**A Biological Approach to Repair and Rehabilitation of Concrete Structures**

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**Abstract**

 The extent of deterioration to concrete structures globally is occurring at an alarming rate, which challenges engineers throughout the world on a daily basis. This includes damage to bridges, buildings, parking structures, environmental facilities, as well as other structures. Unfortunately, repair costs can be staggering. Delaying repairs usually results in much more costly repairs later. Furthermore, if concrete deterioration or damage is not timely addressed, some of these structures eventually may cease to be serviceable and worse yet, failures could occur. The micro-cracks and porosity of concrete structures are very common problems due to the fact that this material has a high permeability which allows water and other aggressive media to enter thus leading to deterioration. The use of traditional organic polymer based crack sealers is a common way of contributing to concrete durability. However, the most common organic polymers have some degree of toxicity and are not environmental friendly. Recent investigations in the field of biotechnology show the potential of bio-inspired materials in the development of low toxic solutions. Calcium carbonate is one of the most well known mineral that bacteria deposit by the phenomenon called bio-cementation or microbiologically induced calcite precipitation (MICP). An alkalophilic aerobic soil bacterium *Bacillus subtilis* JC3 was incorporated into concrete at different cell concentrations with the mixing water. The study showed that a 30 % increase in 28 days compressive strength of concrete was achieved with the addition of 105 bacterial cells per ml of mixing water. This paper presents the research findings to suggest the potential use of the microbial calcite precipitation process in remediation of the surface cracks and pores present in concrete.

***Keywords:*** *Bacterial Concrete, bio-calcification, microbiologically induced calcite precipitation, self-healing, Bacillus subtilis JC3.*

**Introduction**

Concrete is most used construction material in the world today. There are two probable reasons for deterioration of concrete; they are human inflicted causes such as low strength concrete, inadequate concrete cover, poor construction techniques etc and environment related causes freezing and thawing, early-drying shrinkage, chemical attack, carbonation etc. Concrete crack repair could be done to accomplish the following objectives such as restoring and increasing strength and stiffness, to improve structural integrity, to provide water tightness, improve appearance of the concrete crack surface area, to improve durability and to prevent corrosion in steel. So there are many different forms of causes for cracking to deal with on a daily basis. When ignored can lead to more serious problems with corrosion. Before you begin to repair these cracks in concrete, identifying the nature of cause and method of repair is chosen based on whether to achieve structural integrity, focus on aesthetics, seal against intrusion of foreign materials, protect against carbonation, protect against chloride and water ingress; and/or seal in preparation for additional topping material. Hairline cracks are often ignored because they are thought of as nonstructural and, therefore, not a threat to the integrity of the structure. If left untreated, hairline cracks will eventually become larger and lead to more costly repairs. To minimize future deterioration of concrete, cracks exposed to a moist or corrosive environment should be sealed by using various available engineering solutions for structural crack repair. An innovation based on biomimicry and biotechnology has lead to the method of sealing up of micro cracks in concrete by itself using microorganisms as a sustainable alternative to other available chemical methods of crack repair such as epoxy treatment etc.

**Bio-deposition Versus Natural Carbonation**

Compared to natural carbonation of concrete, bio-deposition is a relatively quick process. Natural carbonation occurs from the dissolution of atmospheric CO2 in the pore solution and formation of CaCO3 from CSH or portlandite. In the bio-deposition treatment however, calcium ions are also provided by an externally added calcium source, while the carbonate ions result from the microbiological hydrolysis of amino acids. As a result of the rapid hydrolysis of amino acids (under optimal conditions), the majority of the calcium ions added to the specimens are precipitated within a couple of days.

**Mechanism of Bio-based Concrete Crack Repair**

In nature, microorganisms can induce calcite mineral precipitation through nitrogen cycle either by ammonification of amino acids/ nitrate reduction/ hydrolysis of urea. *Bacillus subtilis* JC3is able to precipitate calcium carbonate (CaCO3) in its micro-environment by the ammonification of amino acids into ammonium (NH4+) and carbonate (CO32-) ions. The precipitated bio-CaCO3 has a great potential ability to heal concrete cracks because it is natural, environmentally friendly and compatible with the concrete matrix. Biomineralization in concrete is the process by which micro organisms that produces minerals is uses as a possible method to promote concrete crack remediation.But the challenge was finding the bacteria that would be active in concrete’s environment of high alkalinity and low oxygen. *Bacillus subtilis* JC3 a non-pathogenic alkalophilic microorganism commonly found in soil and is known to deposit the calcite minerals when it is supplied with nutrients and right conditions to grow. The bacteria introduced into the concrete during mixing process will form spores in the highly alkaline environment of concrete. Once a crack forms, the pH level at the cracked surface will drop due to the exposure to air. The combination of the pH drop and a flow of oxygen, moisture and carbon dioxide at the crack face will activate the microorganisms and will provide the conditions favorable for growth. The microorganisms will deposit calcium carbonate, and as the crack fill up, the supply of oxygen and carbon dioxide will be interrupted, causing the microorganisms to hibernate again, ensuring the continual effectiveness of the microorganisms in filling up cracks at the same location. Bio-mineralizationby *Ammonification* (Ammo acid degradation**)** is mediated by *Bacillus subtilis* JC3. Ammonification usually occurs under aerobic conditions (known as oxidative deamination) with the liberation of ammonia (NH3) or ammonium ions (NH4) when dissolved in water. The ammonia liberated will provide the conditions favorable for growth and also maintains the pH of concrete.

**Experimental Investigations**

**Effect of Bacterial Cell Concentration on Strength**

Effect of cell concentration of *Bacillus subtilis* JC3 on the strength is studied by determining the compressive strength of standard cement mortar cubes incorporated with various bacterial cell concentrations as per IS: 4031-part 6 as shown in Figure 1.

**Compressive Strength Studies on Bacterial Concrete**

Compressive strength of bacterial concrete is tested as per IS: 516-1959 and plotted in Figure 2.

**Ultrasonic Pulse Velocity Test (USPV)**

The test is performed as per IS code 13311 (Part 1) 1992 to find out the homogeneity of bacterial concrete, presence of cracks, voids and other imperfections and changes in concrete structure with time. In this method, velocity is co-related to strength and quality of bacterial concrete specimens as shown in Table 5.

**Table 1: Quality of concrete based on Ultrasonic pulse velocity**

|  |  |
| --- | --- |
| Velocity | Quality of concrete |
| > 4.5 km/s | excellent |
| 3.5 to 4.5 km/s | Good |
| 3.0 to 3.5 km/s | medium |
| < 3.0 km/s | doubtful |

**Rebound Hammer Test**

As per IS 13311, (Part 2): 1992, this test measures the surface hardness of concrete and is co-related to the strength and quality of concrete. Harder the surface of the material tested, greater is the rebound. Table2 shows Guidelines for qualitative interpretation of rebound hammer test results as tabulated in Table 6.

**Table 2: Quality of concrete based on Average Rebound Hammer**

|  |  |
| --- | --- |
| Average rebound number | Quality of concrete |
| > 40 | Very good hard layer |
| 30 to 40 | Good layer |
| 20 to 30 | Fair |
| < 20 | Poor concrete |

**Diffusion Characteristics of Bacterial Concrete**

Understanding transport phenomena in concrete at its micro-structural level has become of increasing importance in elucidating the deterioration process of concrete such as corrosion of reinforcement embedded in concrete which is caused by penetration of aggressive substances into concrete. The chloride resistance of concrete is governed primarily by the pore structure and the concrete diffusivity. Chloride ion penetration is one of the main parameter affecting the durability of reinforced cement concrete structures. The most important concrete characteristic, apart from permeability, is diffusion. The mode of transport of chloride ion through concentration gradient is called Diffusion. The rate at which chloride ions penetrate into concrete determines the time period after which the passivity of reinforcing bars begin to break down. Chloride diffusivity in terms of charge passed of bacterial concrete using Rapid Chloride Penetration Test (RCPT) as per ASTM C 1202 is investigated. Usually chlorides penetrate in concrete by diffusion along water paths or open pores. Some of these chlorides can react with the cement compounds, mainly tri-calcium aluminates (C3A), forming stable chloro complexes. The excess of chloride, which is free, leads to the initiation of the corrosion process.

In the AASHTO T277 (ASTM C1202) test (Electrical indication of concrete’s ability to resist chloride ion penetration**)**, a water-saturated, 50-mm thick, 100-mm diameter concrete specimen is subjected to a 60 V applied DC voltage for 6 hours. In upstream reservoir is a 3.0% NaCl solution of 2.4N concentration (Cathode) and in the downstream reservoir is a 0.3 M NaOH solution (chloride free) (Anode). The total charge passed is determined and this is used to rate the quality of the concrete according to the criteria rating mentioned in the code. Rapid chloride ion penetrability tests were conducted on controlled and bacterial specimens. The total charge passing through from one reservoir to another reservoir through centrally placed concrete specimen in 6 hrs was measured, at an interval of 30 min, indicating the degree of resistance of the specimen to chloride ion penetration as shown in Table 7. The following formula, based on the trapezoidal rule can be used to calculate the average current flowing through one cell.

Q = 900(I0+2I30+2I60+2I90+2I120+…+2I300+2I330+I360)

Where, Q = current flowing through one cell (coulombs)

I0 = Current reading in amperes immediately after voltage is applied, and

It = Current reading in amperes at t minutes (30 min interval) after voltage is applied

The electric charge passed, Q in coulombs, obtained from Rapid chloride ion penetrability test was used to calculate Chloride Migration Diffusion Coefficient in steady state conditions from Berke’s empirical Equation.

DC=0.0103 x 10-12 x Q0.84 m2/s

The calculated diffusion coefficient values, in Table 8, are used to classify the concrete in terms of their permeability as per the recommendations of the Concrete Society, UK:

High permeability concrete: >5x10-12 m2/s.

Average permeability concrete: (1 to 5) x 10-12 m‑/s.

Low permeability concrete :< 1 x 10-12 m2/s.

In addition, resistivity or conductivity can also be determined from the initial current reading, since the resistance of the specimen can be calculated immediately from Ohm’s law:

R=V/I

Where R is electrical resistance in ohm (Ω), V is voltage in volts, and I is current in ampere.

The electrical resistivities of normal and bacterial concrete specimens, shown in Table 9 are determined:

Resistivity (Ω .cm) =RA/L

Where A is area of the specimen, and L is thickness of the specimen.

**Table 3: RCPT and Resistivity Criteria Ratings**

|  |  |  |
| --- | --- | --- |
| Permeability Class | Rapid Chloride Permeability Charge Passed (Coulombs) as per ASTM C1202 | Electrical Resistivity (kΩ-cm) as per Concrete Society, UK |
| High  | > 4,000  | < 12  |
| Moderate | 2,000 - 4,000  | 12 - 21  |
| Low | 1,000 - 2,000  | 21-37 |
| Very Low | 100 - 1,000  | 37-254 |
| Negligible | < 100  | >254 |

**Sea Water Resistance**

Sea water is a complex solution of many salts containing living matter, suspended silt, dissolved gases and decaying organic material. The average salt concentration of sea water is about 3.5% although it varies from sea to sea depending upon geological location. Seawater containing up to 35,000 ppm of dissolved salts is generally suitable as mixing water for concrete not containing steel. About 78% of the salt is sodium chloride, and 15% is chloride and sulfate of magnesium. Although concrete made with seawater may have higher early strength than normal concrete, strengths at later ages (after 28 days) may be lower. This strength reduction can be compensated for by reducing the water-cement ratio. Seawater is not suitable for use in making steel reinforced concrete and it should not be used in prestressed concrete due to the risk of corrosion of the reinforcement, particularly in warm and humid environments.Sodium or potassium in salts present in seawater used for mix water can aggravate alkali-aggregate reactivity. Thus, seawater should not be used as mix water for concrete with potentially alkali-reactive aggregates. Seawater used for mix water also tends to cause efflorescence and dampness on concrete surfaces exposed to air and water. Concrete exposed to sea water is wetted by a solution of salts-- principally sodium chloride and magnesium sulfate. Damage to concrete, if it occurs, usually results from failure to use good practices in concrete construction, and often is the result of freezing and thawing or wetting and drying as much as or more than the results of the effects of sea water as such. Magnesium sulfate may attack most, if not all, of the constituents of hardened Portland cement paste, especially the aluminate constituent; chlorides may promote corrosion of steel; and alkalies may participate in alkali-aggregate reaction.

The amounts of salts in Table 4 were dissolved in plain water to prepare 1000gm of sea water of 1N concentration. Cubes of 100mm size were weighed and immersed in water diluted with composition of sea water prepared in the laboratory as per ASTM D1141 for 90 days continuously and then the cubes were taken out and weighed. The percentage losses in weight, percentage reductions in compressive strength, Acid durability factors (ADF) and Acid Attack factors(AAF) were calculated and tabulated in Table 10.

**Table 4: Composition of artificial sea water**

|  |  |
| --- | --- |
| Composition | Concentration, g/lit |
| Sodium chloride | 24.53 |
| Magnesium chloride | 5.2 |
| Sodium sulphate | 4.09 |
| Calcium chloride | 1.16 |
| Potassium chloride | 0.695 |

**Cost Analysis**

The cost/benefit analysis of bacterial concrete balances the increased cost of the concrete against substantial repair material costs, enhanced durability and aesthetic benefits. The benefits are apparent at strength and performance of the finished product. Only expensive component in the development of bacterial concrete is nutrients. In this project, one litre of nutrients mixed bacterial culture costs Rs 60.

**TEST RESULTS AND DISCUSSIONS**

The following plot shows effect of bacterial cell concentration on the compressive strengths of cement mortar cubes.



**Figure 1: Effect of bacterial cell concentration on the strength of concrete**

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**Figure 2: Strength development of a Normal concrete and Bacterial concrete**

In bacterial concrete, as it gains strength, hardness increases and as a result, the rebound hammer values are more because of greater elastic rebound. In order to assess particle continuity inside the concrete specimen, USPV test is recommended.

**Table 5: Ultrasonic pulse velocity test results of various grades of normal and bacterial concretes**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Type of Concrete | Age of Concrete(in days) | M20 | M40 | M60 | M80 |
| Velocity | Quality of Concrete | Velocity | Quality of Concrete | Velocity | Quality of Concrete | Velocity | Quality of Concrete |
| Normal Concrete | 28 | 3.26 | medium | 4.39 | Good | 4.89 | Excellent | 5.13 | Excellent |
| 60 | 3.36 | medium | 4.43 | Good | 4.92 | Excellent | 5.19 | Excellent |
| 90 | 3.41 | medium | 4.50 | Good | 4.99 | Excellent | 5.33 | Excellent |
| Bacterial Concrete | 28 | 4.27 | Good | 4.73 | Excellent | 5.22 | Excellent | 5.94 | Excellent |
| 60 | 4.33 | Good | 4.89 | Excellent | 5.36 | Excellent | 6.02 | Excellent |
| 90 | 4.39 | Good | 4.92 | Excellent | 5.41 | Excellent | 6.05 | Excellent |

**Table 6: Rebound hammer test results of various grades of normal and bacterial concrete specimens**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Type of Concrete | Age of Concrete(in days) | M20 | M40 | M60 | M80 |
| Average Rebound Number | Quality of Concrete | Average Rebound Number | Quality of Concrete | Average Rebound Number | Quality of Concrete | Average Rebound Number | Quality of Concrete |
| Normal Concrete | 28 | 25 | Fair | 34 | Good Layer | 46 | Very Good Hard Layer | 51 | Very Good Hard Layer |
| 60 | 28 | Fair | 36 | Good Layer | 49 | Very Good Hard Layer | 53 | Very Good Hard Layer |
| 90 | 29 | Fair | 38 | Good Layer | 51 | Very Good Hard Layer | 54 | Very Good Hard Layer |
| Bacterial Concrete | 28 | 33 | Good Layer | 44 | Very Good Hard Layer | 53 | Very Good Hard Layer | 59 | Very Good Hard Layer |
| 60 | 35 | Good Layer | 47 | Very Good Hard Layer | 55 | Very Good Hard Layer | 60 | Very Good Hard Layer |
| 90 | 37 | Good Layer | 49 | Very Good Hard Layer | 58 | Very Good Hard Layer | 63 | Very Good Hard Layer |

**Table 7: Chloride ion Permeability of Normal and Bacterial Concretes**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Charge Passed (Coulombs) | Chloride Permeability as per ASTM C1202 | Charge Passed (Coulombs) | Chloride Permeability as per ASTM C1202 | Charge Passed (Coulombs) | Chloride Permeability as per ASTM C1202 |
| Age(days) | 28 | 60 | 90 |
| Concrete without Bacteria |
| M20 | 2419 | Moderate | 2213 | Moderate | 2100 | Moderate |
| M40 | 2008 | Moderate | 1991 | Low | 1817 | Low |
| M60 | 1022 | Low | 997 | Low | 943 | Low |
| Concrete with Bacteria |
| M20 | 367 | Very Low | 351 | Very Low | 327 | Very Low |
| M40 | 238 | Very Low | 222 | Very Low | 202 | Very Low |
| M60 | 173 | Very Low | 159 | Very Low | 96 | Very Low |

**Table 8: Chloride Diffusion Coefficients of Normal and Bacterial Concretes**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Chloride Migration Diffusion Coefficient (DC) | Chloride Permeability as per Concrete Society,UK | Chloride Migration Diffusion Coefficient (DC) | Chloride Permeability as per Concrete Society,UK | Chloride Migration Diffusion Coefficient (DC) | Chloride Permeability as per Concrete Society,UK |
| Age(days) | 28 | 60 | 90 |
| Concrete without Bacteria |
| M20 | 7.16E-12 | High | 6.64E-12 | High | 6.36E-12 | High |
| M40 | 6.12E-12 | High | 6.08E-12 | High | 5.63E-12 | High |
| M60 | 3.47E-12 | Medium | 3.40E-12 | Medium | 3.24E-12 | Medium |
| Concrete with Bacteria |
| M20 | 1.47E-12 | Medium | 1.41E-12 | Medium | 1.33E-12 | Medium |
| M40 | 1.02E-12 | Medium | 0.96E-12 | Low | 0.89E-12 | Low |
| M60 | 0.78E-12 | Low | 0.73E-12 | Low | 0.66E-12 | Low |

Grades of Normal concrete have higher current flow when compared to Grades of Bacterial concrete. The diffusivity of chloride through concrete therefore depends on the microstructure of the concrete cover. Bacterial concrete will have dense microstructure due to precipitation of mineral in pores of concrete. The impermeability of concrete can be represented by the rate of flow or diffusion coefficient of chloride ions through the unit area of concrete. Diffusion Coefficient (DC) of chloride ions decreases with increase in higher grades in normal concrete but with introduction of bacteria into concrete further decreased the effective diffusion coefficient. Reduction in chloride ion permeability values indicates that bacteria induced concrete has shown between 85% to 90 % higher resistance against the chloride ion movements in bacterial concrete as compared to the chloride movements in normal concrete.

**Table 9: Electrical Resistivity of Normal and Bacterial Concretes**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Electrical resistivity (ρ) | Chloride Permeability as per Concrete Society,UK | Electrical resistivity (ρ) | Chloride Permeability as per Concrete Society,UK | Electrical resistivity (ρ) | Chloride Permeability as per Concrete Society,UK |
| Age(days) | 28 | 60 | 90 |
| Concrete without Bacteria |
| M20 | 84 | Very Low | 86 | Very Low | 95 | Very Low |
| M40 | 101 | Very Low | 105 | Very Low | 113 | Very Low |
| M60 | 200 | Very Low | 209 | Very Low | 242 | Very Low |
| Concrete with Bacteria |
| M20 | 554 | Negligible | 589 | Negligible | 628 | Negligible |
| M40 | 856 | Negligible | 942 | Negligible | 1178 | Negligible |
| M60 | 1178 | Negligible | 1570 | Negligible | 1884 | Negligible |

Induction of bacteria increases the electrical resistivity (ρ). The concretes containing bacteria presented a higher resistivity than the reference one. Therefore, the resistivity of the concrete is related to the inhibition of the migration of chloride ions, which are subordinated to the flow paths in the microstructure of the paste. The formation of flow paths in the reference concrete results from the hydration of the cement. The mineral precipitation alters the original microstructure formed by the cement and fills the pores increasing the tortuosity of the capillary network, resulting in longer paths and smaller pore diameters. The reduction in pore diameter intensifies the interaction between the soluble ions, the particles, and the hydrates. In consequence, the ionic mobility in electrolytic solutions is decreased.

**Table 10: Seawater resistance studies on Bacterial Concrete**

|  |
| --- |
| **SEA WATER ATTACK RESISTANCE STUDIES** |
|  |  |  |  |  |  |  |  |  |
| **Grade of concrete** | **M20** | **M40** | **M60** | **M80** | **M20** | **M40** | **M60** | **M80** |
| **Age** | Loss in weight (%)  |
| 28 days | 3.41 | 1.58 | 1.23 | 1.05 | 2.22 | 1.09 | 0.85 | 0.77 |
| 60 days | 5.12 | 1.98 | 1.45 | 1.33 | 3.01 | 1.56 | 1.21 | 1.04 |
| 90 days | 7.58 | 3.55 | 2.19 | 1.97 | 4.16 | 2.41 | 1.66 | 1.30 |
|  | Loss in compressive strength (%) |
| 28 days | 10.41 | 6.50 | 3.65 | 3.35 | 7.25 | 4.51 | 1.88 | 1.64 |
| 60 days | 15.58 | 9.12 | 5.26 | 4.58 | 9.12 | 6.08 | 3.51 | 1.99 |
| 90 days | 19.25 | 11.02 | 7.16 | 6.19 | 10.56 | 8.09 | 4.11 | 3.15 |
|  | Acid Durability Factor (ADF)(%) |
| 28 days | 19.22 | 26.52 | 19.22 | 37.02 | 41.84 | 27.62 | 39.71 | 51.72 |
| 60 days | 37.65 | 41.01 | 37.65 | 49.75 | 54.18 | 46.44 | 51.63 | 58.67 |
| 90 days | 47.37 | 52.28 | 47.37 | 55.84 | 59.27 | 56.70 | 61.75 | 65.18 |
|  | Acid Attack Factors (AAF)(mm) |
| 28 days | 0.10 | 0.09 | 0.06 | 0.04 | 0.07 | 0.06 | 0.05 | 0.03 |
| 60 days | 0.27 | 0.23 | 0.16 | 0.10 | 0.25 | 0.18 | 0.10 | 0.06 |
| 90 days | 0.47 | 0.40 | 0.28 | 0.17 | 0.40 | 0.34 | 0.24 | 0.14 |

From the results of percentage loss in weight and percentage reduction in compressive strengths as shown in Table 10, it has been observed that bacterial concrete of all grades were less attacked by sea water and are more durable than controlled concrete. The loss in mass and the reduction in compressive strength in chloride solution were reduced by around 25 to 35% in bacterial concrete specimens for all grades. The hydration of cement fills the volume initially occupied by the water, reducing the total porosity of the systems. The mineral precipitation in Bacterial concrete reduces the interconnectivity of the pore structure by decreasing the pore size (pores refinement), which is directly related to durability.

**CONCLUSION**

Improvement in compressive strength reaches a maximum at about 105/ml cell concentration. SEM examination reveals the growth of fibrous filler material within the pores due to the presence of such microorganisms. This growth is beneficial by the modification of the porosity and pore size distribution of cement mortar which it generates. The presence of biogenic calcite crystals in pores of concrete resulted in a decrease of its permeation properties. As a result, an increased resistance towards chloride migration and freezing and thawing was noticed. Precipitation of these crystals inside the gel matrix may enhance the durability of concrete significantly. Bacteria incorporated concrete specimens reports an increase in ultrasonic pulse velocity, indicating that pore structure is modified.

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