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Effect of Microbiologically Induced Calcite Precipitation in Concrete with 'Bacillus Halodurans'.

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Abstract: *Concrete has been widely used for many years as a composite material for various types of structures. One of the major weaknesses of concrete is that it cannot withstand tension that can cause cracks easily and reduce the service life of the structure. Calcium carbonate is one of the most well known mineral that bacteria can deposit by the phenomenon called bio cementation or microbiologically induced calcite precipitation. (MICP). To ensure that, this study presents the effect of bacillus halodurans, bacteria on the strength and durability of M_{20} grade concrete. Tests were performed for strength and durability criteria's. The test results showed that addition of bacteria improves strength and durability appreciably.*

Keywords: *Bacillus halodurans, Calcium carbonate, Concrete, Cracks, Durability, Strength, MICP.*

1. INTRODUCTION

Humans have ability to precipitate minerals in the form of bones and teeth continuously. This ability is not only confined to human beings even bacillus species, a common soil bacterium can continuously precipitate calcite. This phenomenon is called microbiologically induced calcite precipitation. The 'bacterial concrete' is an innovative approach to enhance the durability of concrete by embedding bacteria in to the concrete that is able to continuously precipitate impermeable calcite on the surface of existing concrete. Calcium carbonate precipitation, a wide spread phenomenon among bacteria, has been investigated due to its wide range of scientific and technological implications.

1.1 Microbiologically Induced Calcite Precipitation

Like other bio mineralization processes, calcium carbonate precipitation can occur by two different mechanisms: BIOLOGICALLY CONTROLLED OR INDUCED. In biologically controlled mineralization, the organism controls the process, i.e., nucleation and growth of the mineral particles, to a high degree. The organism synthesizes minerals in a form that is unique to that species, independently of environmental conditions (Lowenstean & Weiner) [1]. Examples of controlled mineralization are magnetite formation in magnetotactic bacteria (Bazylinski) [2] and silica deposition in the unicellular algae coccolithophores and diatoms, respectively. However, calcium carbonate production by bacteria is generally regarded as "induced", as the type of mineral produced is largely dependent on the environmental conditions (Rivadeneyre) [3].

Calcium carbonate precipitation is a rather straightforward chemical processes governed mainly by four key factors:

a) The calcium concentration
b) The concentration of dissolved inorganic carbon (DIC)
c) The p^H
d) The availability of nucleation sites

1.2 Bacterial Concrete

(V.Ramakrishnan et al) [4] First introduced the concept of bacterial concrete. A novel technique is adopted in remediating cracks and fissures in concrete by utilizing microbiologically induced calcite (CaCO3) precipitation (Stocks – Fischer et al.,) [5]. Bacillus *halodurans*, a common soil bacterium can induce the precipitation of calcite. As a microbial sealant, CaCO3 exhibited its positive potential in selectively consolidating simulated fractures and surface fissures in granites and in the consolidation of sand. Microbiologically induced calcite precipitation is highly desirable because the calcite precipitation induced as a result of microbial activities, is pollution free and natural. The technique can be used to improve the compressive strength and stiffness of cracked concrete specimens. The pioneering work on repairing concrete with MICP is reported by the research group of Ramakrishnan V and others at the South Dakota School of Mines & Technology, USA.

MICP is a process by which living organisms or bacteria form inorganic solids. Bacillus *halodurans*, a common soil bacterium, can induce the precipitation of calcite. Under favorable conditions Bacillus *halodurans* which is used in concrete, can continuously precipitate a new highly impermeable calcite layer over the surface of the already existing concrete layer. The precipitated calcite has a coarse crystalline structure that readily adheres to the concrete surface in the form of scales. In addition to the ability to continuously grow upon itself, it is highly insoluble in water. It resists the penetration of harmful agents (chlorides, sulphates, carbon dioxide) into the concrete thereby decreasing the deleterious effects they cause. Due to its inherent ability to precipitate calcite continuously, bacterial concrete can be called a ―Smart Bio Material for repairing concrete. The MICP comprises a series of complex biochemical reactions. It is selective and its efficiency is affected by the porosity of the medium, the number of cells present and the total volume of nutrient added. The phosphate buffer or urea-CaCl2 has been found effective as nutrients. The bacteria precipitate calcite in the presence of nutrients. The optimum pH for growth of *B. pasteurii*is around 9. The alkaline environment of concrete with pH around 12 is the major hindering factor for the growth of bacteria. However, *B. pasteurii*has the ability to produce endospores to endure an extreme environment, as observed by (V. Ramakrishnan et al) [6] and the research team.

The microbial modified mortar or concrete has become an important area of research for high-performance construction materials. (Ghosh et al) [7]. investigated the effects of incorporating a facultative anaerobic hot spring bacterium on the microstructure of a cement–sand mortar. Environmental scanning electron microscopic (ESEM) views and image analysis (IA) of the bacteria modified mortar (thin-section) showed significant textural differences with respect to the control (without bacteria) samples.

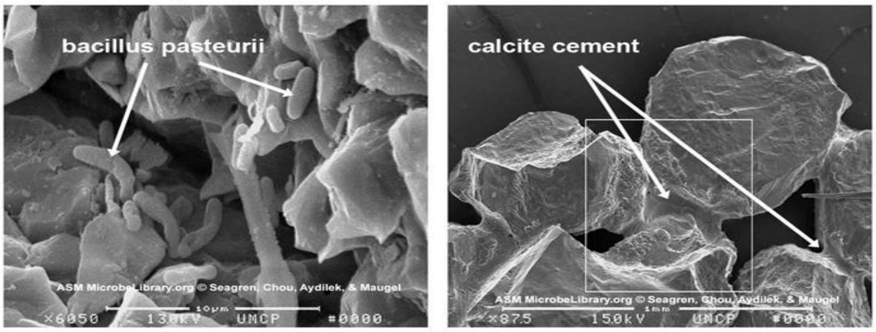

Fig 1.1Magnified image of Rod shaped impressions consistent with the dimensions of B. pasteurii, spread around the calcite crystals.

2. SCOPE AND OBJECTIVES

2.1 Scope of the present investigation

Crack widths in concrete structures should be limited, mainly for durability reasons. If cracks widths are large, the cracks need to be repaired or extra reinforcement is needed in the design. If a method could be developed to automatically repair cracks in concrete, this would save an enormous amount of money, both on the costs of injection fluids for cracks and also on the extra steel that is put in structures only to limit crack widths. A reliable self-healing method for concrete would lead to a new way of designing durable concrete structures which is beneficial for national and global economy. The Bacterial Concrete can be made by embedding bacteria in concrete that are able to constantly precipitate calcite. This phenomenon is called microbiologically induced calcite precipitation. As per the present investigation it has been shown that under favorable conditions for instance *Bacillus halodurans*, a common soil bacterium, can continuously precipitate a new highly impermeable calcite layer over the surface of an already existing concrete layer. Detailed investigations carried out by V. Ramakrishnan have shown that *Bacillus pasteuri* bacteria can be used for improving the strength and durability of concrete. However, not much investigation is carried out in India for producing bacterial concrete. Keeping this in view, the present experimental investigations have been taken up to study the strength and durability of Ordinary grade (M20) concrete with and without addition of bacteria *Bacillus halodurans*.

2.2 Objectives of the Present Investigation

The main objectives of the present experimental investigation are,

1] To study the compressive strength and split tensile strength of concrete. (With and without addition of bacteria)

2) To study the stress-stain behavior of concrete. (With and without addition of bacteria)
3) To study the flexural behavior of concrete. (With and without addition of bacteria)
4) To study the water absorption of concrete. (With and without addition of bacteria)
5) To study the chloride penetration of the concrete. (With and without addition of bacteria)
6) To study the weight loss and strength loss due to acid attack (H_2SO_4). (With and without addition of bacteria)

3. EXPERIMENTAL INVESTIGATION

3.1Materials Used and Their Properties

3.1.1 Cement

Ordinary Portland cement of 53 grade, available in local market was used in the investigation. The cement used for all tests is from the same batch. The cement used has been tested for various properties as per IS: 4031-1988 and found to be conforming to various specifications of IS: 12269-1987. The physical properties of cement are shown in Table 3.1.

Table – 3.1 Physical Properties of Cement

Sl No	Characteristics	Experimental Value
1.	Standard consistency	28
2.	Setting time	
	1) Initial	1) 90 mins
	2) Final	2) 410 mins
3.	Specific gravity	3

3.1.2Coarse Aggregate

Crushed angular granite from local quarry was used as coarse aggregate. The cleaned coarse aggregate is chosen. The size of the aggregate used was below 20mm. The physical characteristics were tested in accordance with IS: 2386 – 1963. The physical properties of coarse aggregate are shown in Table 3.2.

Table – 3.2 Physical Properties of Coarse Aggregates

Sl No	Characteristics	Experimental Value
1.	Specific gravity	2.86
2.	Water absorption	0.46%

3.1.3Fine Aggregate

The locally available river sand was used as fine aggregate in the present investigation. The fine aggregate was tested for various properties such as specific gravity, sieve analysis, fineness modulus etc. in accordance with IS: 2386-1963. The physical properties of fine aggregate are shown in Table 3.3.

Table – 3.3 Physical Properties of Fine Aggregates

Sl No	Characteristics	Experimental Value
1.	Specific gravity	2.66
2.	Fineness modulus	2.2
3.	Grading zone	Zone III

3.1.4Water

Water used for mixing and curing was fresh potable water, conforming to IS: 3025 – 1964 part 22, part 23 and IS: 456 – 2000.

3.1.5 Nutrient Broth

Peptone, glucose, sodium chloride, beef extract were mixed with distilled water. Those chemicals were collected from environmental laboratory.

3.1.6 Bacteria

Bacillus *halodurans*, a laboratory cultured bacterium was used.

3.2Mix Design

Mix design can be defined as the process of selecting suitable ingredients of concrete such as cement, aggregates, water and determining their relative proportions with the object of producing concrete of required strength, workability and durability as economically as possible. The purpose of designing can be seen from the above definitions. The first objective is to achieve the stipulated strength and durability. The second objective is to make the concrete in the most economical manner. The grade of concrete used in the present investigation was M20. The mix was designed using IS: 10262-1982. The mix design and the proportions of the mixes of Materials required for 1 cubic meter of concrete in ordinary grade concrete is 1:1.77:3.40 and w/c ratio is 0.5

3.3 Growth of Bacteria –Bacillus *halodurans*

The pure culture was bought from MTCC, Chandigarh and was maintained constantly on nutrient agar slants. It forms irregular dry white colonies on nutrient agar plate. Whenever required a single colony of the culture was inoculated into nutrient broth of 25 ml in a 100 ml conical flask and the growth conditions were maintained at 37°C temperature.

3.4 Casting of Specimens

Based on the mix design for M20 grade concrete, specimens were cast with and without addition of bacteria and cured for 28 days in water. Bacteria were added by means of replacing potable water by bacterial water for the casting of bacterial concrete specimens. Casting and curing of specimens is shown in Figure 3.1. The number of specimens cast is given in Table 3.4

Fig 3.1.a Casting of Cubes

Fig 3.1.b Casting of Cylinders

Fig 3.1.c Casting of Prisms

Fig 3.1.d Curing of Specimens

Fig 3.1 Specimens with Fresh Concrete and Curing

Table 3.4 Number of Specimens Cast

Type of Tests	**No. of Cubes (100mm)**		**No. of Cylinders (100mm dia)**		**No. of Prisms**		**No. of Cylinders (150mm dia)**	
	W.B	W.O.B	W.B	W.O.B	W.B	W.O.B	W.B	W.O.B
Compressive	6	6	-	-	-	-	-	-
Split tensile	6	6	-	-	-	-	-	-
Stress – Strain	-	-	-	-	-	-	6	6
Flexural	-	-	-	-	6	6	-	-
Water absorption	3	3	-	-	-	-	-	-
Rapid chloride penetration	-	-	3	3	-	-	-	-
Acid resistance	3	3	-	-	-	-	-	-

3.5 Mechanical properties

3.5.1 Compressive strength test

After 28 days of continuous curing, the cubes are taken out and they are exposed to atmosphere for some time and it is then taken for testing based on IS: 516 – 1959. The specimen testing in compression machine is shown in Figure 3.2

Fig 3.2 Compression Test on Cube

Calculation:

The measured compressive stress of the specimen was calculated by dividing the maximum load, applied to the specimen during the test by the cross-sectional area, calculated from the mean dimension of the section.

$$Pc = \frac{P}{A}$$

Where, P = Maximum compressive load in 'N'.

A = Cross-sectional area of the specimen in 'mm^2'.

The compressive strength for conventional and bacterial cubes was tabulated in Table 4.5 and Table 3.6 respectively. The comparison of results of conventional and bacterial concrete cubes are plotted in bar chart is shown in Figure 3.3

Table 3.5 Compressive Strength for Conventional Concrete Cubes.

Sl No	Days	Size of specimen in mm	Area of Specimen in mm^2	Weight of Specimen in gms	Load applied in kN	Compressive strength in N/mm^2	Avg Compressive N/mm^2
I	**Mix Ratio 1:1.77:3.40:0.5**						
1.	7	100x100x100	10000	2.489	236	23.6	23.4
2.	7	100x100x100	10000	2.500	248	24.8	
3.	7	100x100x100	10000	2.495	217	21.7	
4.	28	100x100x100	10000	2.429	281	28.1	28.43
5.	28	100x100x100	10000	2.430	287	28.7	
6.	28	100x100x100	10000	2.459	285	28.5	

Table 3.6 Compressive Strength for Bacterial Concrete Cubes

Sl No	Days	Size of specimen in mm	Area of Specimen in mm^2	Weight of Specimen in gms	Load applied in kN	Compressive strength in N/mm^2	Avg Compressive N/mm^2
I	**Mix Ratio 1:1.77:3.40:0.5**						
1.	7	100x100x100	10000	2.421	167	16.7	16.9
2.	7	100x100x100	10000	2.410	173	17.3	
3.	7	100x100x100	10000	2.466	168	16.8	
4.	28	100x100x100	10000	2.510	315	31.5	31.9
5.	28	100x100x100	10000	2.411	327	32.7	
6.	28	100x100x100	10000	2.442	315	31.5	

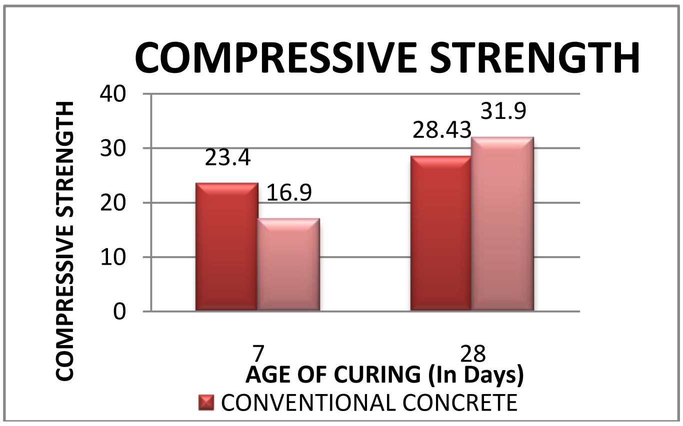

Fig 3.3 Compressive Strength for Conventional and Bacterial Concrete Cubes

3.5.2 Split Tensile Test

After 28 days of continuous curing, the cubes are taken out and they are exposed to atmosphere for some time and it is then taken for testing based on IS: 5816 – 1999. The specimen testing in compression machine is shown in Figure 3.4

Fig 3.4 Split Tensile Test on Cube

Calculation

The measured split tensile stress of the specimen was calculated by dividing the maximum load, applied to the specimen during the test by the diagonal area, calculated from the mean dimensions of the section.

$$P_t = \frac{2P}{\pi d l}$$

Where, P = Maximum compressive load in 'N'.
d = lateral dimension of the specimen in 'mm'.
l = length of the specimen in 'mm'.

The tensile strength for conventional and bacterial cubes was tabulated in Table 3.7 and Table 3.8 respectively. The comparison of results was plotted in bar chart for conventional and bacterial concrete cubes are shown in Figure 3.5.

Table 3.7 Split Tensile Strength for Conventional Concrete Cubes

Sl No	Days	Size of specimen in mm	Area of Specimen in mm^2	Weight of Specimen in gms	Load applied in kN	Compressive strength in N/mm^2	Avg Compressive N/mm^2
I	**Mix Ratio 1:1.77:3.40:0.5**						
1.	7	100x100x100	10000	2.510	46	2.93	3.10
2.	7	100x100x100	10000	2.481	50	3.18	
3.	7	100x100x100	10000	2.504	50	3.18	
4.	28	100x100x100	10000	2.484	59	3.75	3.96
5.	28	100x100x100	10000	2.467	61	3.88	
6.	28	100x100x100	10000	2.525	67	4.26	

Table 3.8 Split Tensile Strength for Bacterial Concrete Cubes

Sl No	Days	Size of specimen in mm	Area of Specimen in mm^2	Weight of Specimen in gms	Load applied in kN	Compressive strength in N/mm^2	Avg Compressive N/mm^2
I	**Mix Ratio 1:1.77:3.40:0.5**						
1.	7	100x100x100	10000	2.447	43	2.74	2.84
2.	7	100x100x100	10000	2.391	50	3.18	
3.	7	100x100x100	10000	2.394	41	2.61	
4.	28	100x100x100	10000	2.482	77	4.90	4.58
5.	28	100x100x100	10000	2.499	73	4.65	
6.	28	100x100x100	10000	2.470	66	4.20	

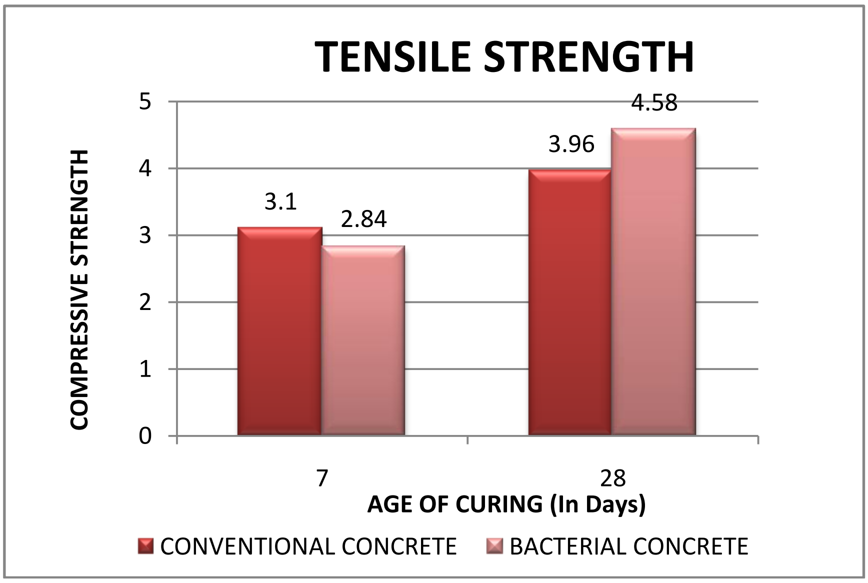

Fig 3.5 Split Tensile Strength for Conventional and Bacterial Concrete Cubes.

3.5.3. Flexural Strength Test

The Prism specimens of size (100 x 100 x 500mm) were cast in steel mold. Casting was conducted in three layers with each layer compacted by using electronic vibrator. The specimens remained in the steel mold for 24 hours and then it is de-molded and then placed in curing tank. After 28 days prisms were taken out and exposed to atmospheric condition so as to obtain dry surface. Two point loading was used to determine the flexural strength of the prism in accordance with the IS: 516 – 1959. The test setup is shown in Figure 3.6

Fig 3.6 Flexural Test on Prism

Calculation

The flexural strength of the specimen was expressed as the modulus of rupture f_{cr}. The measured modulus of rupture of the specimen was calculated as.

$$f_{cr} = \frac{pl}{bd^2}$$

Where, P = the maximum flexural strength in 'N'.
l = length of the specimen in mm.
b = breadth of the specimen in mm.
d = depth of the specimen in mm.

The flexural strength for conventional and bacterial prisms was tabulated in Table 3.9 and Table 3.10 respectively. The comparison of results was plotted in bar chart for conventional and bacterial concrete prisms are shown in Figure 3.7.

Table 3.9 Flexural Strength for Conventional Concrete Prisms

Sl No	Days	Size of Specimen in mm	Load Applied		Flexural Strength N/mm^2	Avg Flexural Strength N/mm^2
			Div	kN		
1.	7	500x100x100	28	11.67	5.83	5.06
2.	7	500x100x100	25	10.42	5.21	
3.	7	500x100x100	20	8.33	4.16	
4.	28	500x100x100	28	11.67	5.83	5.62
5.	28	500x100x100	28	11.67	5.83	
6.	28	500x100x100	25	10.42	5.21	

Table 3.10 Flexural Strength for Bacterial Concrete Prisms

Sl No	Days	Size of Specimen in mm	Load Applied		Flexural Strength N/mm^2	Avg Flexural Strength N/mm^2
			Div	kN		
1.	7	500x100x100	29	12.08	6.04	5.34
2.	7	500x100x100	25	10.42	5.21	
3.	7	500x100x100	23	9.58	4.79	
4.	28	500x100x100	30	12.5	6.25	6.25
5.	28	500x100x100	32	13.33	6.66	
6.	28	500x100x100	28	11.67	5.83	

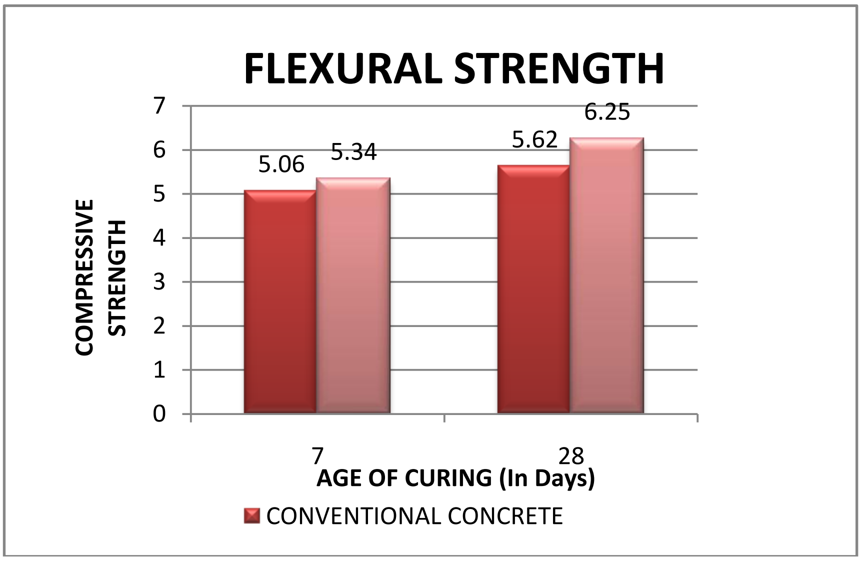

Fig 3.7 Flexural Strength for Conventional and Bacterial Concrete Prisms.

3.5.4 E for Concrete

In solid mechanics, the slope of the stress-strain curve at any point is called the tangent modulus. The tangent modulus of the initial, linear portion of a stress-strain curve is called Young's modulus, also known as the tensile modulus. It is defined as the ratio of the uniaxial stress over the uniaxial strain in the range of stress in which Hooke's Law holds. It is a measure of the stiffness of an elastic material and is a quantity used to characterize materials. It can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material. In anisotropic materials, Young's modulus may have different values depending on the direction of the applied force with respect to the material's structure. The test setup for Elasticity of modulus is shown in Figure 3.8

Fig 3.8 Test setup for E

The modulus of elasticity for conventional and bacterial cylinders was tabulated in Table 3.11 and Table 3.12 respectively. The stress–strain behaviors for conventional and bacterial concrete cylinders are shown in Figure 3.9.

Table 3.11 Modulus of elasticity for Conventional Concrete

Sl No	Specimen	Days	Modulus of Elasticity (N/mm^2)
1.	Cylinder	7	1.20 x 10^4
2.	Cylinder	28	1.95 x 10^4

Table 3.12 Modulus of elasticity for bacterial Concrete

Sl No	Specimen	Days	Modulus of Elasticity (N/mm^2)
1.	Cylinder	7	1.98 x 10^4
2.	Cylinder	28	2.37 x 10^4

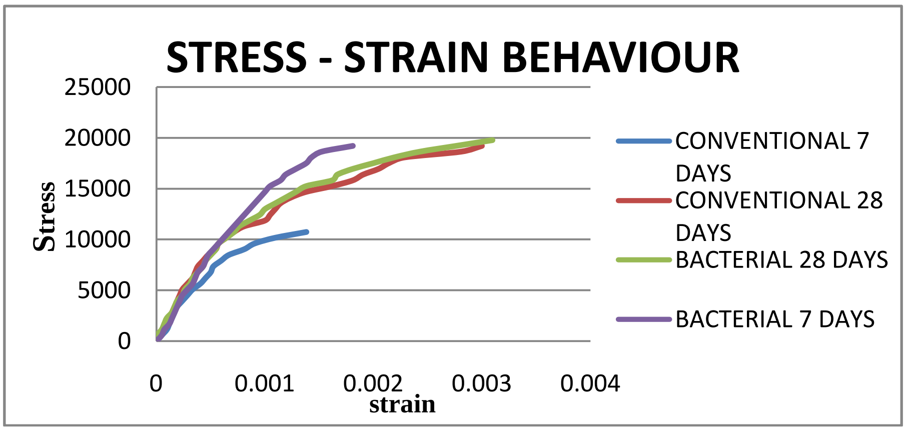

Fig 3.9 Stress – Strain Behavior

3.6 Durability Properties

3.6.1 Water Absorption Test

Concrete cube, specimens of size 100 x 100 x 100 mm were cast and kept in the aggressive medium for the period of 28 days. After 28 days, specimens were taken out and placed in oven dry at the temperature of 105°c to remove the moisture content. Then the dry weight of the specimen was measured by using electronic weigh balance. The specimens were immersed in curing tank- after an hour and minutes, the specimens were taken out dried and weights were recorded. The water absorption was calculated with reference to above weights of the specimen. This procedure was repeated for several trials till it obtains a saturation value. The specimen in water is shown in Figure 3.10. The water absorption for conventional and bacterial concrete cubes was tabulated in Table 3.13 and Table 3.14 respectively.

Fig 3.10 Water Absorption Test

Calculation

$$\%\, waterabsorption = \frac{(wetweight - dryweight)}{dryweight} \times 100$$

Table 3.13 Water Absorption for Conventional Concrete

Sl No	Specimen	Size of the Specimen in mm	Oven Dry Mass "A" in gms	Saturated Mass "B" in gms	Water Absorption in %
1.	Cube	100x100x100	2304	2436	5.73
2.	Cube	100x100x100	2332	2474	6.09
3.	Cube	100x100x100	2308	2441	5.76
				Mean	5.86

Table 3.14 Water Absorption for bacterial Concrete

Sl No	Specimen	Size of the Specimen in mm	Oven Dry Mass "A" in gms	Saturated Mass "B" in gms	Water Absorption in %
1.	Cube	100x100x100	2339	2425	3.68
2.	Cube	100x100x100	2290	2393	4.50
3.	Cube	100x100x100	2356	2441	3.61
				Mean	3.93

3.6.2 Acid Resistance Test

Owing to the highly basic character of Portland cement, an acid cannot penetrate dense concrete without being neutralized as it travels inwards. Therefore, it cannot cause deterioration in the interior of the specimen without the cement paste on the outer portion being completely destroyed. The rate of penetration is thus inversely proportional to the quantity of acid neutralizing material, such as the calcium hydroxide, C-S-H gel, and aggregates. Concrete is considered to be an alkali resistivity in nature.

The acid solution was prepared by mixing 3% sulphuric acid (H_2SO_4) in distilled water. At the end of the 28 days of curing period for concrete specimens used in the sulphuric acid test, the specimens were oven dried at 105ºC until constant mass, cooled at room temperature, weighed using an electronic scale and then immersed into the sulphuric acid bath. The initial weight of all the specimens were found and recorded before the immersion. Then the weighed specimens were immersed in the Acid solution for 15 days. After the specified period the specimens were taken out from the acid and it was allowed to dry for 24 hours at room temperature. Then the specimens were brushed with a soft nylon brush and rinsed in tap water to remove loose surface material. Then the final weight and compressive strength of the cubes were found. The loss in weight and loss in strength were calculated using the following equations. For determining the resistance of concrete specimens to aggressive environment like acid attack, the durability factors are used based on relative compressive strength. The specimens after 15 days of immersion in acid are shown in Figure 3.11.

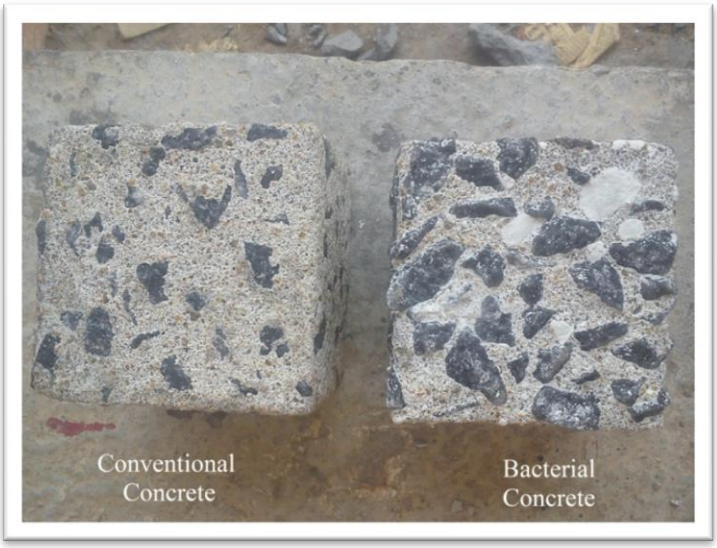

Fig 3.11 Specimens after Immersion in Acid

The results of acid resistance for conventional and bacterial concrete cubes were tabulated in Table 3.15 and Table 3.16 respectively.

$$\text{Loss in weight \%} = \frac{(W1 - W2)}{W1} \text{x } 100$$

$$\text{Loss in compressive strength \%} = \frac{(\sigma 1 - \sigma 2)}{\sigma 1} \text{x } 100$$

Where

W1 = Weight of concrete cube specimen before immersion in acid.
W2 = Weight of concrete cube specimen after immersion in acid.
σ1 = Compressive strength of concrete cube before immersion in acid
σ2 = Compressive strength of concrete cube after immersion in acid

Table 3.15 Acid Resistance for Conventional Concrete

Sl No	specimen	Weight after 28 days curing	Weight after 24 hrs oven drying	Weight after 15 days immersion in acid	Weight loss in %	Strength loss in %
1.	Cube	2.527	2.406	2.408	0.08	24.38
2.	Cube	2.486	2.360	2.363	0.13	26.49
3.	Cube	2.547	2.418	2.422	0.17	17.34
				Mean	0.13	22.73

Table 3.16 Acid Resistance for Bacterial Concrete

Sl No	specimen	Weight after 28 days curing	Weight after 24 hrs oven drying	Weight after 15 days immersion in acid	Weight loss in %	Strength loss in %
1.	Cube	2.354	2.308	2.094	9.27	61.44
2.	Cube	2.440	2.312	2.102	9.08	36.05
3.	Cube	2.318	2.290	2.008	8.31	51.72
				Mean	8.88	49.74

3.6.3 Rapid Chloride Permeability Test (RCPT ASTM C1202)

In the ASTM C1202 test, a Water -Saturated, 50-mm thick, 100-mm diameter concrete specimen is subjected to a 60 V applied DC voltage for 6 hours using the apparatus shown in Figure4.2.2In one reservoir is a 3.0 % NaCl solution and in the other reservoir is a 0.3 M NaOH solution. The total charge passed is determined and this is used to rate the concrete according to the criteria included as Table. This test, originally developed by Whiting [1981], is commonly (though inaccurately) referred to as the "Rapid Chloride Permeability Test" (RCPT). This name is inaccurate as it is not the permeability that is being measured but ionic movement. In addition, the movement of all ions, not just chloride ions, affects the test result (the total charge passed). Diagrammatic representation of RCPT setup is shown in Figure 3.12. RCPT test for conventional and bacterial slices is shown in Figure 3.13.

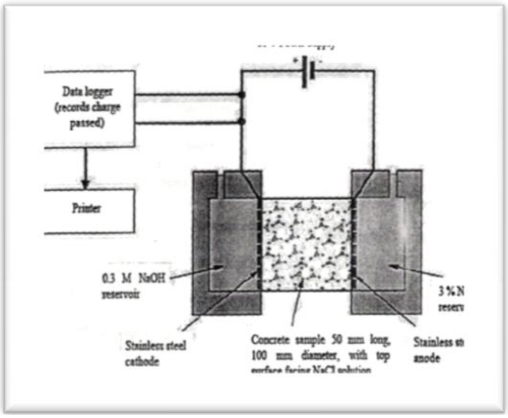

Fig 3.12 RCPT Test Setup (ASTM C1202) Fig 3.13 Rapid Chloride Permeability Test

There have been a number of criticisms of this technique, although this test has been adopted as a standard test, is widely used in the literature and has been used to limit permeability in at least one standard [CSA/S413-94]. The main criticisms are: (i) the current passed is related to all ions in the pore solution not just chloride ions, (ii) the measurements are made before steady-state migration is achieved, and (iii) the high voltage applied leads to an increase in temperature, especially for low quality concretes, which further increases the charge passed. Lower quality concretes heat more as the temperature rise is related to the product of the current and the voltage. The lower the quality of concrete, the greater the current at a given voltage and thus the greater heat energy produced. This heating leads to a further increase in the charge passed, over what would be experienced if the temperature remained constant. Thus, poor quality concrete looks even worse than it would otherwise.

Calculation:-

$Q = 900\ [I_o + 2I_{30} + 2I_{60} + \ldots\ldots + 2I_{330} + 2I_{360}]$

Where,

Q = Charge Passed (coulombs)

I_o = Current (Amperes) immediately after voltage is applied

I_t = Current (amperes) at t min after voltage is applied

$Q_s = Q \times \{\frac{95}{x}\}^2$

Where,

Q_s = Charge passed (Coulombs) through a 100mm diameter specimen.

x = Diameter of the non-standard specimen

The chloride ion penetrability of conventional and bacterial specimens were correlated with the Table 3.17 given below

Table 3.17 Correlation between the Charge Passed and Penetration of Chloride Ions

Charge Passed (Coulombs) Q_s	**Chloride Ion Penetrability**
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

The chloride penetration of conventional and bacterial concrete slices at 7 days and 28 days are given in Table 3.18 and 3.19

Table 3.18 Chloride Penetration for Conventional Concrete

Sl No	Specimen	Days	Charge Passed 'Q' in coulombs	Remarks
1.	Cube	7	2410	Moderate penetration
2.	Cube	28	2400	Moderate penetration

Table 3.19 Chloride Penetration for Bacterial Concrete

Sl No	Specimen	Days	Charge Passed 'Q'in coulombs	Remarks
1.	Cube	7	1288	Low penetration
2.	Cube	28	754	Very low penetration

3.7 Discussion on Test Results

3.7.1 Compressive Strength of Concrete

The compressive strength of conventional and bacterial concrete cubes and cylinders at 7 days and 28 days are given in Table 3.5 and 3.6 respectively. It is observed that with addition of bacteria the compressive strength of concrete cubes showed significant increase by 10.87 % at 28 days respectively.

3.7.2 Split Tensile Strength of Concrete

The split tensile strength of conventional and bacterial concrete cubes and cylinders at 7 days and 28 days are given in Table 3.7 and 3.8 respectively. It is observed that with addition of bacteria the split tensile strength of concrete cubes showed significant increase by 13.54 % at 28 days respectively.

3.7.3 Flexural Strength of Concrete

The flexural strength of conventional and bacterial concrete prisms at 7 days and 28 days are given in Table 3.9 and 3.10 respectively. It is observed that with addition of bacteria the flexural strength of concrete prisms showed significant increase by 10.08 % at 7 days and 28 days.

3.7.4 Stress – Strain Behavior

The stress strain behavior of conventional and bacterial concrete cylinders is shown in Figure 3.9. The moduli of elasticity of conventional and bacterial concrete cylinders are given in Table 3.11 and 3.12 respectively. It is observed that with the addition of bacteria the modulus of elasticity is increased by 17.72% at 28 days. The stress – strain curve also shows significant increase.

3.7.5 Water Absorption of Concrete

The percentage of water absorption of conventional and bacterial concrete cubes is given in Table 3.13 and 3.14 respectively. It is observed that there is a significant decrease in the absorption of water by 33% in the bacterial concrete cubes.

3.7.6 Acid Resistance of Concrete

After the immersion of 15 days in acid, the loss in weight and loss in compressive strength of conventional and bacterial concrete specimens are given in Table 3.15 and 3.16 respectively. It is observed that with the addition of bacteria there is more percentage of loss in weight and compressive strength when compared to the conventional concrete cubes.

3.7.7 Rapid Chloride Penetration Test

The chloride penetration on conventional and bacterial concrete slices at 7 days and 28 days are given in Table 3.18 and 3.19 respectively. It is observed that with the addition of bacteria there is a significant decrease in the chloride penetration, which shows the bacterial concrete slices are densely packed when compared to the conventional concrete slices.

4. CONCLUSION

Based on the present investigation, the following conclusions are drawn

- Bacillus *halodurans* can be cultured in laboratory which is proved to be safe and cost effective.
- The addition of Bacillus *halodurans* bacteria improves the hydrated structure of cement concrete
- The addition of Bacillus *halodurans* bacteria increases the compressive strength of concrete. In ordinary grade concrete (M20) the compressive strength is increased up to 20.85% at 28 days by addition of Bacillus *halodurans* bacteria when compared to conventional concrete.
- The addition of Bacillus *halodurans* bacteria increases the split tensile strength of concrete. In ordinary grade concrete (M20) the split tensile strength is increased up to 23.60% at 28 days by addition of Bacillus *halodurans* bacteria when compared to conventional concrete.
- The addition of Bacillus *halodurans* bacteria increases the flexural strength of concrete. In ordinary grade concrete (M20) the flexural strength is increased up to 10.08% at 28 days by addition of Bacillus *halodurans* bacteria when compared to conventional concrete.

- From the durability studies, the reduction in the absorption of water is achieved by the addition of Bacillus *halodurans* bacteria. In ordinary grade concrete the water absorption is decreased up to 33% by addition of Bacillus *halodurans* when compared to the conventional concrete.
- The reduction in the penetration of chloride ions is achieved by the addition of Bacillus *halodurans* bacteria. In ordinary grade concrete the chloride penetration becomes low at 7 days and very low at 28 days whereas in conventional concrete the chloride penetration is moderate at both 7 days and 28 days.
- Durability studies carried out in the investigation through acid attack test with 3% H_2SO_4 revealed that bacterial concrete is less durable than conventional concrete.
- From the above it can be concluded that Bacillus *halodurans* can be easily cultured and safely used in improving the performance characteristic of concrete

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