-HEALING BACTERIAL CONCRETE

Self-Healing 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. Which includes some widespread possibilities to close cracks in a cementatious material.

Most significant is precipitation of calcium carbonate. Average limit for which healing can still occur is a crack width of 0.2 mm. Carbonation reaction lies at the base of the calcium carbonate production, where diffused carbon dioxide reacts with the hydration product calcium hydroxide as can be seen in Eq. (1).

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \text{ .....} \quad . (1)$$

The principle of microbial healing also lies in the precipitation of calcium carbonate. Ingress water activates dormant bacteria. Dense layers of calcium carbonate are produced by bacterial conversion of an incorporated mineral precursor compound. In case of calcium lactate the reaction is as given in Eq. (2), where bacteria only act as a catalyst.

$$Ca(C_3H_5O_2)2 + 7O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O.. \quad . (2)$$

From the metabolic conversion of calcium lactate carbon dioxide is produced, which further reacts with the calcium hydroxide from the concrete matrix according to the chemical reaction in Eq. (1), producing additional calcium carbonate. Massive production of large, over 100 µgm sized crystalline calcium carbonate precipitates seal and block cracks, preventing further ingress of water.

3.1 Microcapsules

A mix consisting of healing agent filled microcapsules and catalyst-filled microcapsules are shown in Fig. No.1. Both types of capsules (5 nm to >2000 µm in size) are mixed through the matrix (i). When a crack propagates through this matrix, both of the microcapsules will crack and release their content (ii). When the catalyst and the healing agent meet, the hardening process starts and the crack will be closed (iii).

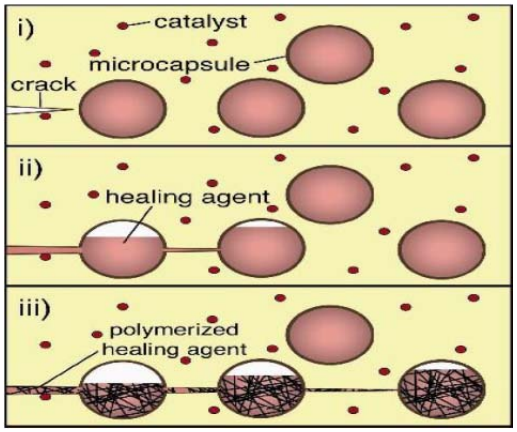

Fig. 1: Microcapsules and catalyst-filled microcapsules

3.2 Biologically induced self-healing

From the literature it could be observed that bacteria embedded in the cementations matrix, these bacteria can survive for over 50 years in a low-nutritious environment with a pH-value higher than 11. When a crack propagates, free water and oxygen migrate into the matrix. When the bacteria are contacted with the oxygen [O_2], they will start to change the chemical composition of their environment. The free water contains some hydroxide [OH-] which will react to carbonate [CO_3^{2-}] in presence of carbon dioxide [CO_2] produced by the bacteria. The result of free calcium ions [Ca^{2+}] in contact with carbonate [CO_3^{2-}] is the formation of calcium carbonate [$CaCO_3$] which is an important mineral in self-healing.

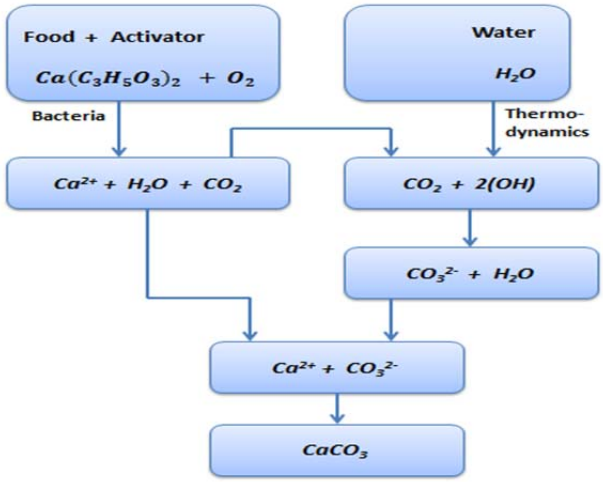

Fig. 2: Chemical flowchart of self healing process by bacteria.

4. LITERATURE REVIEW

Bacterial material as a smart material can be utilized in various construction areas to improve the performance of structure in new era. 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". Calcium carbonate precipitation, a widespread phenomenon among bacteria, has been investigated due to its wide range of scientific and technological implications.

Calcite precipitation induced by microorganisms and the feasibility of using microbiologically-induced $CaCO_3$ in concrete crack remediation[3, 6] in which the main focus is sealing of cracks and thus blocking of the path to the reinforcement in order to improve the durability of concrete. Laboratory technique based on the application of mineral -producing bacteria repair is to incorporate an autonomous self -healing mechanism in concrete[1]. The potential of self-healing of cracks in concrete by means of calcium carbonate (CaCO3) precipitating bacteria[2] . Strength improvement studies using new type wild Strain Bacillus Cereus on cement mortar is significantly higher[4] for the concentration of 10^6 c-ells/ml , the increase in strength could be due to the formation of calcite and its precipitation is substantiated with relevant characterization studies. The improvement of concrete durability by bacterial mineral precipitation. Bacillus bacteria as promising self -healing agent in concrete. The calcite precipitation induced by bacteria and bacterially produced carbonic anhydrate using X-ray diffractometry and Field Emission Scanning Electron Microscopy (FE-SEM) results showed that calcite was the dominant mineral phase [5, 6], Microbial calcite precipitation was quantified by X-ray diffraction (XRD) analysis and by SEM. XRD analysis and SEM evidenced that direct involvement of microorganisms in $CaCo_3$ precipitation . The Various bacteria used in the concrete are viz. Bacillus pasteurii, Bacillus sphaericus, Bacillus cereus, Bacillus haladurans, Bacillus pseudofirmus, Escherichia coli, Lysinibacillus fusiform,. In the present study an attempt was made by using the bacteria Bacillus subtilis strain JC3 on compressive strength.

5. AIM AND SCOPE OF PRESENT INVESTIGATION

The objective of the research is to investigate the potential use of self healing of concrete using bacteria namely " Bacillus subtilis JC3" in concrete matrix to improve the mechanical properties of normal concrete and also determining calcite precipitation of bacterial concrete using XRD Analysis and SEM observation of fractures surface of hardened concrete. The main obstacles has to be overcome which lies in the difficulty in Culture of bacteria and Maintenance of stock culture.

The main tasks can be broken down into two major areas in the following order:

1. Primary Phase : Culture of bacteria and maintenance of stock culture and dispersion of same in mixing water.
2. Secondary Phase: the Compressive strength characteristics ,XRD Analysis and SEM observation.

6. MATERIALS AND MIX PROPORTIONS

In present work ordinary portland cement 53 grade ultra tech Birla super, crushed granite with a maximum nominal of 20mm size,fine aggregates satisfying the requirements of zone II, Microorganisms Bacillus subtilis JC3 and water. Detailed mechanical properties of concrete making materials and biochemical characteristic of pure culture Bacillus subtilis bacteria are shown in Table no.1 and Table no.2

Table 1: Properties of Materials used

Parameters	Specification
cement specific gravity	3.12
Standard consistency	32%
Fineness modulus of FA	3.86
Specific Gravity of FA	2.62
Fineness modulus of CA	6.10
Specific Gravity of CA	2.68
Water	
PH	7.00
Alkalinity(Total) mg/l	22.00
Total Solid mg/l	1.10
Suspended Solids mg/l	0.55

6.1 Culture of Bacteria

The following procedure is adopted for culture of bacteria. The pure culture was isolated from the soil sample of Bangalore University and is maintained constantly on nutrient agar slants. It forms irregular dry white colonies on nutrient agar. Whenever required a single colony of the culture is inoculated into nutrient broth of 100 ml in 250ml conical flask and the growth conditions are maintained at 37^0C temperature and placed in 140 rpm orbital shaker. It was carried out at microbiology department in Bangalore University.

The culture medium composition required for growth of culture are Tryptone : 1%, Yeast : 0.5%,NaCl : 0.05%, Calcium Acetate : 1%, Distilled Water : 1000ml having PH 7

All the above components was dissolved in 1000ml of distilled water and sterilized by autoclaving at 121° (15lbs pressure for 15min).

6.2 Maintenance of Stock Culture

Stock cultures of Bacillus subtilis strain JC3 were maintained on nutrient agar slants. The culture was streaked on agar slants with an inoculating loop and the slants were incubated at 37°C. After 48-72 hours of growth, slant cultures were preserved under refrigeration (4°C) until further use. Contamination from other bacteria was checked periodically by streaking on nutrient agar plates.

6.2.1 Nutrient Agar Composition

The nutrient agar composition consists of Peptone: 5 g/lt, NaCl : 5 g/lt, Yeast Extract: 3 g/lt, Beef Extract: 3g/lt, Agar: 15g/lt, Distilled Water : 1000 ml having PH 7.All the above components was dissolved in 1000ml of distilled water and

sterilized by autoclaving at 121°(15lbs pressure for 15min). Media was cooled at 4°C and poured into sterilized test tubes and kept in slant position. After the media gets solidified a loop full of bacteria culture was streaked on the slants and kept at 37°C for 24 hours. After which the slants were shifted to 4°C for further maintained.

Table 2: Biochemical characteristics of the pure culture Bacillus subtilis JC3

Characteristics	Bacillus Subtilis JC3
Shape, size, gram stain	Long rods, 0.6-0.8 ìn in width and 2.0 to 3.0 ìn in length, gram positive (see fig.3.3)
Colony morphology (on nutrient agar plate)	Irregular, dry, white, opaque colonies (see fig.3.2)
Colony morphology (on nutrient agar plate)	Irregular, dry, white, opaque colonies (see fig.3.2)
Fermentation: Lactose Dextrose Sucrose	No acid, no gas No acid, no gas Acid and gas

Fig. 3.2: Colony morphology of strain JC3 on nutrient agar plate (Irregular, dry, white, opaque colonies)

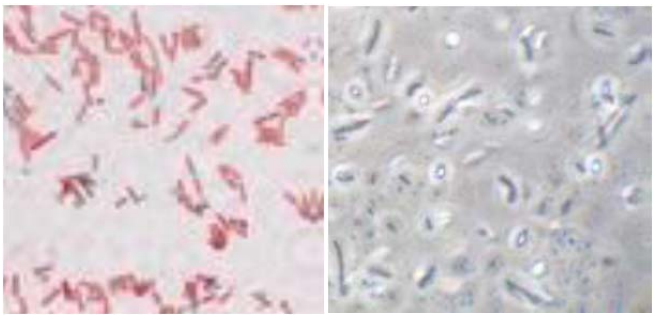

Fig. 3.3: Phase contrast microphotograph of strain JC3 (Long rods, 0.6-0.8 µm in width and 2.0 to 3.0µm in length, gram positive)

7. TEST SPECIMENS AND TEST PROGRAMME

In secondary phase, weigh batching for materials was used for the experimental study. cement, fine aggregate, coarse aggregate, water mixed with Bacillus subtilis bacteria JC3 of known concentration, care should be taken when using Bacillus subtilis bacteria. The dispersed solution is added to the mix & the mixing is continued until the lump free homogeneous concrete mix is obtained. A series of test specimens are chosen for the investigation and all are having a unique nominal dimension of 150 mm cube. The test programme consists of four different trail mixes of designed grade of M20 with varying concentration of Bacillus subtitles bacteria JC3.The four different trial mixes are:

Mix1= M20+10^4 cells/ml of media

Mix2= M20+10^5 cells/ml of media

Mix3= M20+10^6 cells/ml of media

Mix4= M20+10^7 cells/ml of media

Above mentioned trail mixes, Mix2(M20+10^5 cells/ml of media) was found to satisfy sustainable point of view and optimized.

Table 3: Slump values for various mix with Bacillus subtilis bacteria JC3

Concrete Matrix	Slump (mm)
Mix1=M20+10^4cells/ml concentration	78
Mix2=M20+ 10^5cells/ml concentration	75
Mix3=M20+10^6cells/ml concentration	78
Mix4=M20+10^7cells/ml concentration	79

7.1 SEM (Scanning Electron Microscope)

Scanning electron microscopy is used for inspecting the structural morphology at very high magnifications level. SEM inspection is often used in the analysis of cracks and fracture surfaces, bond failures, and physical defects. Fig. 3(a) &3(b) shows the comparison between fracture surface of control concrete and Bacterial concrete composite.

7.2 X-Ray Diffraction (XRD)

XRD is a technique used for chemical analysis of materials. An X-ray source is used to irradiate the specimen and to cause the elements in the specimen to emit (or fluoresce) their characteristic X-rays. A detection system (wavelength dispersive) is used to measure the peaks of the emitted X-rays forqual/quant measurements of the elements and their amounts. In the present study the precipitation was analysed for its chemical characteristics by X-Ray Diffraction and result indicated positively as Calcium Carbonate. Fig. 4 (a) & (b) shows the comparison between control concrete and Bacterial concrete composite.

8. TESTS AND RESULTS

Most concrete structures designed under all assumption that the concrete develops compressive but not tensile stress. The compressive strength is the main criteria for the purpose of structural design. The compressive tests are relatively easy to carry out.

Among all strengths, the compressive strength is generally considered as most important property of concrete and gives overall picture of quality of concrete. The required slump values of various mixes with different cell concentration are

shown in Table.3 it is seen that 10^5 cell concentration suits the required slump value for mix proportion.

Table 4. shows results obtained for compressive strength for 7, 14, 28 days for the concrete matrix for the Mix1 to Mix 4 with 10^4 to 10^7 cell/ml concentration of bacteria for optimization with respect to control concrete. It is seen that Mix2 shows the significant increase in the load carrying capacity. and optimized to obtain maximum compressive strength. Hence Mix2 (M20+10^5 cells/ml concentration) is used in research investigations. Experimental results as shown in Table 6.

Table 4: Compressive strength of concrete for optimization of cell concentration of Bacillus subtilis JC3.

Cell/ml of media (Concentration)	Average Compressive Strength of Concrete N/mm^2					
	7 Days	Increase	14 Days	% Increase	28 Days	% Increase
Control Concrete : M20	16.56	-	21.12	-	28.34	-
Mix1= M20+ 10^4	17.44	5.31	22.54	6.72	30.92	9.10
Mix2= M20+ 10^5	18.02	8.81	24.43	15.67	33.02	16.51
Mix3= M20+ 10^6	17.20	3.86	23.08	9.28	31.87	12.47
Mix4= M20+ 10^7	16.70	0.84	22.67	7.33	29.26	3.24

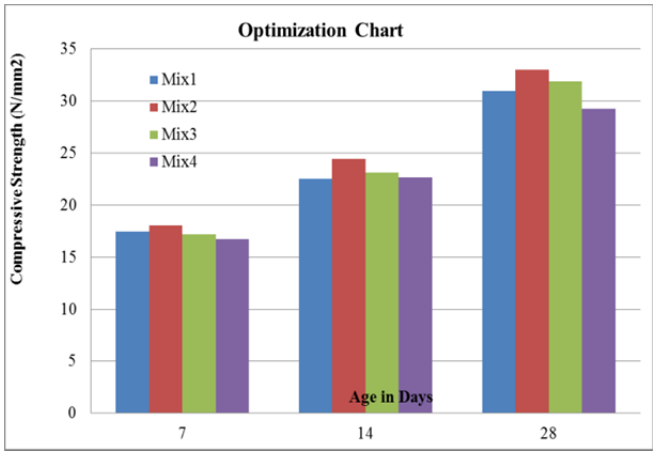

Fig. 2: Compressive strength of concrete for optimization of cell concentration of Bacillus subtilis JC3.

Table 5: Compressive strength of control concrete

Grade of concrete	Age of sample in days	Load (KN)	Strength ((N/mm^2)	Average strength (N/mm^2)
M20	7	313	13.95	16.56
		392	17.44	
		412	18.31	
	14	392	17.44	21.12
		510	22.67	
		568	25.28	
	28	618	27.46	28.34
		618	27.46	
		676	30.08	

Table 6: Compressive strength of Bacterial Concrete

Grade of Concrete	Age of sample in days	Load (KN)	Strength ((N/mm^2)	Average strength (N/mm^2)
M20+10^5 cells/ml concentration	7	387.00	17.20	18.02
		414.90	18.44	
		414.90	18.44	
	14	564.30	25.08	24.43
		555.07	24.67	
		529.65	23.54	
	28	748.35	33.26	33.02
		739.57	32.87	
		740.92	32.93	

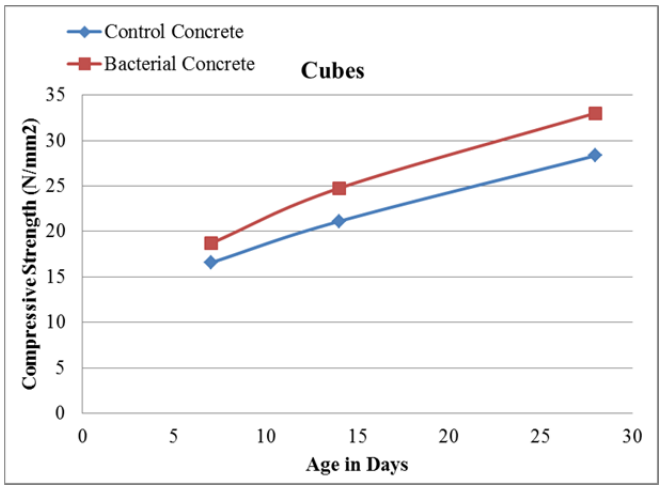

Fig. 3: Compressive Strength of MIX 2 with10^5 cells/ml Concentration

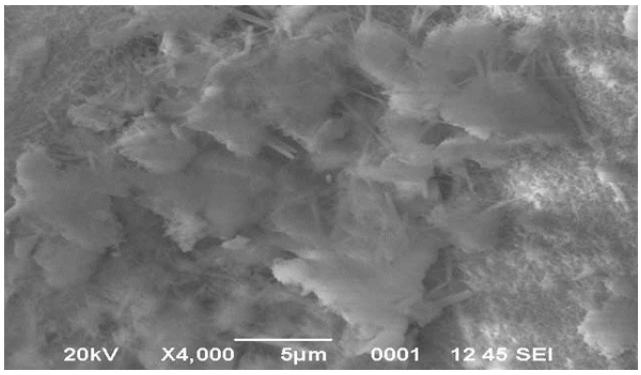

Fig. 3: (a) SEM image of fracture surface of bacteria concrete.

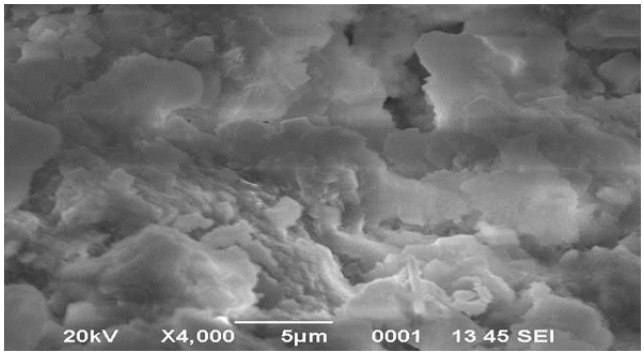

Fig. 3: (b) SEM image of fracture surface Control concrete

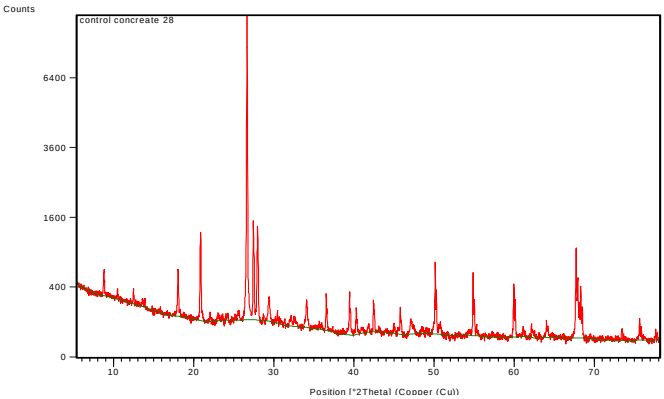

Fig. 4: (a) X-ray diffraction spectrum of control concrete

Table 7: The identified phases of Control Concrete with their relative distribution.

Compound Name	Remark
Quartz	~72 %
Albite	~13%
Microcline	~10%
Portlandite	~3%
Calcite	~2%

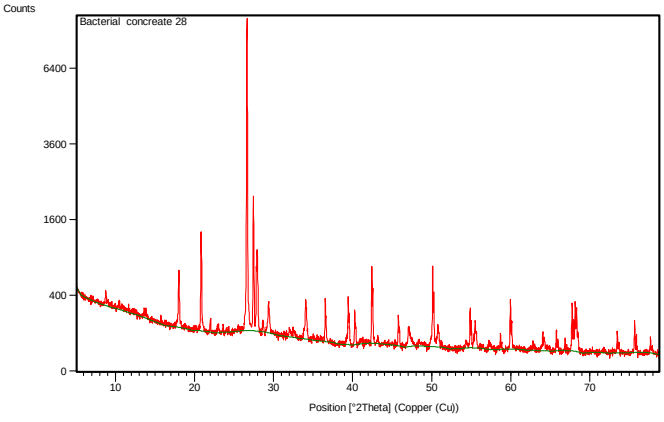

Fig. 4: (b). X-Ray Diffraction Spectrum Of Bacterial Concrete

Table 8: The Identified Phases Of Bacterial Concrete with their relative distribution

Compound Name	Remark
Quartz	~66%
Albite	~18%
Portlandite	~6%
Titanite	~6%
Calcite	~3%

9. CONCLUSIONS

i. Bacillus subtilis JC3 can be easily cultured in the laboratory which is proved to be safe and cost effective. The compressive strength of concrete is maximum with the addition of Bacillus subtilis JC3 at 10^5 cells/ml concentration.

ii. The addition of Bacillus subtilis JC3 bacteria improves the hydrated structure of cement mortar as bacterial deposition and precipitation of calcite minerals in cement matrix which improves adhesive properties by pore filling of bacteria itself.

iii. The addition of Bacillus subtilis JC3 bacteria increases the compressive strength of concrete upto 8.81%, 12.98% and 15.67% at 7, 14 and 28 days respectively compared to control concrete. The results showed that there is a significant improvement in the load carrying capacity of bacterial concrete.

iv. Bacterial Concrete has served its purpose by the enhancement of compressive strength as self healing process which involves closing of cracks by precipitation of calcite minerals, and is initiated without human intervention.

SEM Analysis

Structural morphology of any material is investigated using Scanning Electronic Microscope

i. It is evident from Fig. 3 (a) &(b) that pores are partially filled up by material growth with the addition of the bacteria. Reduction in pore due to such material growth will obviously increase the material strength and makes concrete more and more durable. which is due to calcite crystalline structures were found inside the pores of the mortar with addition of bacteria.

ii. The spherical particles in the Fig. show the presence of calcite. This microbiologically produced calcite is responsible in filling up the pores in cement composites and hence increasing the strength and durability.

XRD Analysis

Microbial calcite precipitation is quantified by X-ray diffraction (XRD) analysis.

i. It is evident from experimental studies Fig. 4(a) &(b) the principal calcite peak scan were observed at 23.3°, 29.6°, 36.2°, 39.2°, 43.4°, 47.7° and 57.4° which validate presence of calcite in the bacterial concrete and also in control concrete.

ii. The bacteria are able to produce higher amount of calcite thus resulting in significant increase in compressive strength of mortar.

Finally SEM and XRD analysis shows that the presence of calcite inside the cement composite specimen which makes concrete more and more durable thereby increasing in strength and durability characteristics of concrete.

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