Study on The Behaviour of Concrete Under The Influence of Bacillus Subtilis As A Self-Healing Agent

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Abstract- *As we know Concrete is a major construction material in the world but due to its low level tensile strength and other factors of nature, forming of cracks in concrete is a very common problem and without proper and quick treatment, cracks in concrete structure begins to expand more and ultimately lead to failure of structure. Cracks in concrete also develop an open passage to the reinforcement bars leading leads to corroded steel bars, which leads to durability problems of structure. For many years now proper healing of concrete cracks is prime object of investigation. In order to vanish this huge problem, an efficient technique has been introduced in fixing cracks with environmental friendly biological process that is also known as self-healing process based on the use of smart concrete which is generally known as Self-healing concrete. The principal motivation for our research is the inadequate research done over the use of bacillus subtilis as a self-healing agent. Hence principal objective of the research is to develop self-healing concrete by incorporation of bacteria named as bacillus subtilis acting as self-healing agent. In the current study, bacteria termed as Bacillus Subtilis was incorporated with concrete in different concentrations. Evaluation of healing effect was worked out by comparing compressive strength, water absorption content, Ultrasonic Pulse Velocity (UPV) of bacterial concrete to conventional concrete. Other tests like Slump cone test, UPV test, water absorption tests were also conducted. Finally, healing of cracks was visualized at the age of 60 days and analyzed using Scanning Electron Microscope (SEM) studies. The results pointed that that a significant amount of self-healing of cracks was achieved and use of bacteria named Bacillus Subtilis proved to be a better choice.*

Keywords- Concrete, Bacteria, UTM, SEM

I. INTRODUCTION

In modern period concrete is considered to be backbone of all the construction projects. However the major problem with concrete being low tensile strength of it makes it more prone to progression in cracks resulting in low strength and less durability. These cracks decrease the quality and durability of concrete. Micro cracks allow the water entrance and other impurities like sulphate, chloride ions in concrete. With the entry of water and harmful chemicals, concrete deteriorates and also embedded reinforcement gets corroded (Reinhardt and Joss, 2003). This deterioration of concrete along with reinforcement results in high cost for maintenance. The strong negative effect of cracks and the maintenance cost involved have increased the importance of assessment; repair of structural cracks. As there can be cracks in any type of structure which can lead to structural failure, therefore cracks in structure cannot be ignored. A continuous effort through research and development programmes all over the world is being made to find a solution for the cracks in concrete. Hence a tough challenge was in front of the civil engineers to develop a concrete that can self-remediate structural cracks and make structures more durable and strong.

Henk M. Jonkers at el, 2007 developed a self-healing bacterial concrete that senses damage done to it and then reacts to cure itself without any human intervention. Bacteria in concrete produces limestone when exposed to water and calcium lactate food. The accumulation of limestone on the surface of cracks helps in healing of cracks. Naturally only a limited crack width of 100μm can be repaired (Neville, 2002) but with the use of self-healing method it is possible to seal the maximum crack width of about 300 μm (Jonkers et al., 2010). This Autonomous crack healing increases the structure durability and also decreases the manual maintenance required for the structural stability. Also this self-healing technique reduces the use of non-eco-friendly repair materials and increases compressive strength of concrete, hence saving the environment and economy (Vekariya and Pitroda, 2013). In short, it was analyzed from past studies that once water rushes through freshly formed cracks, inactive bacteria immobilized in concrete mix become metabolically active, then these active bacteria will heal the cracks by precipitation of calcite crystals, thus preventing further ingression of water and other impurities. Different bacteria are used in concrete for different purposes however. The most efficient bacterial agents used for self-healing appear to be aerobic, alkaliphilic and spore-forming bacteria of genus Bacillus (Jonkers et al, 2010). As we know cement and water when mixed together create a high value of pH up to 13, which is very harmful environment for life of microorganisms. Hence most of microorganisms die in highly alkaline environment with 10 or more as pH value. So the bacteria commonly found in soil which belong to the family of Genus Bacillus were found to sustain in such high-alkaline environment. Bacteria namely Bacillus Subtilis was chosen in this study as it met the demanded criteria for surviving in tough environment. It is a gram-positive bacteria which has an ability to form spores when subjected to unfavorable conditions. The test to check temperature sustainability of Bacillus Subtilis in bio concrete was performed at varying temperatures (A.T. Manikandan et al, 2001). The results pointed out that Bacillus Subtilis was found to be alive at -3º C low temperature to 80ºC high temperature. On the other hand calcium lactate food was used as a nutrient supplement for bacterial activities as calcium lactate is the better choice because it starts off dissolving during the mixing phase and does not intervene with concrete's setting time (Jonkers et al, 2010).

Fig. 1: Self-Healing Concrete

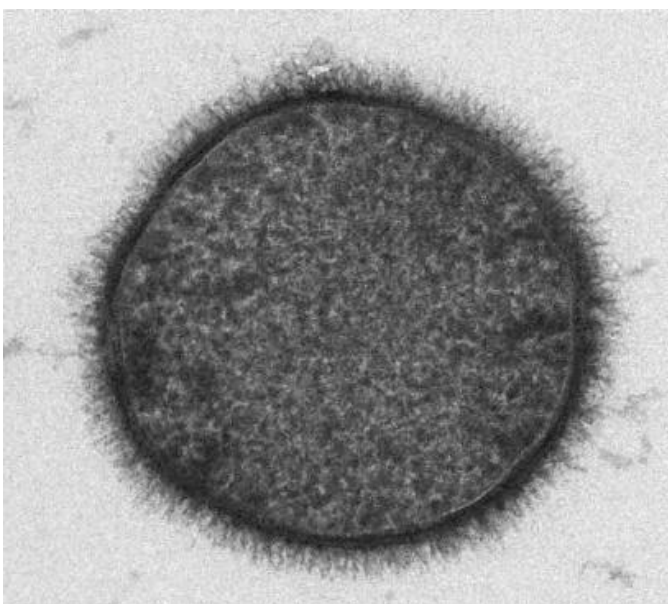

Fig. 2: Microscopic View of Bacillus Subtilis

II. SELF HEALING MECHANISM

Generally, bacteria are incorporated in inactive form along with the nutrient compound which stays inactive until cracks are produced allowing water penetration in the concrete. Bacteria becomes metabolically active when it gets addressed with water and begins to feed on nutrient compound. Calcium carbonate is produced as the result of metabolic action of bacteria on calcium lactate, which seals the crack, restricting the further water penetration in concrete hence increasing durability of concrete. The process of healing of crack with the help of bacteria is illustrated in the figure 1.3 At the instant when a concrete structure gets damaged and water starts off to leak in between the cracks of it, the microbial spores flourish on getting in contact with the water and supplements. As the microorganisms gets activated, the solvent calcium lactate is changed over to insoluble limestone. The limestone sets up over the fractured surface, ultimately fixing it up. Figure 3 shows how the bacteria gets activated by coming in contact with water and also portrays how an activated bacteria reacts with the precursor or nutrient compound and forms a base of calcium carbonate called as Limestone to fill the cracked surface.

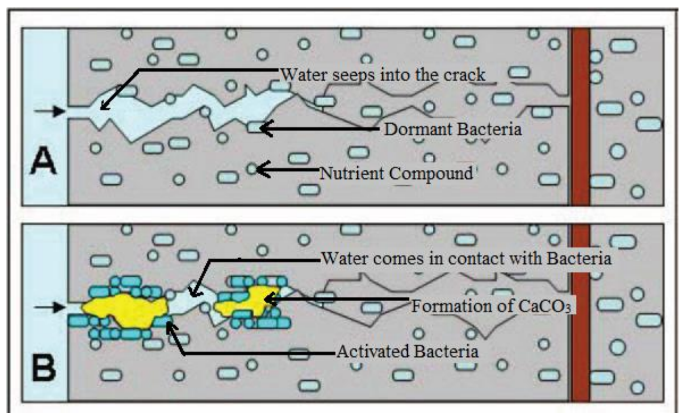

Fig. 3: Activation of bacteria by water

III. NECESSARY CONDITIONS FOR SELF HEALING

There are generally five important conditions for the occurrence of self-healing of cracks which are as follows;

- Presence of water: It is the most basic and essential condition to facilitate in the healing of the cracks (Qian et al., 2009).
- Presence of chemicals: Certain chemical species in examples of carbonate ions, bicarbonate ions and free dissolved calcium ions, play a serious role for the facilitation of healing mechanisms (Van der Zwaag, 2007).
- Width of crack: It is another essential condition which is actually related directly to self-healing

efficiency of cementious materials. Normally crack width below the range of 50 µm to 150 µm is suitable to for self-healing effect to take place (Yingzi et al., 2009). However, smaller cracks will require less self-healing products to fill the crack easily as compared to large ones.

- Water Pressure: If the water flows quickly through the cracks, the self-healing effect of cracks will not take place. Therefore the water pressure should not be too wild. It depends on ratio between height of water and structural thickness (Schlangen, 2007).
- Stability of cracks: In order to make sure that the cracks does not get damaged again, the crack should be in a stable condition with the constant crack width instead of varying with time (Hua, 2010)

IV. ROLE OF BACTERIA

The most efficient bacterial agents used for self-healing appear to be aerobic, alkaliphilic and spore-forming bacteria of genus *Bacillus* (Jonkers et al, 2010) and also similar genera like Sporosarcina. In the previous researches *Sporosarcina pasteurii* and *Bacillus Subtilis* were the most often used bacteria. While *Bacillus psuedofirmus*, and *Bacillus cohnii* have also been tested to some extent. An involvement in precipitation of calcite was found to be linked with various sub species of *Bacillus Subtilis*. However, on the contrary it was noticed that the bacterial microorganism namely *Escherichia coli* has no role at all to play in improving the healing property. From this, it can be proposed that the selection of micro-organism plays relatively a huge role in the improvement of compressive strength (Jonkers, 2007). The bacteria can be practiced in concrete for different purposes as stated under:

Table 1: Bacteria used in concrete for different purposes

Type of Bacteria	Application	Metabolism
Bacillus Cereus	Biological mortar	Oxidative deamination of amino acids
Bacillus Subtilis	Concrete crack remediation	Hydrolysis of Urea
Bacillus Sphaericus	Concrete crack remediation, for surface treatment	Hydrolysis of Urea
Bacillus Subtilis	Bacterial concrete	Hydrolysis of Urea
Bacillus Subtilis	Crack healer in concrete	Oxidative deamination of amino acids
Bacillus Pasteurii	Crack healer in concrete	Hydrolysis of Urea

V. ROLE OF NUTRIENT COMPOUND

As we know nutrients are like food and the main sources of energy for bacteria, therefore it becomes compulsory to provide proper and sufficient nutrient for self-healing bacteria. Nutrients are generally supplied to bacteria either during culture stage or stage of treatment majorly depending on the type of application. The common nutrients to be served to bacteria are CO_2, N, P, K, Mg, Ca and Fe (Mitchell and Santamaria, 2005). A Number of other researches have been performed on calcite precipitation using different calcium sources e.g. calcium chloride, calcium lactate, calcium glutamate, calcium acetate and calcium nitrate.

It has been reported that calcium lactate is the better choice because it starts off dissolving during the mixing phase and does not intervene with concrete's setting time (Jonkers et al, 2010). On the contrary calcium chloride as a nutrient source is not considered as ideal because the chloride ions are dangerous for the concrete reinforcement (Jonkers and Schlangen, 2009). However, more studies are required to identify the effects from different types of nutrients used for growing calcite producing microorganisms and their influence on survival, growth and calcite crystal formation.

VI. TEMPERATURE SUSTAINABILITY OF BACTERIA

Bacteria namely *Bacillus Subtilis* was chosen in this study as it met the demanded criteria for surviving in tough environment. It is a gram-positive bacteria which has an ability to form spores when subjected to unfavorable conditions. The protection is ensured by formation of spores against immense mechanical pressure and alkaline surroundings which makes it preferable selection. Members belonging to genus bacillus produce spores which can remain inactive for the maximum ages of 200 years (Schlegel, 1993). The test to check temperature sustainability of *Bacillus Subtilis* in bio concrete was performed at varying temperatures by A.T. Manikandan et al, 2001 and the results are tabulated in Table 2. The results pointed out that Bacillus Subtilis was found to be alive at -3º C low temperature to 80ºC high temperature.

Table 2: Temperature sustainability of Bacillus Subtilis

Temperature	Bacteria Condition
-3°C	Alive
10 °C	Alive
20 °C	Alive
30 °C	Alive
40 °C	Alive
50 °C	Alive
60 °C	Alive
70 °C	Alive
80 °C	Alive
90 °C	Dead

VII. OBJECTIVES OF PRESENT STUDY

The Present work includes:

- To study the techniques involved in the mixed of bacteria into the concrete.
- To investigate the efficiency of *Bacillus subtilis* in Concrete
- To study the effect of Self-healing agent on the mechanical properties such as compressive strength of the concrete specimen.
- To evaluate the efficiency of self-healing concrete by conducting water absorption test, Ultrasonic Pulse Velocity test
- To study the micro structure of the concrete specimens using Scanning Electron Microscope (SEM).
- To develop mathematical/statistical models based on experimental results to quantify self-healing of concrete and also to determine improvement of properties in concrete by inclusion of bacteria

VIII. LITERATURE REVIEW

V. Ramakrishnan, R.K.Panchalan, and S.S.Bang (2001) has published a paper on Bacterial Concrete named as Concrete for the Future in which a very common bacteria from soil was taken into consideration to produce crystals of calcite. This technique is immensely preferable because the precipitation of minerals is induced by the help of microbial activities and is environmental friendly. The effect of this technique was found out by drawing a comparison of the compressive strength and stiffness of both bacteria healed cracked samples conventional concrete samples (without bacteria). Experimental tests were done to evaluate the capacity of cracked beams remediated with different concentrations of bacteria to regain strength. The same paper releases durability results of a cement mortar beams mixed with bacteria, alkali exposed, and sulphate and freeze-thaw prone environments. Different bacterial concentrations were practiced for the tests. It was pointed out from tests that stiffness, compressive strength, rupture modulus and concrete durability improved. Scanning electron microscope was made in use to study the role of MICP in strength and durability improvement of concrete.

C. C. Gavimath, B. M. Mali, V. R. Hooli, J. D. Mallpur, A. B. Patil, D.P.Gaddi, C.R. Ternikar, (2015) has published a paper on application of bacteria in order to get improvement in concrete strength in which B.sphaericus is used to accelerate the strength of cement concrete. They have tried to mix inactive bacteria in the concrete so that it may add to the concrete strength. Water enters the concrete and activates the inactive bacteria which provides concrete strength through calcite precipitation process. But Concrete is dangerous place for common bacteria due to internal pH value being high but there are some bacteria forming spores which may be able to live in dangerous home and increase concrete’s strength and durability. In this study, it is found that by adding of Bacillus bacteria there will be no negative effect on strength i.e. concrete’s compressive and split tensile strength.

Kantha D.Arunachalam, K.S. Sathyanarayanan, B.S. Darshan, R.Balaji Raja (2011) has published an article on Bio sealant properties of Bacillus Subtilis bacteria in which they say Bacillus Subtilis bacteria was a underrated bacteria which has properties same as that of bacteria able of precipitating of calcium carbonate crystals. Very less use of this microorganism in remediation aspect was done by researchers. Bacillus Subtilis was cultured and temperature was set at 37°C and pH was value balanced at 7.4. Bacillus Subtilis Growth curve revealed log phase between 4-11 hours and 21 hours later the growing of bacteria was sighted.

Titration of EDTA was done to find $CaCO_3$ crystals and it was max at pH value 8. Atomic Force Microscopic analogy were done to analyze bacterial culture. The presence of calcite was confirmed in dry scrapes as well as bacterial concrete. In the closing of this study, the ability of Bacillus Subtilis concrete was well known.

Dr. Nele De Belie, Ghent University, Belgium, (**2013)** made public a paper on Self-Healing of Concrete and revealed during the presentation of his about, how buildings materials are consolidated and repaired and with inclusion of bacteria, concrete's self-healing is possible. Micro-organisms play a compulsive role in mineral conversions and structural element exchange. In the bacteria related treatment, the concentration of solution used was equimolar of 20g/l of urea & $CaCl_2$ and then dried @ 28ºC for 3 days. B. Sphaericus was taken into account and to safeguard the bacteria from dangerous alkalinity of concrete, they were immersed in gel of Silica Solution. The treatment was done to samples placed on rods made of plastic in the solution of healing where the level of liquid above lower side was about 10 mm. Formation of biocers could possibly help in remediation of cracks.

B.Naveen and S.Sivakamasundari, (2016) cemented a paper on the impact on self-healing component of cement by means of microbially produced calcite crystals. In the same paper crack repaired was achieved through a natural treatment in which culture of Bacillus sphaericus consolidated in a gel grid and a calcium source was given. They have utilized silica gel to secure the microscopic organisms against the pH in solid which was observed to be possibly as $CaCO_3$ crystals which grew inside the grid. The improvement in precious stones in the form of improved solidness was sighted by process of Precipitation of Calcite crystals.

Chintalapudi Karthik and Rama Mohan Rao, (2016) have put forth a paper SHC Properties. In this paper a bacteria importantly Bacillus Subtilis bacteria found to be aerobic is made in use. $CaCO_3$ precipitation is achieved by the help of Bacillus Subtilis when ammonium and carbonate gets converted into $CaCO_3$ crystals by converting of in high alkaline environment. The formation of crystals of calcium carbonate by means of precipitation was viewed using Scanning Electronic Microscope. The whole process resulted in a biological based crack sealing technique. Crack sealing was achieved by treating cement composites biologically, decrease in permeability of water. Also the profits of including biological composites of cement comprised of lowering of maintenance costs & costs of repair and hence durability of the structures was considerably raised.

Day J L et al (2003), this paper points out the consequences of an efficient method in solid break remediation of breaks in solid by use of calcite accelerated by microbes. A special kind of soil bacterium i.e. Bacillus pasteurii was used to accelerate calcite precipitation. The necessary criteria for this application is that urease generated by microbes hydrolyzes urea so that smelly salts and carbon dioxide are produced, and the discharge of alkali in surroundings relatively maintains pH, insoluble calcite being collected. To protect the cells from the high pH value of cement, the microbes were mixed in polymers, lime, silica smoke and fly fiery debris then after that solid crack healing was connected. Microbially upgraded crack healing was examined closely by looking at the qualities like compressive strength of the treated bacterial specimen and those of the conventional specimen.

De Belie and De Muynck (2008) studied the effect of crack healing using bio deposition. Bacillus Sphaericus culture was used in this study. In order to study it standardized cracks of 0.3 mm were created by incorporating thin copper plates in concrete and pulling them out one day after casting or by performing split tensile tests on samples wrapped in fiber reinforced polymer. Cracked samples were cured in nutrient solution containing $CaCl_2$ or $Ca(NO_3)_2$. Bacteria were immobilized in silica gel and introduced in the concrete samples for protection. Visual inspection, ultrasound testing and water permeability tests were conducted. Visual inspection and ultrasound tests confirmed crack healing up to 0.3 mm in width and 10 mm in depth. Water permeability tests showed that 0.6 mm wide cracks were healed through the process of bio deposition.

Ramachandaran et al., (2001) examined the role of micro-organisms in healing of cracks and their relative effect on compressive strength in mortar samples. Micro-organisms used in this research were Bacillus Pasteurii. For this purpose Portland cement mortar specimens and beams of standard dimensions were produced. Solution of urea and $CaCl_2$ was used for placing of samples in it for about 28 days. Compressive tests were performed to find out the compressive strength of samples. In addition to it, the healing efficiency of cracks was analyzed by Semi Electron Microscopy and X-Ray Diffraction test. Results showed that at lower concentrations B.Pasteurii increased the strength of compression of mortar sample.

IX. RESEARCH METHODOLOGY

MATERIALS: The concrete utilized in the test program consisted of following constituents

- Ordinary Portland Cement (53 Grade)
- Graded fine aggregates
- Graded coarse aggregates
- Water

- Bacteria – Bacillus Subtilis

Table 3: Physical and Chemical Properties of Materials

Material	Specific Gravity	Bulk Density (kg/m^3)	Weight Basis (Kg)
Cement	3.14	1450	400
Fine Aggregate	2.7	1650	700
Coarse Aggregate	2.7	1575	1080
Water	-	1000	180

EQUIPMENTS

1. Universal testing Machine (UTM)
2. Semi Electron Microscope (SEM)
3. Ultrasonic Pulse Velocity (UPV) Apparatus

[1] Universal Testing Machine (UTM): Universal testing machine generally known as universal tester or Tensometer is designed specially to evaluate strength of tension and compression features of materials, products and components. As the 'Universal' suggests that it can be used for many standard tensile tests, compressive tests, pull-out tests, bending tests etc. The various materials to be tested by UTM are concrete, steel, cables, springs, steel wires, steel ropes etc. By using UTM, we can draw stress-strain graph. For that UTM gives the value of load applied vs their respective displacement. From the observed values, a load deflection graph is obtained. X-axis represents displacement and Y-axis represents load applied. From load-deflection graph, we can determine stress-strain relationship, modulus of Elasticity, yield strength of the material.

Concrete cubes of size 150mm×150mm×150mm were cast with different concentrations of bacterial content i.e. 0, 20, 40 and ml. The specimen after 24 hours were demoulded and were tested for compressive strength by UTM of capacity 200kN after 7 days, 28 and 56 days of curing in order to investigate the effect of healing agent on the strength of concrete with age. The sample is placed on the center of the base plate of machine as shown in Fig. 4 and the load is applied slowly at the rate of 140 KN per minute till the specimen fails. The Ultimate load at which failure of cube occurs was taken as final reading. Tests were conducted on triplicate specimen and average strength was recorded by comparing 3 samples for different specimen viz. conventional, 20ml, 40ml and 60ml bacterial concrete at the ages of 7 days, 28 days and 56 days.

Fig. 4: UTM under working condition

[2] Scanning Electron Microscope (SEM): A microscope with high magnification making use of a focused beam of electrons to create images of sample of high quality, both cross-sections & top-down. Selected specimens were examined by Scanning Electron Microscopy and Energy Dispersive Spectroscopy to analyze the microstructure and chemical constituents of products and constituents of self-healing to observe the process of healing.

(SEM JEOL JSM- 6480LV) at the desired magnification levels is used in this study for inspecting microstructural morphology of solid objects at very high levels of magnification. The specimen extracted from the concrete cubes after two months of curing were of the size 25mm square with thickness of 5mm. The polish with 120#, 220#, 320# and 600# silicon carbide was done to the specimen using a rotating grinder. Further polishing was executed with aluminum powder of size 100, 50 and 10 micron on the glass plate. After polishing, the specimen were dipped in acetone solution so that residual silica film may be removed from their surfaces. The selected specimen of each mix were put forth for SEM (JEOL JSM- 6480LV) analysis at magnification of 2 microns, 5 microns and 10 microns. Back scattered Electron Imaging (BES) was used for electron micrography. Also healed samples of cracks were cut into small cubes and were completely oven dried at the temperature of 50^{o}c for three consecutive days before the SEM observation. An Energy Dispersive Spectrometer connected with SEM was used to detect the components of precipitation.

Fig. 5: Setup of SEM

[3] **Ultrasonic Pulse Velocity Testing Apparatus:** The measurement of UPV requires apparatus that includes two transducers i.e. transmitting and receiving. Vibrating pulse is transmitted by the transmitting transducer at an ultrasonic frequency which is held in the close contact of surface of the concrete specimen undergoing test procedure. After vibrating pulse is made to pass through the concrete, the vibrations are received and converted into an electronic signal by the transducer which receives vibrations to transmit ultrasonic waves (frequency 10 to 150 kHz) directly through concrete specimen. It measures the path length and travel time of an ultrasonic pulse passing through the concrete. Generally a denser material will have faster velocity.

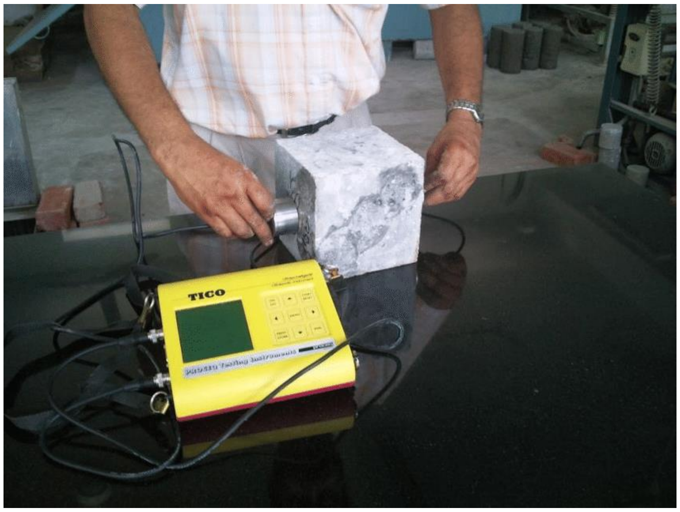

Fig. 6: UPV Testing Setup

X. RESULTS AND DISCUSSION

Following results interpreted from computerized UTM for compressive strength of four different set of mixes @7 days, 28 days and 56 days.

Table 4: Compressive Strength results @7days

Mix Name	Type of Concrete	Compressive Strength of Concrete after 7 days		
		Sample 1	Sample 2	Sample 3
A0	Conventional	22.2	22.5	22.9
A1	20ml	27.4	32.5	32,7
A2	40ml	34.1	33.4	34.5
A3	60ml	34.2	38.2	34.6

Table 5: Compressive Strength results @28days

Mix Name	Type of Concrete	Compressive Strength of Concrete after 28 days		
		Sample 1	Sample 2	Sample 3
A0	Conventional	32.9	34.6	37.8
A1	20ml	47.7	48.9	49.8
A2	40ml	51.2	55.1	55.4
A3	60ml	54.4	54.8	56.4

Table 6: Compressive Strength results @56days

Mix Name	Type of Concrete	Compressive Strength of Concrete after 56 days		
		Sample 1	Sample 2	Sample 3
A0	Conventional	34.1	37.2	38.9
A1	20ml	49.7	52.1	51.3
A2	40ml	53.8	57.2	58.3
A3	60ml	55.9	56.8	59.2

From the above results it can be observed that direct incorporation of more bacillus subtilis shows huge improvement in compressive strength up to a certain point and it is mainly due the calcium carbonate (produced by bacteria) which develops the internal structure of concrete mix more stable and compact.

Table 7: Water Absorption Test Results

Conventional Concrete	Bacterial Concrete		
	20ml	40ml	60ml
2.264	1.281	1.258	1.460
2.543	1.035	1.312	1.255
2.538	1.728	1.032	1.242

It is evident from table 4 that the specimen with bacteria showed a considerable decrease in water absorption because of the fact voids being filled by $CaCO_3$ precipitation. Out the mixes, specimen with bacterial concentration 20ml showed the maximum reduction of water absorption because of the fact bacteria being present in adequate concentration. Hence bio concrete reduces the further ingress of harmful chemicals.

Table 8: Calculated UPV Results

S. No.	Property of Concrete	RCC Member	Size Mm	Time Macro Sec	UPV Km/sec
1	Conventional Concrete	Cube	150	29.4	5.12
2	Bacterial Concrete 20ml 40ml 60ml	Cube Cube Cube	150 150 150	29.8 28.4 31.3	5.08 5.30 5.10

High pulse velocity readings generally indicate high quality concrete. Better correlations can be obtained between cube compressive strength and pulse velocity. These relations enable to predict the strength of structural concrete within ±20 %. The results obtained after conducting the UPV test are presented below in table 5. These results reveal that of all samples tested the travel time of 40ml bacterial concrete found to be much lesser, again velocity is also higher. As we know higher velocities indicate dense concrete which is indication of high quality. Thus, Bacteria increases quality of concrete.
Figure 7 shows the results acquired through self-healing measurements in already- cracked specimen of different mixes after 60 days of curing. It can be spotted that Mix 4 with 60ml bacterial concentration is presenting supreme healing of 0.64 mm consequently higher than all other mixes. The healing exhibited by Mix 3 specimens was 0.51 mm, which is higher than healing of 0.25 mm showed by Mix 2 specimens. While Mix 1 showed negligible healing effect.

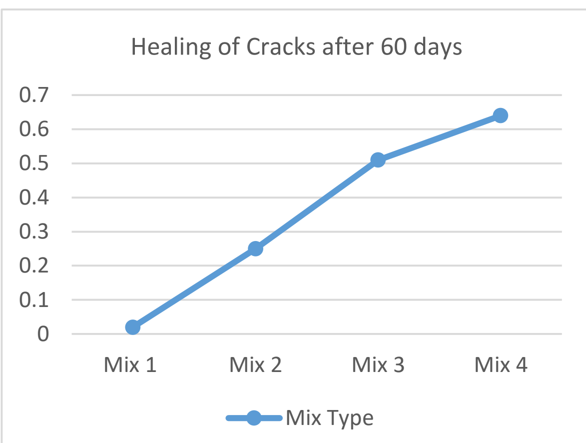

Figure 7: Healing effect of different mixes after 60 days

XI. CONCLUSIONS

Based on the above study, the following observations are made regarding behavior of concrete under the influence of Bacillus Subtilis as a self-healing:

- While other bacteria as proven from previous studies do not show any credible results in the improvement of compressive strength when incorporated directly with concrete. However on the other hand Bacillus subtilis presented extremely good results in the overall compressive strength improvement irrespective of mixing technique involved.
- Compressive strength was found to be increased with bacterial incorporation and this increase is mainly due to deposition layer of microbially induced calcium carbonate within the pores and surface of concrete.
- UPV results also suggested better healing characteristics for bacteria incorporated specimens compared to the conventional ones. It was noted with the inclusion of bacteria in concrete, the concrete becomes denser and quality of concrete improves.
- UPV measurements also indicated that most of the crack filling occurred during the first and second month of healing period. However, after two months of healing the rate of crack filling was significantly reduced. One possible reason could be the lack the calcium lactate food for the bacteria was finished after 2 months.
- SEM analysis on Bacterial concrete specimens visually proved that the bacteria in concrete can produce large mineral amount which can potentially seal freshly formed cracks. It was also observed from Mix 4 that the cracks with a width of more than 100µm were completely sealed by $CacO_3$ precipitation. At the same instant, almost negligible precipitation or a thin lining on the crack wall were observed in the conventional concrete
- One of the main objectives of this study was to check whether bacteria based self-healing will enhance mechanical properties and bonding strength of the concrete mixes. The results showed that bacterial based SHC can accomplish our objective in terms of compressive strength and bonding strength.
- The calcite precipitation by bacteria leads to decrease of capillary pores by clogging pores, which reduces the entrance of harmful chemicals in concrete and increases the durability. Use of bacteria in concrete composites may be highly desirable because the calcite precipitation induced by metabolic activities is pollution free.
- The bacterial based self-healing technique can be employed to concrete structures that are not easily accessible for maintenance and repair e.g. underground structures, bridges and dams

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