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# Self Healing Concrete for the Development of Sustainable Concrete

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***Abstract:*** **In reviewing technology advances through the centuries, it is evident that material development plays a key role, considerable efforts are still being made in every part of world to develop new construction materials, In the construction industry, concrete technology is heading towards entirely new era by way of using 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 CaCO3 has been introduced for remediation of damaged structural formation or micro cracks. Which includes some widespread possibilities to close cracks in a cementations material, since strength and ductility are the two major important factors to be considered in the design of R.C.C structures? The main focus of the present research investigation is to obtain the performance of the concrete by the microbiologically induced special growth/filler. 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 from the soil sample at Microbiology and Biotechnology laboratories of Bangalore University, Bangalore 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 . The investigation further extended to study the flexural behaviour of self healing bacterial reinforced concrete. A three point bending test is carried out on three test beam specimens with dimension 150mmx230mm and an effective length of 2200mm to obtain load deflection characteristics. By summarizing experimental results, it is observed that addition Bacillus subtilis JC3 ensures structural integrity in enhancement of ductility and energy absorption capabilities, this is due to the bio-mineralization of calcium carbonate in the concrete. Also Characterization studies were performed to confirm the calcite precipitation through X-ray Diffraction and Scanning Electron Microscope.**

***Keywords:*** **Self healing concrete, Bacterial Concrete, concrete, Bacteria Bacillus Subtilis JC3, Calcium carbonate precipitation, compressive strength, energy absorption, ductility index, XRD Analysis and SEM**

## I. INTRODUCTION

Concrete is the most common and widely used construction material all over the world. Although reinforced concrete has become the material of choice for general construction, there is a worldwide concern about its durability. The total world consumption of concrete is estimated to be in billions. Concrete is a composite material, where its system behaviour is also 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. 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. The material did not improve in ductility, which implies the cracking can decrease structure strength and so decrease safety.

Besides safety, there is also an economical drawback of crack initiation. 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. One mechanism, 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

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inserted into the matrix, and is initiated by human intervention. Hence attempt has been made Autogenic self healing aspect of Bacterial concrete.

## II. MICROBIALLY INDUCED CRACK

### *1. Remediation (MICP)*

Microbial mineral precipitation involves various microorganisms. Considerable research on Carbonate precipitation by bacteria has been investigated by many researchers by using bacteria[1,2,4 ]. These bacteria are able to influence the precipitation of Calcium Carbonate by the production of a unease enzyme. This enzyme catalyzes the hydrolysis of urea to CO2 and ammonia, resulting in an increase of the pH and Carbonate concentration in the bacterial environment. Precipitation of Calcium Carbonate crystals occurs by heterogeneous nucleation on bacterial cell walls once super saturation is achieved. The fact that hydrolysis of urea is a straight forward common microbial process and that a wide variety of microorganisms produce the unease enzyme makes it ideally suited for crack remediation for building material applications. This precipitation forms a highly impermeable layer which can be used as crack remediation for concrete or any other building material. The precipitated calcite has a coarse crystalline structure that readily adheres to the concrete surface in the form of scales. In addition has the ability to continuously grow upon itself and it is highly insoluble in water

### *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 (used in present study) 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. Mechanisms of self healing bacterial concrete*

With the desire to create a material where the self-healing capacity prevents necessary human intervention, the focus is on autogenic self-healing. Autogenic states the self-healing mechanismis without human intervention, and based on original material components. In concrete the original components are the hydration products, the unhydrated cement powder and water.

Autogenic self-healing cannot be denoted as one mechanism. There are in general 4 different mechanisms observed related to autogenic self-healing. These mechanisms are shown in figure 1. where the numbered mechanisms refer to the following explanation. The formation of calcium carbonate [CaCO3]

Calcium carbonate forms when free dissolved calcium ions [Ca2+] react with carbonate[$CO3^{2-}$], both dissolved in the water. The [$CO3^{2-}$] comes from the reaction between dissolved carbon dioxide [CO2] with hydroxide [OH-]. By thermodynamic laws there is always hydroxide [OH-] present in the water as can be seen in Eq.(1)

$Ca2+ + CO3^{2-} \rightarrow CaCO3$ $CO2 + 2[OH-] \rightarrow CO3^{2-} + H2O$ ............. (1)

The formation of calcium hydroxide [Ca(OH)2], Calcium hydroxide forms when free calcium ions [Ca2+] are dissolved in water as Eq. (2).

$Ca2+ + 2(OH-) \rightarrow Ca(OH)2$............................................. (2)

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. (3).

$CO2 + Ca(OH)2 \rightarrow CaCO3 + H2O$ ................................. (3)

The principle of microbial healing also lies in the precipitation of calcium carbonate. Ingress water activates dormant bacteria. 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 as seen in figure 1 & 2.

 

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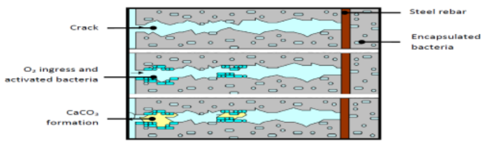


***Figure 1. Schematic representation of self-healing by bacteria. Water activates the bacteria to form CaCO3, which closes the cracks.***

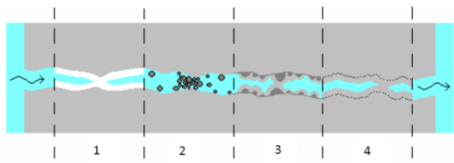


***Figure 2. .Mechanisms for autogenic self-healing in a cementitious matrix***

(1) Formation of calcium carbonate or calcium hydroxide,
(2) sedimentation of particles,
(3) continued hydration,
(4) swelling of the cement matrix

### *4. Literature Review*

Comprehensive literature review on maintenance, repairs and heal up the cracks in distress concrete structures is an evidence of interest generated in the research activity. In concrete, cracking is a common phenomenon due to the low tensile strength. crack repair, a variety of techniques is available but traditional repair systems have a number of disadvantageous aspects such as different thermal expansion coefficient compared to concrete and environmental and health hazards. Therefore, bacterially induced calcium carbonate precipitation has been proposed as an alternative and environmental friendly crack repair technique. Microbial calcite precipitation is mainly due to unrealistic activity and carbonate bio mineralization of bacteria as development of Sustainable concrete.

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[5,6.] 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. The bio-based repair system is a liquid-based system which transports a bio-based agent into concrete. The bio-based repair agent consists of bacteria which produce calcite-based minerals decreasing concrete matrix porosity.

The principle mechanism of bacterial crack healing is that the bacteria themselves act largely as a catalyst, and transform a precursor compound to a suitable filler material. The newly produced compounds such as calcium carbonate based mineral precipitates should than act as a type of bio cement what effectively seals newly formed cracks[7,8]. Thus for effective self-healing, both bacteria and a bio cement precursor compound should be integrated in the material matrix as Calcite precipitation induced by microorganisms and the feasibility of using microbiologically-induced $CaCO_3$ in concrete crack remediation[3,6] Strength improvement studies using new type wild Strain Bacillus Cereus on cement mortar is significantly higher[9] for the concentration of $10^5$ cells/ml , the increase in strength could be due to the formation of calcite and its precipitation

The improvement of concrete ductility and energy absorption by bacterial calcite precipitation. Bacillus bacteria as promising self -healing agent in concrete[10,11] The calcite precipitation induced by bacteria and bacterially produced carbonic anhydrate dominant mineral phase using X-ray diffractometry analysis[5,6] and Scanning Electron Microscopy[4] results showed evidenced that direct involvement of crystalline calcium carbonate precipitates which seal and block cracks and make concrete dense and durable. Hence an attempt has been made through present investigation to study the effect of calcite formation by Bacillus subtilis JC3when it is integrated with normal cement concrete.

### *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 in compressive strength and in flexural strength and also determining calcite precipitation of bacterial concrete using XRD Analysis and SEM observation of fractures surface of hardened concrete.

The main tasks in the present investigations are broken down into three 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: determination of Compressive strength and Flexural strength characteristics of bacterial self healing concrete.
3. Characterization studies phase: XRD Analysis and SEM observation.

### *6. Materials and mix proportions*

In present work OPC 53 grade ultra tech Birla super, crushed granite with a maximum nominal of 20mm size, fine aggregates satisfying the requirements of zone II,

 

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Microorganisms Bacillus subtilis JC3 and water.Detailed biochemical characteristic of pure culture Bacillus subtilis bacteria and mechanical properties of concrete making materials and are shown in Table no.1 & 2

***Table.1.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 |
| Colony morphology (on nutrient agar plate) | Irregular, dry, white, opaque colonies |
| Colony morphology (on nutrient agar plate) | Irregular, dry, white, opaque colonies |
| Fermentation:<br>Lactose<br>Dextrose<br>Sucrose | <br>No acid, no gas<br>No acid, no gas<br>Acid and gas |

***Table No. 2 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 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 370C temperatures 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 which consists of Tryptone : 1%,Yeast : 0.5%,NaCl : 0.05%,Calcium Acetate : 1%and Distilled Water : 1000ml, PH 6.5.All these 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 subtilisJC3 were maintained on nutrient agar slants. The culture was streaked on agar slants with an inoculating loop and the slants were incubated at $37^0$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.

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. and Distilled Water : 1000ml, PH 7. All these 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.

### *7. Test Specimens and Test programmer*

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.

### *7.1 compressive strength*

A series of test specimens are chosen for the investigation of compressive strength and all are having a unique nominal dimension of 150 mm cube which 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

in above mentioned trail mixes, Mix2(M20+$10^5$ cells/ml of media) was found to satisfy sustainable point of view and optimized[14].

 

*7.2 Flexural Behaviour of test beams specimens.*

A three point bending test is carried out on three test beams specimen with dimension 150x230mm and effective length of 2200mm to obtain load deflection characteristics for cracking loads , deflection, ductility index and energy absorption capacity with and without Bacterial Concrete were investigated.

*7.2.1 Flexural Ductility Index*

Ductility is the measure of the element capacity to undergo inelastic behavior and absorb energy. Several forms of ductility are available. These include curvature, rotational, and displacement ductility. In this research, displacement ductility is investigated. Displacement ductility, μd, is defined as the ratio of deflection at ultimate moment to the deflection at first yield of the tensile reinforcement. In general, high ductility ratios indicate that a structural member is capable of undergoing large deflection prior to failure. Displacement ductility is given by

$$\mu d = \delta u / \delta y$$

*7.2.2 Energy Absorption Capacity*

The Energy absorption capacity of given material can be obtained from the load versus deflection curve of the specimen. The value of Energy absorption capacity was computed from the area under the load deflection curve for different concrete mix under investigation.

*7.3 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 as shown in table 7 and 8, for its chemical characteristics by X-Ray Diffraction. Figures 6(a) & 6(b) shows the comparison between control concrete and Bacterial concrete matrix.

*7.4 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. figure 5(a) & 5(b) shows the comparison between fracture surface of 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. It can be observed that $10^5$ cell concentration suits the required slump value for mix proportion. It is observed that Mix2 shows the significant increase in the load carrying capacity and is optimized to obtain maximum compressive strength.

Hence Mix2 (M20+$10^5$ cells/ml concentration)[14] is used in present research investigations for casting of cubes and test beam specimens. Experimental results obtained and tabulated in table 3-6 and shown in figure 3 & 4.

*Table3 . 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 4. 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 | |

*Table 5. load and deflection at various stages in flexural test*

| Mix | First crack load (Kn) | Deflection at first crack load $\delta_u$ (mm) | Ultimate load (Kn) | Deflection on at ultimate load. $\delta_u$ (mm) |
|---|---|---|---|---|
| Control Concrete test beam specimen ( C1) | 10.57 | 1.59 | 40.02 | 17.98 |
| Bacterial Concrete test beam specimen ( C2) | 11.33 | 1.02 | 43.5 | 19.87 |
| Bacterial Concrete test beam specimen ( C3) | 11.43 | 1.09 | 45.82 | 19.10 |

*Table 6. Energy absorption and Ductility Index in flexural test*

| Mix | Energy Absorption Capacity KN-mm | Ductility Index µd =δu /δy mm |
|---|---|---|
| Control Concrete test beam specimen ( C1) | 305.29 | 3.20 |
| Bacterial Concrete test beam specimen ( C2) | 315.61 | 3.42 |
| Bacterial Concrete test beam specimen ( C3) | 342.74 | 3.39 |

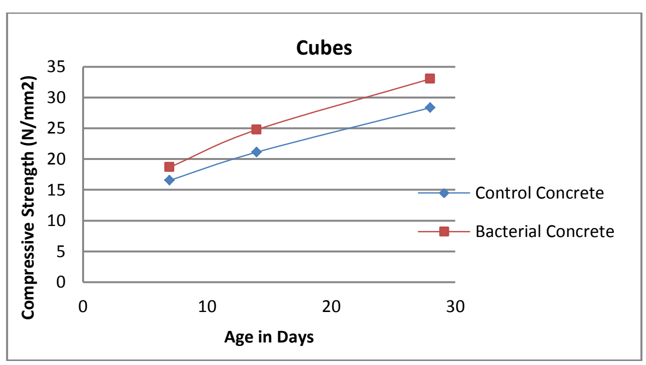


*Figure 3.: Compressive Strength of MIX 2 with10$^5$ cells/ml Concentration[14]*

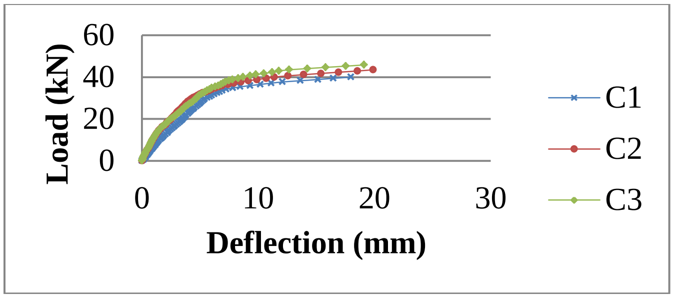


*Figure 4: Load-Deflection Curves for test beam specimens*

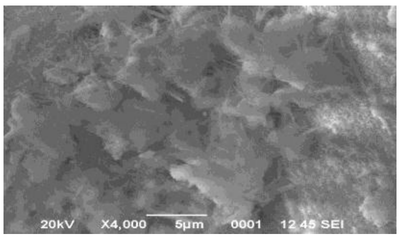


*Figure 5 (a) SEM image of fracture surface of bacteria concrete.[14]*

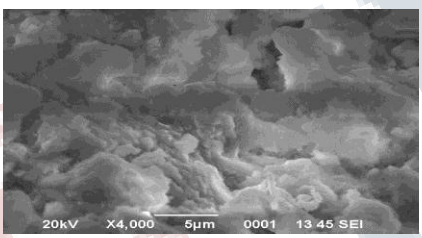


*Figure 5 (b) SEM image of fracture surface Control concrete[14]*

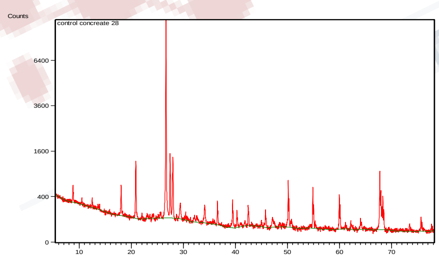


*Figure 6 (a) X-ray diffraction spectrum of control concrete[14]*

*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% |

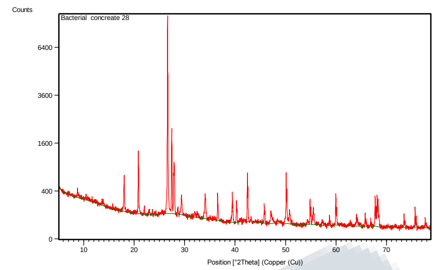


*Figure 6(b). X-Ray Diffraction Spectrum Of Bacterial Concrete[14]*

*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% |

## III CONCLUSIONS

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

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.
Among the parameter studies under in flexural test the ultimate loads are 45.82kN in Bacterial Concrete and were as 40.02kN in Control concrete respectively.

Energy absorption capacity of bacterial concrete is 12.26% and Ductility index about 10% increased Respectively, than compared to the Control concrete.
In the beams C2, C3 the formation of cracks are less in number due to Bacteria Bacillus Subtilis precipitates Calcite which fill up minor cracks.

From the experimental results it is observed that the Bacterial concrete beam behaved much better with regards to first crack load and ultimate load which enhanced the flexural behaviour characteristics.

***SEM Analysis :*** Structural morphology of any material is investigated using Scanning Electronic Microscope. It is evident from figure 5 (a) & (b) that pores are partially filled up by material growth with the addition of the bacteria. The spherical particles in the figure 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. It is evident from experimental studies figure 6(a) & (b) and tabulated in the table 7 and 8. 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. As result indicated positively as calcium carbonate. The bacteria are able to produce higher amount of calcite thus resulting in significant increase in compressive strength of mortar.

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.

## REFERENCES

[1] Henk M. Jonkers, A. T. (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological Engineering.

[2] J.Y. Wang, K. V. (2010). Potential of Applying Bacteria to Heal Cracks in Concrete. 1Magnel Laboratory for Concrete Research.

[3] Ramakrishnan, S. S. (2000). Microbiologically - Enhanced Crack Remediation (MECR). South Dakota School of Mines and Technology.

[4] S.Maheswaran. (2014). Strength improvement studies using new type wild strain Bacillus cereus on cement mortar. 1CSIR-Structural Engineering Research Centre.

[5] Wei Li, L.-P. L.-P.-J.-Y. (2011). Calcite precipitation induced by bacteria and bacterially produced carbonic anhydrase. Institute of Resource Biology and Biotechnology

[6] Jagadeesha Kumar B G, R. P. (2013). Effect of Bacterial Calcite Precipitation on Compressive Strength of Mortar Cubes. International Journal of Engineering and Advanced Technology.

[7] Jonkers, R. M. (2013). Practical Approach for Production of Bacteria-Based Agent-Contained Light Weight Aggregates to Make Concrete Self-Healing. Faculty of Civil Engineering and Geosciences, Materials & Environment section.

[8] Jonkers, V. W. (2012). Application of bacteria-based repair system to damaged concrete structures. Delft University of Technology, Delft, the Netherlands.

[9] M.V. Seshagiri Rao, V. S. (2013). Bioengineered Concrete - A Sustainable Self-Healing Construction Material. Research Journal of Engineering Sciences.

[10] Ramakrishnan, R. K. (2013). Improvement of concrete durability by bacterial mineral precipitation. Department of Civil & Environmental Engineering.

[11] Wiktor, S. S. (2013). Potential of bacteria-based repair solution as healing agent for porous network concrete. Delft University of Technology, Faculty of Civil Engineering & Geosciences.

[12] Aissa, D. E. (2012). Self-Healing Materials Systems: Overview of Major Approaches and Recent Developed Technologies. Advances in Materials Science and Engineering.

[13] Jonkers, V. W. (2012). Application of bacteria-based repair system to damaged concrete structures. Delft University of Technology, Delft, the Netherlands.

[14] Sadath Ali Khan Zai and M.Keshava Murthy, Self healing concrete, 9th International Conference on Innovative research in civil engineering, architecture and environmental engineering for sustainable development (CEAESD 2015) held at Jawahar Lal Nehru, University, Delhi, 12th December 2015. Organized by Krishi Sanskriti.

[15] V. Wiktor, S. S. (2013). Potential of bacteria-based repair solution as healing agent for porous network concrete. Delft University of Technology, Faculty of Civil Engineering & Geosciences.

[16] Varenyam Achal, A. M. (2010). Microbial Concrete: A Way to Enhance Durability of Building Structures. Department of Biotechnology and Civil Engineering.

[17] Vijeth N Kashyap, R. (2013). A study on effect of bacteria on cement composites. International Journal of Research in Engineering and Technology.

[18] Reddy, S. P. (2010). Performance of Ordinary Grade Bacterial (Bacillus Subtilis) Concrete. International Journal of Earth Sciences and Engineering.

[19] S. S. Bang, ,. J. (2010). Microbial calcite, a bio-based smart nanomaterial in concrete remediation. International Journal of Smart and Nano Materials.

[20] Sookie S. Bang, J. K. (2001). Calcite Precipitation induced by polyurethane-immobilized Bacillus Pasteurii. Enzyme and Microbial Technology.