Pretend Intellectual Investigation on Reinforcement Corrosion in Bacterial Concrete Using Impressed Current Technique Method

NAGA ARCHANA N[1], ARAVIND RAJA G[2], SASI KUMAR A[3]
[1, 2, 3] *Department of Civil Engineering, N.S.N College of Engineering and Technology, Karur, Tamil Nadu, India*

Abstract*— Reinforced concrete structures form a major part of the engineering infrastructure of all developed countries, and their integrity over long periods of service is of vital economic importance. But the major drawback is its low tensile strength which causes cracking in concrete. When micro cracks growth reaches the reinforcement, not only the concrete gets damaged, but also corrosion occurs in the reinforcement due to exposure to water and oxygen, and possibly CO2 and chlorides too. Micro-cracks are therefore the main cause for structural failure. For crack repair, a variety of techniques are available but traditional repair systems have a number of disadvantageous aspects such as different thermal expansion coefficient compared to concrete and also have impact on environment and health. Therefore, bio based calcite precipitation has been proposed as an alternative and sustainable environmental friendly crack repair technique. Bio-mineralization of calcium carbonate is one such strategy to remediate cracks in building materials. The consumption of oxygen during the metabolic biochemical reactions to form CaCO3 is expected to help in arresting corrosion of steel because the oxygen is responsible to initiate the process of corrosion thereby increasing the durability of steel reinforced concrete structures. In this thesis, an attempt has been made in the first phase to find the optimum concentration of bacterial cells to be incorporated in concrete. Based on the state-of-the-art information available in the literature three different bacterial samples are considered in concentrations of 104,105 and 106 cells/ml. The bacteria considered are Bacillus subtilis, Pseudomonas aerugonisa and Bacillus megaterium and the optimum concentration is found to be 105, 105 and 104cells/ml respectively based on compressive strength results. The increase in strength is found to be 42.8, 50.5 and 53.5% respectively for Bacillus subtilis, Pseudomonas aerugonisa and Bacillus megaterium respectively. Water absorption test is carried out on cubes cast with optimum concentration of bacterial cells. The percentage water absorbed was found to be lesser for specimens with bacteria. This confirms that the bacteria plug the pores in concrete. A maximum of 20.12% reduction in water absorption was obtained for Bacillus megaterium when compared with control mix. In the next phase of the study, corrosion is accelerated by impressed current technique in the reinforced concrete beams cast with optimum concentration of each bacterium and the conventional RC beams. In this study, the corrosion of tension reinforcement is only considered. Lead wires are connected at two points of each tension reinforcements to induce uniform corrosion in the rebars. 5% sodium chloride solution is used as electrolyte to simulate sea water environment. The rebars are initially weighed before they are embedded in concrete. The acceleration process is carried out for a period of 120 hours by galvanostatic method with steel rebars as anode, stainless steel plate as cathode and NaCl as electrolyte. The beams are then destroyed and the rebars are extracted, cleaned and then weighed. Current applied for inducing corrosion is not found to be fully efficient in causing loss of mass equal to that theoretically predicted by Faraday's Law. Therefore, a plot of Iapp vs Icorr is obtained for each type of specimen to study the relationship between applied and induced current. The degree of induced corrosion is expressed in terms of percentage weight loss. The mass loss percentages were higher for control specimens when compared with bacterial specimens. The average mass loss was found to be 5.17% for control beams, 2.83% for Bacillus subtilis, 3.02% for Pseudomonas aeruginosa, and 2.62% for Bacillus megaterium specimens. Bacillus megaterium specimens exhibited maximum difference of loss in weight when compared to control beams. Thus the corrosion resistance property of bacterial concrete was found to be higher than the control mix without bacteria..

I. INTRODUCTION

Concrete is one of the most versatile and widely used construction materials of all in the world. The proportionate mixture of cementing materials, water and aggregates, and sometimes admixtures, when placed in forms and allowed to cure, hardens into a rock-like mass known as concrete. The hardening is caused by chemical reaction between water and

cement. This hardened concrete may also be considered as an artificial stone in which the voids of larger particles (coarse aggregate) are filled by the smaller particles (fine aggregate) and the voids of fine aggregates are filled with cement. The concept of treating concrete in its entity as a building material rather than its ingredients is gaining popularity. The interest is now in having the desired properties of concrete without bothering about the ingredients. Concrete has high compressive strength, but its tensile strength is very low and hence cracks easily. In situations where tensile stresses are developed, the concrete is strengthened by steel bars forming a composite construction called Reinforced cement concrete (RCC). Reinforced concrete structures form a major part of the engineering infrastructure of all developed countries, and their integrity over long periods of service is of vital economic importance.

II. CRACKS - A PATHWAY FOR CORROSION ACCELERATION

Though concrete is quite strong mechanically, it is highly susceptible to larger tensile stress, and thus concrete structures get damaged and even fail unless some measures are adopted to counteract deterioration of concrete and thereby increasing the durability of concrete structure. A durable concrete is dense, workable having permeability as low as possible under the given situation. In the case of reinforced concrete, the ingress of moisture or oxygen through the cracks may lead to corrosion of steel, and cracking and spalling of concrete cover. Micro-cracks are therefore the main cause for structural failure. Any factor which may help in the development of cracks in concrete will promote the penetration of aggressive solution and gases, and will lead to the faster deterioration of concrete structure. Strength of reinforced concrete structures deteriorate with age also. Most common cause of construction deterioration is the corrosion of embedded steel reinforcement. Corrosion is supposed to affect the long term performance of structures. During the long term in corrosive conditions, the mass loss of the embedded steel rebars steadily increases. As a result there is a significant increase in the applied stresses on account of reduction of cross section of embedded steel and longitudinal cracks are induced in concrete reducing the bond between steel and the surrounding concrete. This may adversely affect the performance of existing structures.

III. CRACK REPAIR SYSTEMS

All the concrete structures crack in some form or the other. An engineer should have a sound knowledge of all the facets of concrete technology. The problem of cracking should be tackled on two fronts, i.e., by adopting preventive measures and repairing them. However, prevention is better than repair. The designer and builders should attempt to reduce the formation of cracks by using appropriate construction materials, and by adopting appropriate design and construction techniques. Crack repairs can particularly be time consuming and expensive because it is often very difficult to gain access to the structure to make repairs, especially if they are underground or at a great height. For 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 also have impact on environment and health. Therefore, bio based calcite precipitation has been proposed as an alternative and sustainable environmental friendly crack repair technique.

IV. ADVANTAGES OF BACTERIAL CONCRETE

Calcium carbonate is one of the most naturally precipitated minerals on earth in the form of natural rocks and exists in environments such as marine water, fresh water, and soils. The evidence of microorganism involvement in calcium carbonate precipitation has lead to the use of these organisms in construction industry. The precipitation of calcium carbonate in concrete is expected to increase the strength of the structure. It is important to realise that micro organisms plug the pores of concrete not only due to its smaller size but also precipitates calcium carbonate when the micro organisms come into contact with air and moisture through the cracks. This precipitated calcium carbonate helps in filling the crack thereby reducing the probability of further propagation of cracks. The consumption of oxygen during the metabolic biochemical reactions to form $CaCO_3$ helps in arresting corrosion of steel because the oxygen is responsible to initiate the process of corrosion.

V. SIGNIFICANCE OF THE CURRENT THESIS

The significance of this work is the effective use of bacteria to increase the strength of concrete. The durability aspect has also been considered by studying the deterioration of the bacterial concrete in corrosive environment and thus examining whether the presence of bacteria increases the rate of corrosion or vice versa. Furthermore the bacteria are expected to reduce the permeability and porosity of concrete and thus decelerating the propagation of crack.

OBJECTIVE

- The main objective of this study is to determine the effect of bacteria in the corrosion of concrete
- To determine the optimum concentration of bacterial cells to be incorporated in concrete based on compressive strength, considering three different bacterial samples (Bacillus subtiltis, Pseudomonas aerugonisa, Bacillus megaterium) in three different dilutions (104,105 and 106 cells/ml)
- To study the percentage water absorption in concrete cubes with optimum concentration of each bacteria and for control mix to check its potency in plugging the pores in concrete
- To accelerate corrosion in the reinforced concrete specimens cast with optimum concentration of bacteria
- To compare the corrosion results of bacterial specimens with control specimens which are cast without bacteria
- To estimate actual mass loss and degree of induced corrosion
- To study the relation between the applied current (Iapp) and the current utilized to cause actual mass loss (Icorr)

SCOPE

This thesis considers the use of only three selective concentrations of three chosen bacteria. To check the plugging of pores, only water absorption test was done. This study is limited to the determination of corrosion efficacy of the tension reinforcement alone.

VI. MATERIALS USED

CEMENT:

The type of cement used for this study is ordinary Portland cement 53 grade conforming to IS 12269:1987

Si. No	Test Performed	Fresh Water
1	Initial setting time	35min
2	Final setting time	430 min
3	consistency	27%
4	Specific Gravity	3.2

COARSE AGGREGATE:

Si. No	Test Performed	Result
1	Specific Gravity (20mm)	2.844
2	Bulk density	1540.74 kg/m3(loosely packed)
3	Bulk density	1762.96 kg/m3 (compacted)
4	Fineness modulus	5.13

FINE AGGREGATE:

Si. No	Test Performed	M Sand
1	Specific Gravity	2.659
2	Bulk density	1481.48 kg/m3(loosely packed)
3	Bulk density	1807.41 kg/m3 (compacted)

WATER:

Potable water was used in the experimental work for both mixing and curing purposes conforming to IS:456-2000.

BACTERIA:

Currently urease enzyme activity in most of microorganism metabolism process has been used as a tool to induce the precipitation of calcite crystals. Bacteria added to concrete mix in suspension state must meet certain criteria. Concrete is a highly alkaline building material, so bacteria used must be able to survive in this high alkaline environment for long durations and be able to form spores (highly resistant structures) withstanding mechanical forces during concrete mixing. Gram positive bacteria have extremely thick outer cell membrane that enables them to remain viable until a suitable environment is

available to grow. They would become lively when the cracks form on concrete surface allowing water to ingress into the structure. This phenomenon will reduce the pH of the concrete environment where the bacteria incorporated become activated. A peptone based nutrients supplied along with bacteria in suspension helps in producing calcite crystals. It is found that this biomineralisation process will not interfere with the setting time of the concrete.

MICROBIAL PRECIPITATION OF $CACO_3$

Bacterial cell walls, which comprise the cell surface, are known to be central to Microbially Induced Calcite Precipitation. Bacterial cell walls are negatively charged under environment of neutral or alkaline pH, attract the calcium ions (Ca^{2+}) in the extracellular environment to react with the carbonate ions (CO_3^{2-}) and form calcium carbonate ($CaCO_3$) minerals on the cell surface, which serve as nucleation site for further mineralization. In medium, it is possible that individual microorganisms produce ammonia as a result of enzymatic urea hydrolysis to create an alkaline micro-environment around the cell. The high pH of these localized areas, without a significant increase in pH in the entire medium at the beginning, apparently commences the growth of $CaCO_3$ crystals around the cell. Possible biochemical reactions to precipitate $CaCO_3$ at the cell surface can be summarized as follows.

$Ca_2^{+} + Cell \rightarrow Cell\text{-}Ca^{2+} \longrightarrow$ Eqn 4.1

$Cell\text{-}Ca^{2+} + CO_3^{2-} \rightarrow Cell\text{-}CaCO_3\downarrow \longrightarrow$ Eqn 4.2

BACTERIAL CULTURE:

Culture of bacteria in the required concentration was obtained from Bharathiyar University, Coimbatore and the stock was preserved under refrigeration until further use. The cultures of Bacillus subtilis, Bacillus megaterium and Pseudomonas aeruginosa were used in concentrations of 104, 105 and 106 cells/ml.

VII. CONCRETE MIX DESIGN

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design

Mix proportions
Cement: 413.33 kg/m3
Water: 186 kg/m3
Fine aggregate: 607.23 kg/m3
Coarse aggregate: 1203.86 kg/m3
Water-cement ratio: 0.45

CEMENT	FINE AGGREGATE	COARSE AGGREGARE	WATER
413.33	607.23	1203.86	186
1	1.469	2.913	0.45

Mixing

The concrete using grade M20 (1:1.469:2.913) with water cement ratio 0.45 were used. Concrete is mixed in roller type of mixing machine.

VIII. EXPERIMENTAL METHODOLOGY

COMPRESSIVE STRENGTH OF CONCRETE

Compressive Strength of concrete is an important element in designing R.C.C. structures. It is given in terms of the characteristic compressive strength (fck) of 150 mm size cubes tested at 28 days.

PREPARATION OF TEST SPECIMENS:

Initially the cube moulds are fixed and oiled before pouring concrete into it. The mould shall be of 150 mm size conforming to IS:10086-1982. The materials shall be mixed properly in proper proportions arrived from mix design and the concrete shall be fil led into the mould in layers approximately 5cm deep. Each layer shall be compacted either by hand subjected to 35 strokes per layer or by vibration. De-moulding shall be done after 24 hours with utmost care to prevent any damage to the specimen and must be ensured that concrete has attained hardened state before demoulding. The specimen shall be stored in water at a temperature of 27°± 2°C until the time of test.

Testing Procedure

Tests shall be made at recognized ages of the test specimens, the most usual being 7 and 28 days. The specimen shall be placed in the machine in such a manner that the load shall be applied to opposite sides of the cubes as cast. The load shall be applied without shock and increased continuously at a rate of approximately 140 kg/sq.cm/min until the resistance

of the specimen to the increasing load breaks down and no greater load can be sustained. The maximum load applied to the specimen shall then be recorded. In this thesis, the cubes were cast for the control mix and for three concentrations of three bacterial specimens, 104, 105, 106 cells/ml of mixing water for Bacillus subtilis, Bacillus megaterium and Pseudomonas aeruginosa. The cubes were tested at the ages of 7 and 28 days. The total numbers of cubes cast were 60.

WATER ABSORPTION TEST

The water absorption test was done on 70.6 mm size cubes which were cast for the control mix and the optimum concentration of each bacterium.

MECHANISM OF REINFORCEMENT CORROSION

Corrosion of steel embedded in concrete is an electrochemical process involving the flow of charges (electrons and ions). The surface of the corroding steel functions as a mixed electrode that is a composite of anodes and cathodes electrically connected through the body of steel itself, upon which coupled anodic and cathodic reactions take place. Concrete pore water functions as an aqueous medium, i.e., a complex electrolyte. Therefore, areinforcement corrosion cell is formed as shown in Fig.6.4.

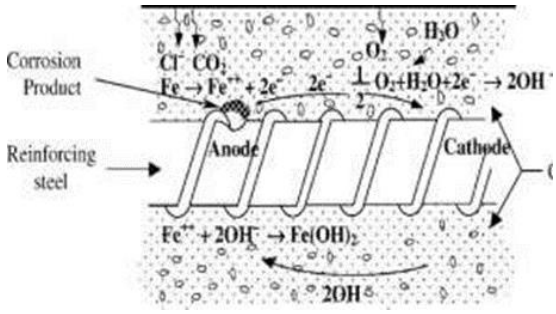


Fig.6.4 Corrosion of steel in concrete - as an electrochemical process

At active sites on the bar, called anodes, iron atoms lose electrons and move into the surrounding concrete as ferrous ions. This process is called a half-cell oxidation reaction, or the anodic reaction, and is represented as:

$Fe \rightarrow Fe^{2+} + 2e$ ⟶ Eqn.6.1

The electrons remain in the bar and flow to sites called cathodes, where they combine with water and oxygen in the concrete. The reaction at the cathode is called a reduction reaction.A common reduction reaction is:

$H_2O + ½ O_2 + 2e^- \rightarrow 2OH^-$ ⟶ Eqn.6.2

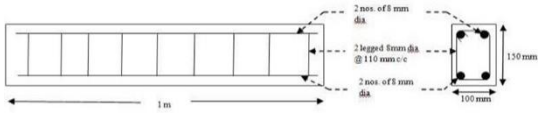
To maintain electrical neutrality, the ferrous ions migrate through the concrete pore water to these cathodic sites where they combine to form iron hydroxides, or rust:

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$ ⟶ Eqn.5.3

This initial precipitated hydroxide tends to react further with oxygen to form higher oxides. The increases in volume as the reaction products react further with dissolved oxygen leads tointernal stress within the concrete that may be sufficient to cause cracking and spalling of theconcrete.

REINFORCEMENT DETAILING IN CURRENT THESIS

The beams used in this study were of length 1m and of cross section 100mm x 150mm. Two bars of 8mm diameter were used as tension reinforcement and two bars of 8mm diameter were used as hangar bars. The stirrups were of 2 legged 8mm diameter bars spaced at 110mm centre to centre.



Longitudinal Section CrossSection

Fig.6.5 Beam detailing

ACCELERATED CORROSION

Corrosion is generally a slow process and it takes many years for the first crack to appear on the surface of reinforced cement concrete (R.C.C). It is normal practice to adopt the 28-acceleration technique in the laboratory study of corrosion processes. The corrosionof reinforcing steel is generally accelerated by means of the impressed current technique. This is done to induce a significant degree of corrosion of reinforcing bars embedded in concrete in limited available time. The impressed current technique has been frequently used to study the effect of reinforcement corrosion on the cracking of concrete cover, bondbehaviour, and loadbearing capacity of reinforced concrete structural members. One

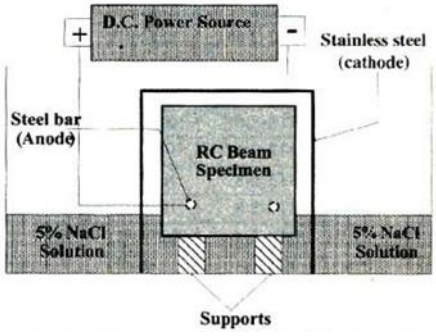
advantage over other accelerated techniques is the ability to control the rate of corrosion, which usually varies due to changes in the resistivity, oxygen concentration, andtemperature.

IMPRESSED CURRENT TECHNIQUE

The impressed current technique, also called the galvanostatic method, consists of applying a constant current from a DC source to the steel embedded in concrete to induce significant corrosion in a short period of time. After applying the current for a given duration, the degree of induced corrosion can be determined theoretically using Faraday's law, or the percentage of actual amount of steel lost in corrosion can be calculated with the help of a gravimetric test conducted on the extracted bars after subjecting them to accelerated corrosion. Using the actual amount of steel lost in corrosion, an equivalent corrosion current density can be determined.

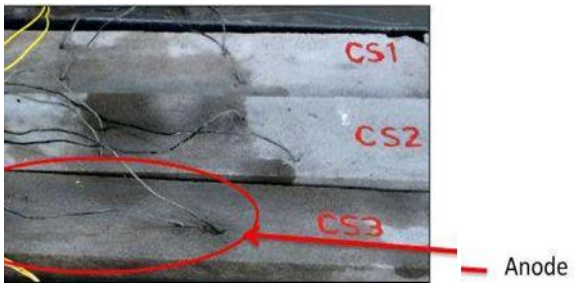
TEST SET-UP FOR INDUCING REINFORCEMENT CORROSION

Set-ups used for inducing reinforcement corrosion through impressed current consist of a DC power source, a counter electrode, and an electrolyte. The positive terminal of the DC power source is connected to the steel bars (anode) and the negative terminal is connected to the counter electrode – stainless steel (cathode). The current is impressed from counter electrode to the rebars through concrete with the help of the electrolyte (normally sodium chloride solution).

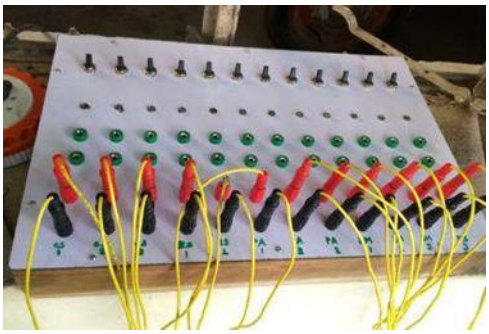


Lead wires were connected at two points of each tension reinforcement to ensure uniform corrosion throughout the length of the beam. Corrosion of tension reinforcement is only considered in this thesis.

Below setup gives an actual setup of the corrosion process and the connections made to thebeam and the stainless steel plate, with 5% NaCl as electrolyte



Circuit board was made with three DC packs of 12V and 10A capacity to impart voltage to the reinforcement bars in the beams.



The beams were cast for the optimum concentration of each bacterium and for the control mix. These beams were cast in replicates of three for each type of mix and there were totally 12 beams cast. Lead wires were connected to all beams and the stainless steel plates were placed beneath each beam. The stainless steel plates were connected with wires to thenegative electrode. 5% NaCl solution was used as electrolyte for the electrochemical processto occur. The Fig.5.10 gives an overall picture of the corrosion acceleration process.

Current readings were noted every one hour using a multimeter and the average current reading was used

in the calculation as applied current (Iapp). The beams were kept in acceleration corrosion process for 120 hours.

GRAVIMETRIC TESTING OF CORRODED REBARS

After inducing corrosion on the beams, the bars were extracted from the beams by breaking the concrete for measurement of the average loss of steel owing to induced corrosion, using the gravimetric test. The bars were cleaned to remove all rust products using chemical cleaning process and then they were weighed to find the net weight of steel. Preparation, cleaning, and evaluation of corrosion test specimens were carried out in accordance with ASTM G-1-90 (ASTM, 1990).

Drilling of Beam specimen

Rebars extracted after drilling

IX. RESULTS AND DISCUSSION

CUBE COMPRESSIVE STRENGTH

The compressive strength test was carried out on cubes cast for the concentrations (10^4,10^5,10^6 cells/ml) of all bacteria considered (Bacillus subtilis, Bacillus megaterium, Pseudomonas aeruginosa). The test was done at the age of 7 and 28 days and the results are shown in the following tables 7.1,7.2,7.3,7.4. The optimum cell concentration of each bacterium was found based on these results.

Control specimen

Compressive strength results of Control specimen

S.No.	Compressive strength (N/mm^2)	
	7 days	28 days
1	20.00	30.27
2	22.22	30.06
3	21.33	30.95
Average	21.18	*30.43*

Bacillus megaterium

Compressive strength results of Bacillus megaterium

S.No.	Compressive strength (N/mm^2)					
	10^4 cells/ml		10^5 cells/ml		10^6 cells/ml	
	7 days	28 days	7 days	28 days	7 days	28 days
1	24.63	45.95	22.33	33.15	21.01	32.79
2	29.89	46.37	24.52	36.23	20.04	32.44
3	28.06	47.45	23.28	37.46	19.01	30.22
Average	27.53	*46.59*	23.38	35.61	20.02	31.82

Bacillus subtilis

Compressive strength results of Bacillus subtilis

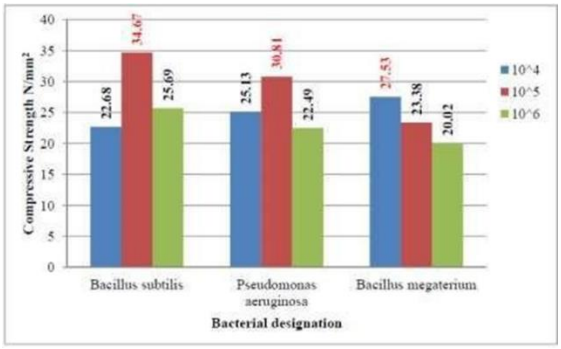
S.No.	Compressive strength (N/mm^2)					
	10^4 cells/ml		10^5cells/ml		10^6 cells/ml	
	7 days	28 days	7 days	28 days	7 days	28 days
1	22.36	35.36	33.87	46.59	24.89	34.67
2	21.57	32.21	36.62	41.15	29.04	37.78
3	24.12	36.56	33.52	42.65	23.15	35.56
Average	22.68	34.71	34.67	*43.46*	25.69	36.00

Pseudomonas aeruginosa

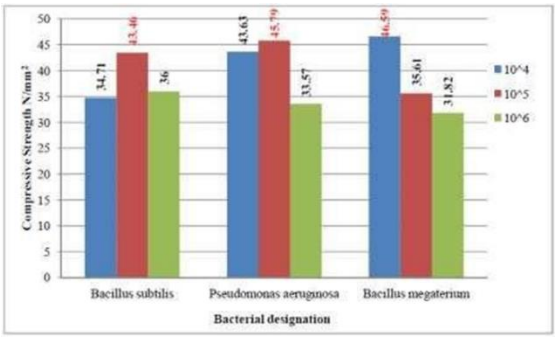
Compressive strength results of Pseudomonas aeruginosa

S.No.	Compressive strength (N/mm^2)					
	4 10^4 cells/ml		5 10^5 cells/ml		6 10^6 cells/ml	
	7 days	28 days	7 days	28 days	7 days	28 days
1	24.72	44.39	29.42	45.04	21.18	34.60
2	27.64	45.70	32.09	46.87	23.36	33.84
3	23.02	40.80	30.92	45.45	22.22	32.26
Average	25.13	43.63	30.81	*45.79*	22.49	33.57

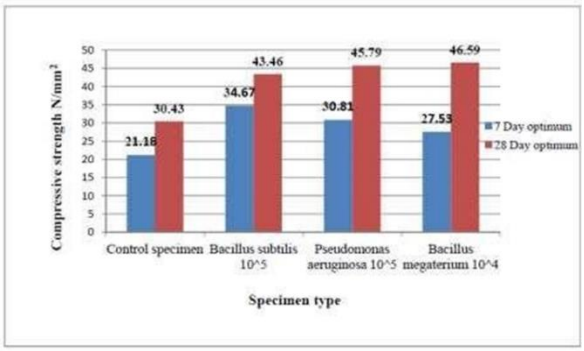
It was observed that the compressive strength of the cubes with bacteria was higher than those cast without bacteria. It can be seen that the maximum compressive strength was obtained for 10^5cells/ml for Bacillus subtilis and Pseudomonas aerugonisa and 10^4cells/ml for Bacillus megaterium.



7 days average compressive strength of Bacterial specimens



28 days average compressive strength of Bacterial specimens



Comparison of optimum compressive strength at 7 and 28 days

The optimum concentrations of the bacterial specimens showed an increase in compressive strength at 7 and 28 days when compared with control specimens.

Effect of bacteria addition on compressive strength of concrete

Specimen type	Average 28 days compressive strength, Mpa	ncrease in strength
Control specimen	30.43	-
Bacillus subtilis (10^5cells/ml)	43.46	42.8
Pseudomonas aerugonisa (10^5cells/ml)	45.79	50.5
Bacillus megaterium (10^4cells/ml)	46.59	53.5

It was observed that there was a maximum of 53.5 % increase in compressive strength for the cubes cast with 10^4 cells/ml concentration of Bacillus megaterium. The optimum concentrations of other considered bacteria also showed a significant increase in compressive strength.

WATER ABSORPTION TEST ON CUBES

Concrete cubes of size 70.6mmx70.6mmx70.6mm were cast for the optimum concentration of bacteria, concluded from compression test results and also for control specimens. From the difference of surface-dry mass after immersion and oven dried mass, the percentage of water absorbed after immersion was determined and the results are given in Table

Effect of bacteria on water absorption of concrete

Specimen type	Water absorption, %			Average water absorption after immersion, %	% reduction in water absorption
Control specimen	2.05	1.98	2.06	2.03	-
acillus subtilis (105cells/ml)	1.81	1.83	1.88	1.84	10.33
Pseudomonas aerugonisa (105cells/ml)	1.75	1.81	1.79	1.78	14.04
Bacillus megaterium (104cells/ml)	1.64	1.67	1.76	1.69	20.12

The percentage water absorbed was found to be lesser for specimens with bacteria. This confirms that the bacteria plug the pores in concrete. Maximum of 20.12 % reduction in water absorption was observed for 104cells/ml of Bacillus megaterium.

CORROSION OF RC BEAMS

The reinforced concrete beams were cast for control mix and for the optimum cell concentration of each bacterium. Accelerated corrosion was induced for 120 hours and the results of the gravimetric test conducted are tabulated and is given in Table

Corrosion results of RC Beams

eam ID	Average I_{app} (Amps)	nitial mass (g)	Final mass (g)	Actual mass loss (g)	eoretical mass loss (g)	Actual mass loss %	Theoretical mass loss %	Equivalent corrosion current, I_{corr} (Amp)
CS1	1.01	2823	2704	119	126.56	4.22	4.48	0.95
CS2	1.20	2808	2666	142	150.11	5.06	5.35	1.14
CS3	1.58	2835	2658	177	197.84	6.24	6.98	1.42
BS1	0.77	2842	2765	77	95.67	2.71	3.37	0.62
BS2	0.75	2854	2775	79	93.63	2.77	3.28	0.63
BS3	0.86	2850	2764	86	107.69	3.02	3.78	0.69
PA1	0.86	2862	2774	88	107.38	3.07	3.75	0.70
PA2	0.77	2857	2776	81	96.35	2.84	3.37	0.65
PA3	0.90	2826	2737	89	112.29	3.15	3.97	0.71
BM1	0.82	2861	2781	80	102.14	2.80	3.57	0.64
BM2	0.72	2836	2768	68	89.60	2.40	3.16	0.54
BM3	0.76	2809	2734	75	95.05	2.67	3.38	0.60

For the current capacity of the circuit, the current applied to the bacterial specimens were found to be lesser than that of the control specimens. From this it can be understood that the conductance of the bacterial specimens were lesser compared to control specimens, which in turn indicate higher porosity of control specimens. Thus, it can be concluded that the bacteria has higher resistance to corrosion and it can effectively be used in aggressive environment. The mass loss percentages of bacterial specimens were found to be lesser than the control mix cast without bacteria.

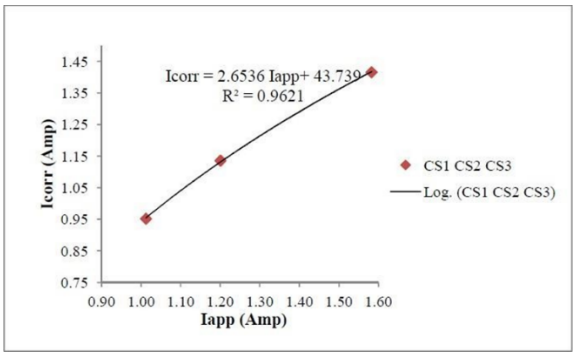
The average mass loss was found to be 5.17% for control beams, 2.83% for Bacillus subtilis, 3.02% for Pseudomonas aeruginosa, and 2.62% for Bacillus megaterium specimens. Bacillus megaterium specimens exhibited maximum difference of loss in weight when compared to control beams. This further coincides with the water absorption results and confirms that the maximum plugging of pores had occurred in Bacillus megaterium specimens.

Relationship between I_{app} and I_{corr}

Current applied for inducing corrosion is not found to be fully efficient in causing loss of mass equal to that theoretically predicted by Faraday's Law.
i.e., $I_{app} \neq I_{corr}$

It will be convenient if an empirical relationship between Iapp and Icorr is developed so that the value of Icorr can be quickly determined by substituting Iapp in the equation relating I_{app} and I_{corr}.

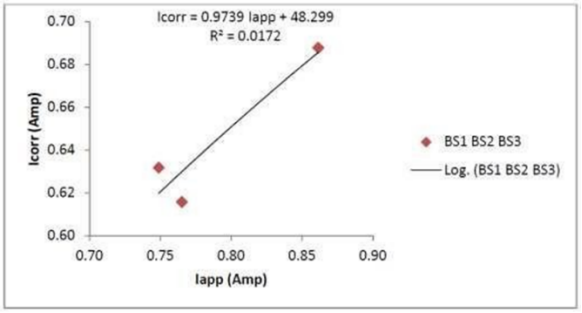
Control Specimens



Plot of Iapp Vs Icorr for control specimens

The equation of the best fit I_{app} versus I_{corr} curve is given as I_{corr} = 2.6536 ln(I_{app})+ 43.739 (R^2 = 0.9621) → Eqn.7.1

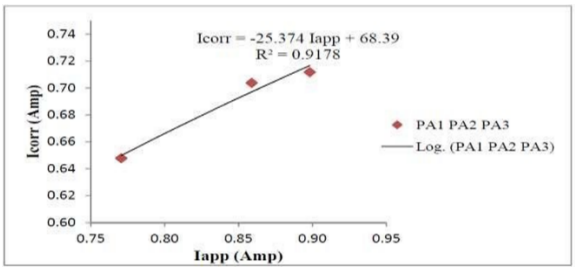
Bacillus subtilis



Plot of Iapp Vs Icorr for Bacillus subtilis specimens

The equation of the best fit Iapp versus Icorr curve is given as Icorr = 0.9739 ln(Iapp) + 48.299 (R^2 = 0.0172) → Eqn.7.2

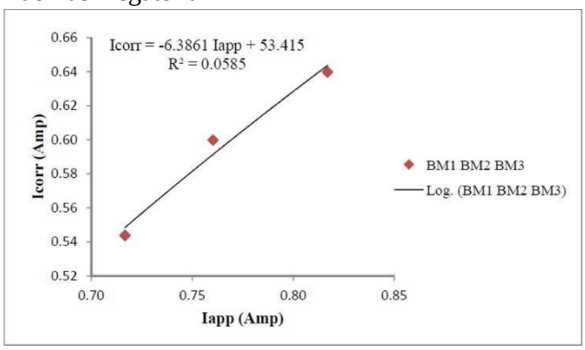
Pseudomonas aeruginosa



Plot of Iapp Vs Icorr for Pseudomonas aeruginosa specimens

The equation of the best fit Iapp versus Icorr curve is given as Icorr = -25.374 ln(Iapp) + 68.39 (R^2 = 0.9178) → Eqn.7.3

Bacillus megaterium



Plot of Iapp Vs Icorr for Bacillus megaterium specimens

The equation of the best fit Iapp versus Icorr curve is given as Icorr = -6.3861 ln(Iapp) + 53.415 (R^2 = 0.0585)

The actual value of I_{corr} can be obtained only from the gravimetric results but with the help of the above equations Eqn.7.1 to Eqn.7.4 the value of I_{corr} can be obtained for similar type of specimens without actually breaking the specimens by substituting the value of I_{app}. With this I_{corr} value, the approximate value of actual mass loss can be obtained.

CONCLUSION

- The addition of bacteria highly influences the compressive strength of concrete specimen and the strength is on par with control specimen. Based on compressive strength results, the optimum cell concentration of Bacillus subtilis and Pseudomonas aeruginosa was found to be 105

cells/ml and it was 104 cells/ml for Bacillus megaterium.

- The maximum increase in compressive strength of 53.5% was obtained for 104 cells/ml concentration of Bacillus megaterium. Water absorption results also show that the plugging of pores due to microbes was better than the conventional concrete. Maximum of 20.12 % reduction in water absorption was observed for 104cells/ml of Bacillus megaterium.
- The corrosion resistance property of bacterial concrete was found to be higher than the control mix without bacteria. The mass loss percentages were higher for control specimens when compared with bacterial specimens. The average mass loss was found to be 5.17% for control beams, 2.83% for Bacillus subtilis, 3.02% for Pseudomonas aeruginosa, and 2.62% for Bacillus megaterium specimens.
- Applied current and the current utilised to induce corrosion are not the same and hence the relationship among these values were obtained for each type of specimen to determine the approximate value of actual mass loss without actually breaking the specimens. It can be observed that the bacterial concrete is an effective way to develop sustainable and eco- friendly structures.

SUGGESTIONS FOR FUTURE WORK

- The durability properties of the bacterial specimens used can be studied in depth.
- The use of other types of bacteria in concrete may be studied.
- Other corrosion accelerating techniques can be used to accelerate corrosion in RC beams and its relation with impressed current technique could be studied.
- In this study, the corrosion of tension reinforcement is only considered. The corrosion of compression reinforcement bars and stirrups in the beam could be studied in detail.
- The reduction in strength of the corroded specimens can be studied.
- Long term corrosion resistance property of bacterial concrete could be studied by increasing the duration of accelerated corrosion (days)

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