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Experimental Investigations on Strength and Durability Characteristics of Bacterial Concrete

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Abstract : High Performance Concrete (HPC) appears to be a better choice for a strong and durable structure. Suitable addition of mineral admixtures such as silica fume, ground granulated blast furnace slag, rice husk ash, fly ash and highly reactive metakaolin in concrete or induction of suitable bacteria in concrete improve the strength and durability of concrete due to considerable improvement in the microstructure of concrete composites. One effective remedy for closure of cracks is the Bacterial Concrete (BC) which will continuously deposit calcite in concrete. This, phenomenon is called as Microbiologically Induced Calcite Precipitation (MICP). The urease enzyme enables the deposition of calcium carbonate (CaCO3) with the help of bacteria. The bacterial remediation technique surpasses other techniques as it is bio-based, eco-friendly and durable. Bacteria need to offer resistance to withstand high pH of concrete and mechanical stresses during mixing.

Key Words: High Performance Concrete, Bacterial Concrete, Microbiologically Induced Calcite Precipitation, Urease, Enzyme.

1.INTRODUCTION

During the last two decades, it has been observed that durability and corrosion are considered as vital criteria for analysing the behaviour of concrete in addition to strength. Therefore, for improving the service life of customary 40 - 50 years to 150 years of concrete, research activities are undertaken to find suitable potential material to provide reliable performance under different environments. The major shortcoming of Conventional Cement Concrete (CCC) is that it develops cracks under tension. Small cracks formed on the surface of the concrete make the entire structure to lose strength due to permeation of water in the concrete. Therefore, it leads to corrosion of steel and reduction of life span of the structure. It may not be possible to visualize the cracks, but they may tend to propagate into fissures in due course and affect the reinforcement of the structure. The deterioration of reinforced concrete results in high maintenance costs. Micro-cracks are therefore precursors to structural failure.

1.1 Need for Bacterial Concrete

Bio concrete is emerging as a viable solution for controlling crack propagation. Bio concrete is a product which involves healing cracks by production of mineral compounds through microbial activity in the concrete. This technique is more required, owing to the mineral precipitation which is pollution free and natural. The use of concrete is rapidly increasing worldwide and therefore the development of bacterial mediated concrete is urgently needed for providing sustainable concrete. The mechanisms that would contribute to a longer service life of concrete structures would make the material not only more durable but that would also be more sustainable is the need for the day. Microbial carbonate precipitation decreases the permeation properties of concrete. The potential of bacteria to precipitate calcium carbonate in concrete has proven to be a promising future.

1.2 Advantages of Bacterial Concrete

The microbial cementation could be used for the civil and environmental engineering applications like, to enhance stability of retaining walls, embankments and dams, reinforcing underground constructions, constructing a permeable reactive barrier in mining and environmental engineering, increasing the resistance to petroleum borehole degradation during drilling and extraction, controlling erosion in coastal areas and rivers, increasing the bearing capacity of piled or non-piled foundation and treating pavement surface.

1.3 Applications of Microbial Cementation

The microbial cementation could be used for the civil and environmental engineering applications like, to enhance stability of retaining walls, embankments and dams, reinforcing underground constructions, constructing a permeable reactive barrier in mining and environmental engineering, increasing the resistance to petroleum borehole degradation during drilling and extraction, controlling erosion in coastal areas and rivers, increasing the bearing capacity of piled or non-piled foundation and treating pavement surface.

1.4 Objectives of Study

The objectives of the present work are summarized as follows;

- To produce bacterial concrete by adding bacteria into M20 grade conventional concrete.
- To obtain the optimum dosage of cell concentration of various types of bacteria like Bacillus Megaterium (BM), Bacillus Subtilis (BS) and Pseudomonas Aeruginosa (PA) to be added into concrete for better strength and durability characteristics of bacterial concrete.
- To increase the mechanical properties of concrete using bacteria.
- To enhance the durability characteristics of concrete using bacteria.
- To improve the corrosion resistance of concrete using bacteria.
- To enrich the microstructure properties of concrete.

2. INGREDIENTS USED IN BACTERIAL CONCRETE

While developing the concrete mix for Bacterial Concrete (BC), it is important to decide right composition of various elements and assess their performance and analyze their properties and understand the interaction among different elements for optimum usage. The ingredients used for this investigation are the same as those used for normal strength concrete such as cement, Fine Aggregate (FA), Coarse Aggregate (CA) and water except bacteria which is generally not used in conventional concrete. The performance requirements of concrete may involve enhancement of the following properties,

- Ease of placement and compaction without segregation
- Long-term mechanical properties
- Early strength
- Toughness
- Volume stability
- Long-term durability properties
- Longer service life

Effective production of BC is achieved by carefully selecting, controlling and proportioning all ingredients. In order to achieve quality BC, optimum proportions must be selected, considering the characteristics of cement, aggregate quality, paste proportion, aggregate paste interaction, admixture type, dosage of bacteria and meticulous care in mixing and handling.

2.1 Cement

Cement plays a vital role in concrete. The criterion for the selection of cement is its property of producing improved microstructure in concrete. For the present investigation, 53 grade OPC conforming to IS: 12269 - 2013 was used. The cement sample was tested as per the procedures given in IS: 4031-1988 and IS : 4032-1985.

2.2 Fine Aggregate

Fine Aggregates used for BC should be properly graded to give minimum void ratio and be free from deleterious materials like clay, silt content and chloride contamination etc.For this present investigation, locally available Penna river sand was used as fine aggregate. The sand was washed and screened at site to remove deleterious materials and tested as per the procedure given in IS: 2386 – 1963

2.3 Coarse Aggregate

The coarse aggregate, meeting the requirements of IS : 383-1970, is suitable for making BC. Considering all the above aspects, blue granite crushed stone aggregates of nominal size 20 mm and of typical particle shape “average and cubic” were used as the coarse aggregates for the present investigation. The aggregates were tested as per the procedure given in IS: 2386 - 1963.

2.4 Water

Water conforming to the requirements of IS: 456-2000 is found to be suitable for making BC. It is generally stated that water fit for drinking is fit for making concrete. For this present investigation, drinking water was used for making BC and curing.

2.5 Bacteria

Bacillus Megaterium (BM), Bacillus Subtilis (BS) and Pseudomonas Aeruginosa (PA) were found to thrive in this high-alkaline environment under conditions of high pH value up to 13 of the cement-water mixer. Based on the above criteria, the bacteria used in this study are Bacillus megaterium, Bacillus subtilis and Pseudomonas aeruginosa in three concentrations of 10^4, 10^5 and 10^6 cells/ml each of mixing water shown in Table 1. The bacterial cultures were obtained from the Department of Microbial Biotechnology, Bharathiar University, Coimbatore. They were suspended in a nutrient broth solution consisting of peptone, NaCl and beef extract. The obtained bacterial cultures were refrigerated until further use.

Table -1: Cell concentrations of Bacterial solution

Bacteria	Cell Concentration / ml
Bacillus Megaterium	10^4
	10^5
	10^6
Bacillus Subtilis	10^4
	10^5
	10^6
Pseudomonas Aeruginosa	10^4
	10^5
	10^6

3. CONCEPTS OF MIX DESIGN FOR BACTERIAL CONCRETE

The main difference between mix design of bacterial concrete and the CCC is the emphasis laid on performance aspect. In bacterial concrete, besides strength, durability considerations are given utmost importance. To achieve high durability of bacterial concrete, the mix design of bacterial concrete should be based on the following considerations:

- The water-cement (w/c) ratio should be as less as possible.
- The coarse aggregates meeting the requirements of IS 383-1970 is suitable for making bacterial concrete.
- The fine aggregate used for bacterial concrete should be properly graded so as to give minimum voids ratio and be free from deleterious materials like clay, silt content, chloride contamination etc.
- The workability of the concrete mix should be good enough to obtain good compaction.
- The transition zone between aggregates and cement paste should be strengthened by adding bacteria.
- The microstructure of cement concrete should be made dense and impermeable by filling pores inside the concrete with Microbiologically Induced Calcite Precipitation (MICP).
- Proper curing regime of concrete should be established.

3.1 Method of Mix Design

Design of bacterial concrete mixes involves determination of the proportion of the constituents, cement, coarse and fine aggregates, water and bacteria, so that resultant composition produces a mix which will possess specified properties in fresh and hardened state. Since there is no code of reference in existence for bacterial concrete, the mix design procedure for Conventional Cement Concrete (CCC) as per IS: 10262 -2009 was followed. For the present investigation M20 ordinary grade concrete was designed and taken as control mix.

- **Mix proportions.**

  Cement: 413.33 kg/m^3
  Water: 186 kg/m^3
  Fine aggregate: 656.84 kg/m^3
  Coarse aggregate: 1221.64 kg/m^3
  Water-cement ratio: 0.45
  Bacteria: Required cell concentration

- **Mix ratio**

  Cement: 1
  Fine aggregate: 1.59
  Coarse aggregate: 2.96

3.2 Mix Designations

The mix proportion was arrived for M20 grade concrete as per IS: 10262 – 2009 and is 1: 1.59: 2.96 with water cement ration of 0.45. The design mix proportion was taken as the control mix and the specimen was designated as control specimen (CS). In that proportion, three types of bacteria namely BM, BS and PA were added in three concentrations of 10^4, 10^5 and 10^6 cells/ml each and the specimens were designated as BM1, BM2, BM3, BS1, BS2, BS3, PA1, PA2 and PA3 respectively. The water-cement ratio was similar for all the proposed mix proportions. Totally, ten different mixes (one control mix and nine bacterial concrete mixes) were prepared. The quantities of different material requirements per cube metre of concrete for M20 grade of bacterial concrete mixes is given in Table 2.

Table -2: Quantity of materials required for 1 m^3 of concrete.

Cement (kg)	Fine aggregate (kg)	Coarse aggregate(kg)	Water(kg)
186	413.33	656.84	1221.64

3.3 Preparation of Test Specimens

After weighing the materials, mixing was done in an ordinary drum type concrete mixer for about 3 minutes. For casting the specimens, cast-iron moulds were used. Oil was applied inside the moulds to facilitate easy removal of specimens. The concrete was placed into the moulds in three layers of equal height and each layer was compacted by using a table vibrator. Control concrete specimens were cast without the addition of microbes. Bacterial concrete specimens were cast with different cell concentrations of each bacterium. Minimum three specimens were cast for each mix for each test. In all mixes, specimens were cast to study the strength and durability – related properties. After twenty-four hours of casting, the test specimens were demoulded and immersed in water for curing, till the age of test. The details of the test specimens are given in Table 3 and Table 4.

4. EXPERIMENTAL INVESTIGATIONS

The experimental investigations carried out to study the workability, strength, durability and microstructural properties of bacterial concrete using Bacillus Megaterium (BM), Bacillus Subtilis (BS) and Pseudomonas Aeruginosa (PA) bacteria. Experimental investigations were carried out on the bacterial concrete test specimens to ascertain the workability and strength-related properties such as compressive strength, splitting tensile strength, flexural strength, elastic modulus, flexural behavior, ultrasonic pulse velocity and bond strength of the designed M20 grade concrete mixes. Also, in this paper, experimental investigations were carried out on the bacterial concrete test specimens to ascertain the durability-related properties such as saturated water absorption, Porosity, sorptivity, permeability, acid resistance, sea water resistance, impact strength, chloride penetration, corrosion resistance and alkalinity measurement (pH) of the designed M20 grade bacterial concrete mixes. Minimum three specimens were tested for each mix for each test. All the tests were performed as per specifications.

5. RESULTS AND DISCUSSION

This deals with strength and other parameters of control and bacterial concrete like workability, compressive strength, splitting tensile strength, Flexural strength, Flexural behaviour, Ultrasonic pulse velocity, Pull- out bond strength and Microstructural analysis. This chapter also deals with durability of control and bacterial concrete like Saturated water absorption,Porosity, Sorptivity, Permeability, Acid resistance, Sea water resistance, Impact strength, Accelerated electrolytic corrosion and Alkalinity measurement.

5.1 Results and Discussion of Strength Characteristics

5.1.1 Workability of Concrete

The workability of concrete is mainly influenced by the water requirements at the time of mixing. For conventional concrete, it is decided mainly on the basis of the maximum size of aggregate used. When bacteria are added to concrete, it influences no demand of excess water. It is generally reported that the bacterial concrete requires less water demand of the concrete mix as compared with concrete mix having the same degree of workability. The test results of workability of this present investigation are presented in Table 5.

5.1.2 Cube compressive strength

The cube compressive strength results of control concrete mix and bacterial concrete mixes at the ages of 7, 14, 28, 56 and 90 days are presented in Table 6 . The development of compressive strengths of M20 grade bacterial concrete mixes containing various types of bacteria with different cell concentration at the various ages are plotted in the form of graphs and are shown in Figures 1 to 4. In view of these comparisons, the compressive strength obtained for the bacterial concrete mixes reported in this present study could be considered to be reasonable. In Table 6.

Table -3: Types of strength – related tests and their specimen sizes

Sl. No	Type of test	Properties studied	Specimen size (mm)	No. of Specimens tested
1	Cube compressive strength	Cube compressive strength at 7, 14, 28, 56 and 90 days	150 x 150 x 150 mm cube	150
2	Cylindrical compressive strength	Cylindrical compressive strength at 28 days	150 mm x 300 mm cylinder	30
3	Splitting tensile strength	Splitting tensile strength at 7 days and 28 days	150 mm x 300 mm cylinder	60
4	Flexural strength	Flexural tensile strength (Modulus of rupture) at 28 days	150 x150 x 750 mm Prism	30
5	Stress - strain curve and elastic modulus	Elastic modulus at 28 days	150 mm x 300 mm cylinder	30
6	Non-destructive test (Ultrasonic pulse velocity test)	Quality of concrete at 28 days	150 x 150 x 150 mm cube	30
7	Flexural behaviour	Flexural behaviour at 28 days	100 x 150 x 1000 mm beam	12
8	Pull-out test	Bond strength at 28 days	150 x 150 x 150 mm cube embedded with 16 mm diameter tor steel	30

Table -4: Types of durability – related tests and their specimen sizes

Sl. No	Type of test	Properties studied	Specimen size (mm)	No. of Specimens tested
1	Saturated water absorption	Percentage water absorption at 28 and 90 days	100 x 100 x 100 mm cube	60
2	Porosity	Porosity at 28 and 90 days	100 x 100 x 100 mm cube	60
3	Sorptivity	Sorptivity at 28 and 90 days	100 mm diameter x 50 mm disc	60
4	Permeability	Permeability at 28 and 90 days	150 x 150 x 150 mm cube	60
5	Acid resistance	Acid resistance at 28 and 90 days	150 x 150 x 150 mm cube	120
6	Sea waterresistae	Sea water resistance at 28 and 90 days	150 x 150 x 150 mm cube	60
7	Impact strength	Quality of impact strength at 28 days	152 mm x 62.5 mm disc	30
8	Rapid chloride penetration	Chloride penetrability at 28 days	100 mm diameter x 50 mm disc	30
9	Acceleratedelectrolyticcorrosn	Quality of corrosive resistance at 28 days	100 mm x 150 mm x 1000 mm beam	30
10	Alkalinity measuremnt	pH of Bacterial Concrete mixes	Bacterial concrete power sampe	30

Table -5: Workability of M20 grade bacterial concrete mixes

Mix designation	Type of bacteria	Cell concentration (cells / ml)	Workability in terms of		
			Slump in 'mm'	Compaction factor	Vee - bee degrees in sec
CS	Control Specimen	-	95	0.93	9
BM1	Bacillus Megaterium	10^4	98	0.94	8
BM2		10^5	102	0.95	8
BM3		10^6	105	0.96	7
BS1	Bacillus Subtilis	10^4	95	0.93	9
BS2		10^5	102	0.95	8
BS3		10^6	106	0.96	7
PA1	Pseudomonas Aeruginosa	10^4	97	0.94	8
PA2		10^5	104	0.95	7
PA3		10^6	108	0.96	7

The strength activity index at the ages of 7, 14, 28, 56 and 90 days for M20 grade of bacterial concrete mixes containing various types of bacteria with different cell concentration are shown in Table 7. From the Table 8, it has been observed that at all ages, the maximum strength activity indices were obtained for the bacterial concrete specimens BM1, BS2 and PA2 as 1.25, 1.21 and 1.22 respectively. The development of compressive strength for bacterial concrete specimens BM, BS and PA bacteria at various ages are shown in Figures 5 to 7.

Table -6: Cube compressive strength of M20 grade bacterial concrete mixes

Mix designation	Type of bacteria	Cell concentration(cells / ml)	Average cube compressive strength in MPa				
			7 days	14 days	28 days	56 days	90 days
CS	Control Specimen	-	18.48	22.56	27.54	28.36	28.94
BM1	Bacillus Megaterium	10^4	22.63	27.56	33.62	34.94	36.31
BM2		10^5	21.47	26.58	32.45	33.61	34.72
BM3		10^6	21.42	26.33	31.98	33.15	34.37
BS1	Bacillus	10^4	20.87	25.52	31.12	32.12	32.90
BS2		10^5	21.63	26.56	32.48	33.87	34.98

BS3	Subtilis	10^6	21.02	25.65	31.28	32.64	33.72
PA1	Pseudomonas Aeruginosa	10^4	21.28	26.10	31.80	32.83	33.87
PA2		10^5	21.77	26.78	32.64	34.21	35.40
PA3		10^6	20.96	25.60	31.20	32.18	32.94

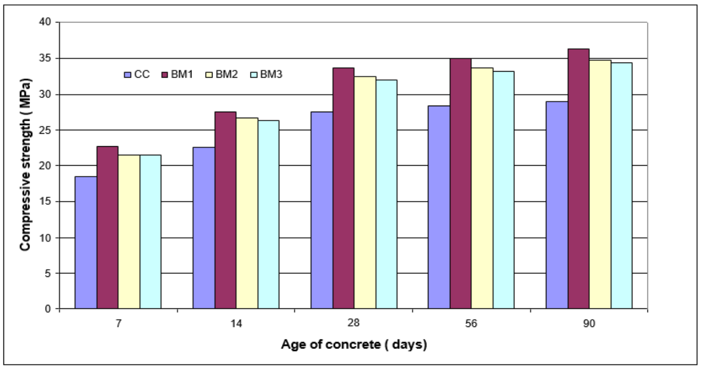

Figure -1: Influence of BM bacteria on compressive strength of M20 grade bacterial concrete mixes at various ages

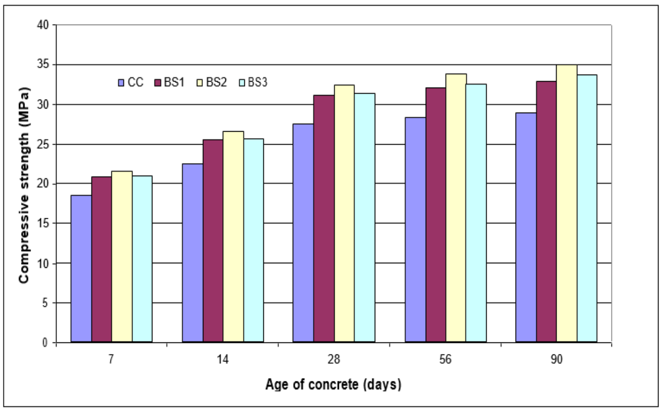

Figure -2: Influence of BS bacteria on compressive strength of M20 grade bacterial concrete mixes at various ages

Table -7: Cube compressive strength developmentof M20 grade bacterial concrete mixes

Mix designation	Type of bacteria	Cell concentration(cells / ml)	Strength gain (%)				
			7 days	14 days	28 days	56 days	90 days
CS	Control Specimen	-	67.10	81.92	100	102.98	105.08
BM1	Bacillus Megaterium	10^4	67.31	81.98	100	103.93	108.00
BM2		10^5	66.17	81.91	100	103.57	107.00
BM3		10^6	66.98	82.33	100	103.66	107.47
BS1	BacillusSubtilis	10^4	67.06	82.01	100	103.21	105.72

BS2		10^5	66.59	81.77	100	104.28	107.70
BS3		10^6	67.20	82.00	100	104.35	107.80
PA1	Pseudomonas Aeruginosa	10^4	66.92	82.08	100	103.24	106.51
PA2		10^5	66.70	82.05	100	104.81	108.46
PA3		10^6	67.18	82.05	100	103.14	105.58

Table -8: Cube compressive strength activity index of M20 grade bacterial concrete mixes

Mix designation	**Type of bacteria**	**Cell concentration(cells / ml)**	**Activity Index**				
			7 days	**14 days**	**28 days**	**56 days**	**90 days**
CS	Control Specimen	-	1.00	1.00	1.00	1.00	1.00
BM1	Bacillus Megaterium	10^4	1.22	1.22	1.22	1.23	1.25
BM2		10^5	1.16	1.18	1.18	1.19	1.20
BM3		10^6	1.16	1.17	1.16	1.17	1.19
BS1	BacillusSubtilis	10^4	1.13	1.13	1.13	1.13	1.14
BS2		10^5	1.17	1.18	1.18	1.19	1.21
BS3		10^6	1.14	1.14	1.14	1.15	1.17
PA1	Pseudomonas Aeruginosa	10^4	1.15	1.16	1.15	1.16	1.17
PA2		10^5	1.18	1.19	1.19	1.21	1.22
PA3		10^6	1.13	1.13	1.13	1.13	1.14

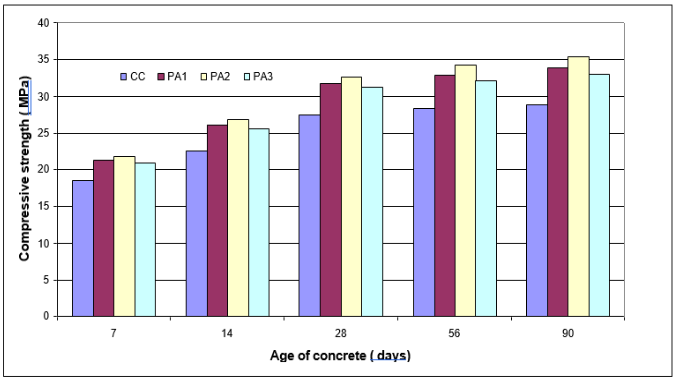

Figure -3: Influence of PA bacteria on compressive strength of M20 grade bacterial concrete mixes at various ages

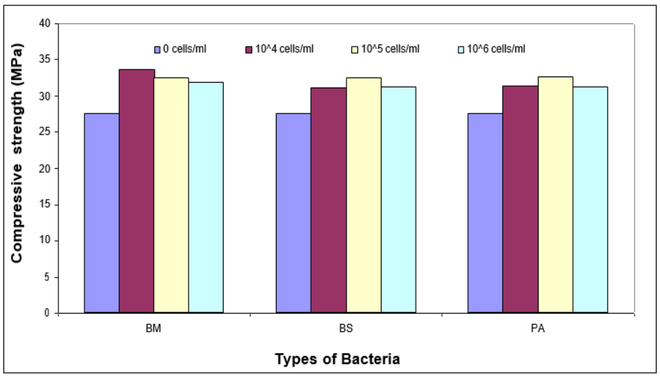

Figure -4: Optimum dosage of cell concentration of various types of bacteria on compressive strength at 28 days

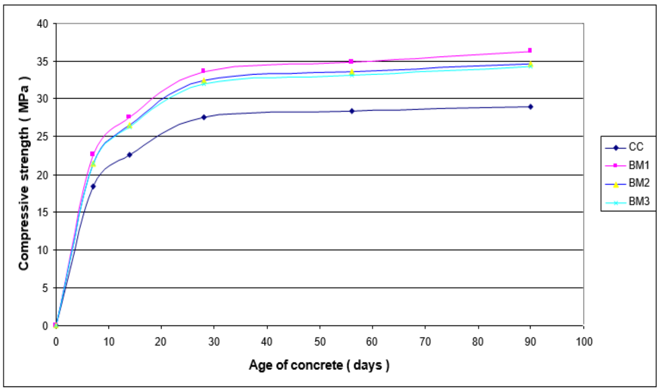

Figure -5: Development of compressive strength for bacterial concretemixes using BM bacteria at various ages

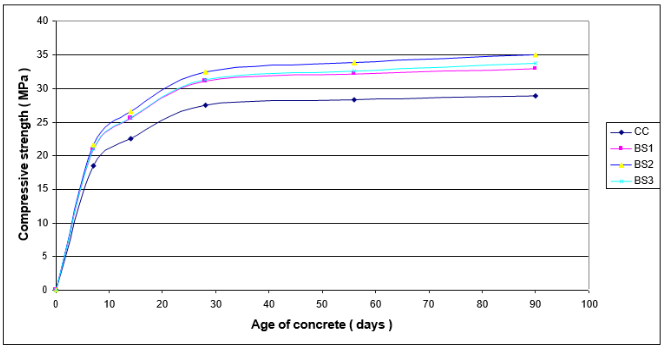

Figure -6: Development of compressive strength for bacterial concrete mixes using BS bacteria at various ages

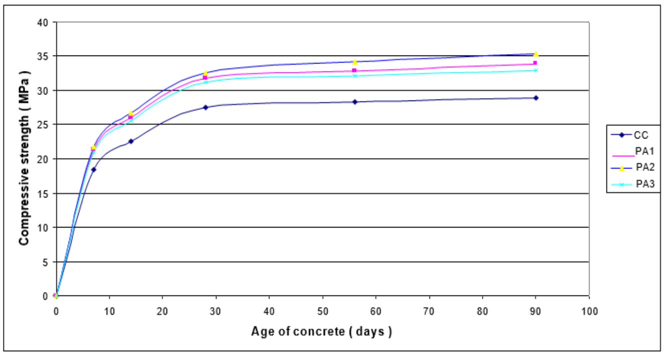

Figure -7: Development of compressive strength for bacterial concrete mixes using PA bacteria at various ages

5.1.3 Cylindrical compressive strength

The influence of bacteria and variation of compressive strength of M20 grade bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 28 days are plotted in the form of graph and shown in Figure 8.

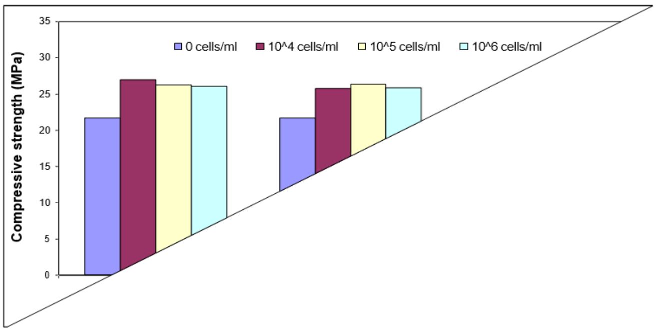

Figure -8: Influence of various types of bacteria on cylindrical compressive strength of M20 grade bacterial concrete mixes at 28 days

5.1.4 Splitting tensile strength

The influence of bacteria and variation of splitting tensile strength of bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 7 days and 28 days are plotted in the form of graphs as shown in Figures 9 and 10.

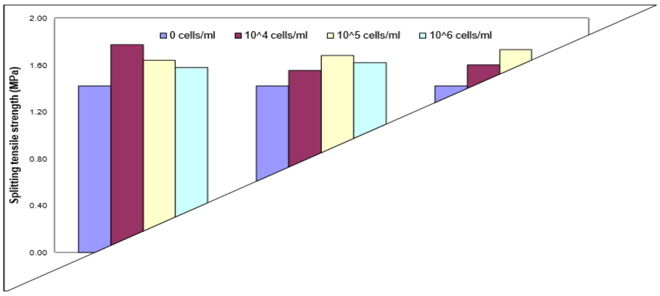

Figure -9: Influence of various types of bacteria on splitting tensile strength of M20 grade bacterial concrete mixes at 7 days

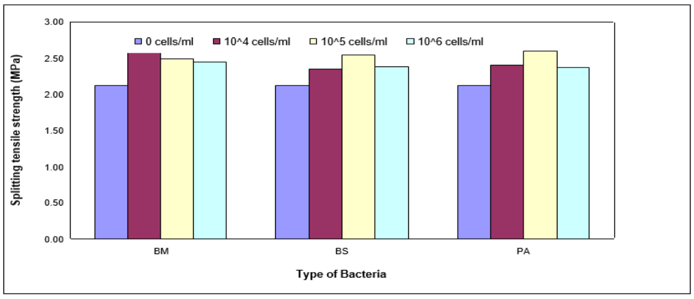

Figure -10: Influence of various types of bacteria on splitting tensile strength of M20 grade bacterial concrete mixes at 28 days

5.1.5 Flexural strength

The influence of bacteria and variation of flexural strength of bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 28 days are plotted in the form of graph as shown inFigure 11.

5.1.6 Stress-Strain curve and Elastic modulus

The stress-strain curve for all the M20 grade mixes was plotted in the form of graphs and the modulus of elasticity (E_C) at the age of 28 days was determined from the stress-strain curve and the results are presented in Figure 12. The influence of bacteria and variation of elastic modulus of bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 28 days are plotted in the form of graph as shown in Figure 13.

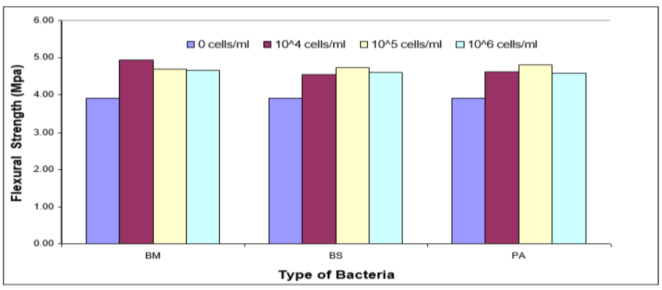

Figure -11: Influence of various types of bacteria on flexural strength of M20 grade bacterial concrete mixes at 28 days

5.1.7 Flexural Behaviour - Experimental Investigation

In flexure test, the beams were exposed to two-point loading to expose the behaviour of the RC beams. The load at first crack, ultimate load and the deflection at salient points were noted for all specimens. The crack pattern and deflected shape of all the beams were observed and marked as shown in Figures 14 to 17. The load at first crack, ultimate load and the corresponding mid-span deflections for all specimens were noted and tabulated as shown Table 9. From the test results, it is observed that the bacterial concrete specimens showed higher value of load carrying capacity compared to control concrete specimen and the deflection values also less for bacterial concrete specimens. The load-deflection curves are plotted for all the beams as shown in Figures 18 to 20.

5.1.8 Ultrasonic Pulse Velocity

This is a test for assessing the integrity of concrete. The non- destructive test results of M20 grade control concrete mix and bacterial concrete mixes at the age of 28 days are presented in Table 10. The influence of bacteria and variation of ultrasonic pulse velocity of bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 28 days are plotted in the form of graph as shown in Figure 21**.**

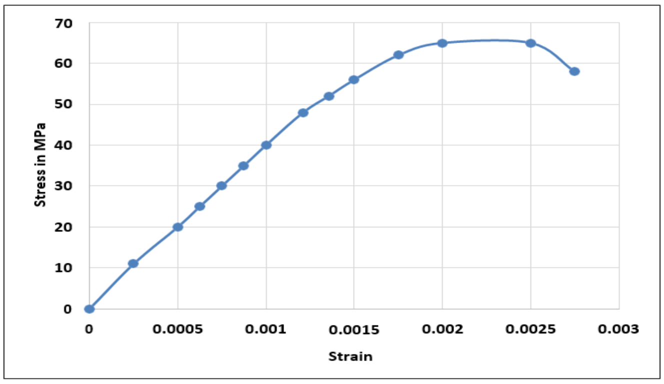

Figure -12: Stress-strain curve at 28 days for M20 grade bacterial concrete mix (BM1)

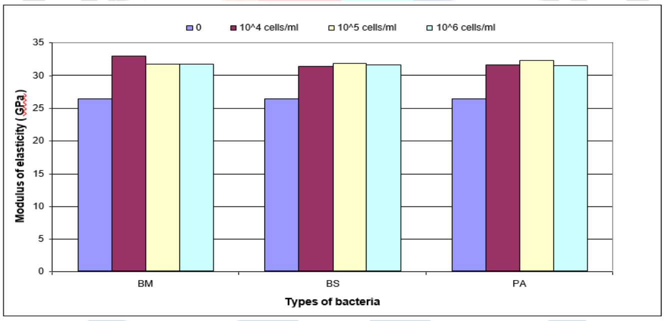

Figure -13: Influence of various types of bacteria on modulus of elasticity of M20 grade bacterial concrete mixes at 28 days

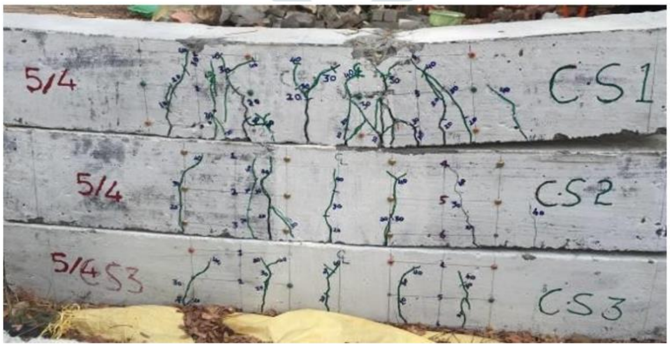

Figure -14: Deflected shape and Crack pattern of control concrete beam specimens

Table -9: Details of load at first crack, ultimate load and corresponding mid-span deflection of M20 grade bacterial concrete specimens

Beam Designation	Cell concentration (cells/ml)	Load at First Crack (kN)	Corresponding mid-span deflection to first crack load (mm)	Ultimate load (kN)	Corresponding mid-span deflection to Ultimate load (mm)
CS	-	11.7	1.06	44.7	10.24
BM1	104	15.3	1.26	49.0	11.42
BM2	105	16.2	1.42	47.5	10.02
BM3	106	16.1	1.38	47.3	9.98
BS1	104	15.5	1.56	46.7	10.11
BS2	105	16.3	1.50	49.0	10.04
BS3	106	15.8	1.48	47.2	10.58
PA1	104	15.9	1.54	47.3	9.89
PA2	105	17.0	1.64	47.3	10.06
PA3	106	15.6	1.62	47.0	9.99

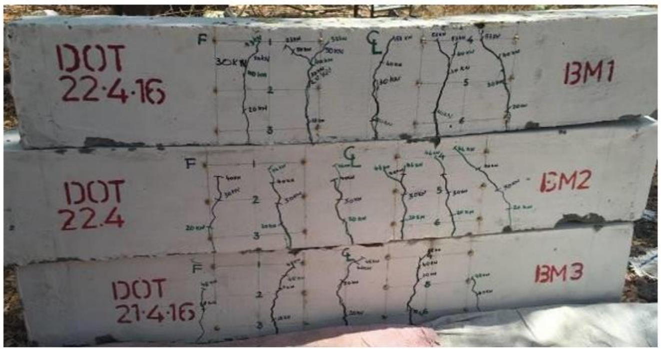

Figure -15: Deflected shape and Crack pattern of BM bacterial concrete beam specimens

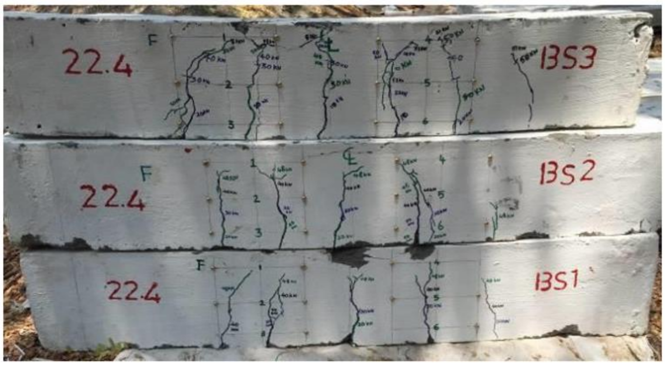

Figure -16: Deflected shape and Crack pattern of BS bacterial concrete beam specimens

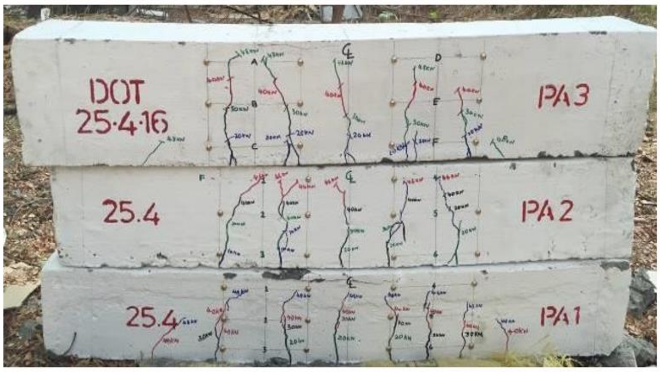

Figure -17: Deflected shape and Crack pattern of PA bacterial concrete beam specimens

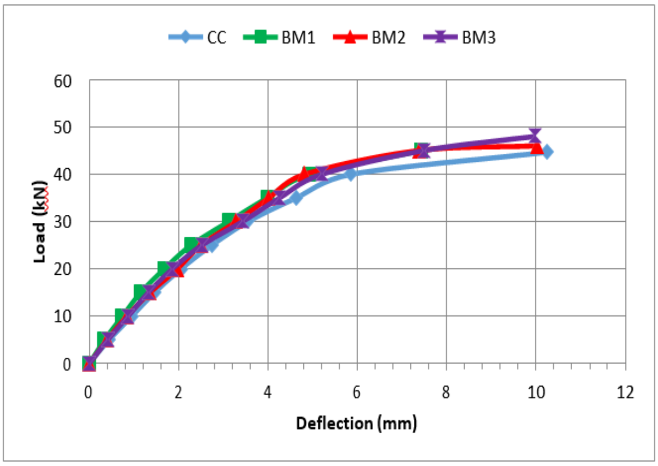

Figure -18: Load vs Deflection Curve for BM Bacterial Concrete

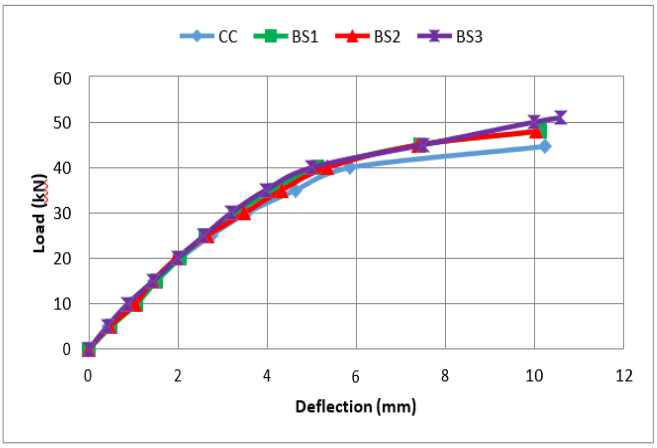

Figure -19: Load vs Deflection Curve for BS Bacterial Concrete

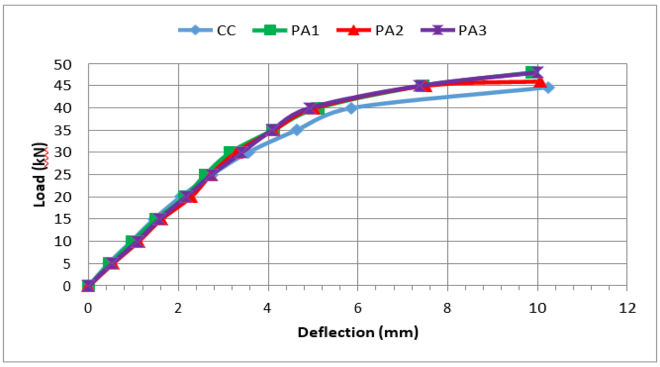

Figure -20: Load vs Deflection Curve for PA Bacterial Concrete

Table -10: Ultrasonic Pulse Velocity results of M20 grade bacterial concrete mixes

Mix designation	Type of bacteria	Cell concentration(cells / ml)	Ultrasonic Pulse Velocity at 28 days (km/sec)	Quality of concrete specimenas per IS: 13311 (Part 1) - 1992
CS	Control Specimen	-	4.25	Good
BM1	Bacillus Megaterium	10^4	5.35	Excellent
BM2		10^5	5.06	Excellent
BM3		10^6	4.98	Excellent
BS1	BacillusSubtilis	10^4	4.82	Excellent
BS2		10^5	5.12	Excellent
BS3		10^6	4.86	Excellent
PA1	Pseudomonas Aeruginosa	10^4	4.92	Excellent
PA2		10^5	5.18	Excellent
PA3		10^6	4.84	Excellent

5.1.9 Bond Strength

The influence of bacteria and variation of bond strength of bacterial concrete mixes containing various types of bacteria with different cell concentration at the age of 28 days are plotted in the form of graph as shown in Figures 22.

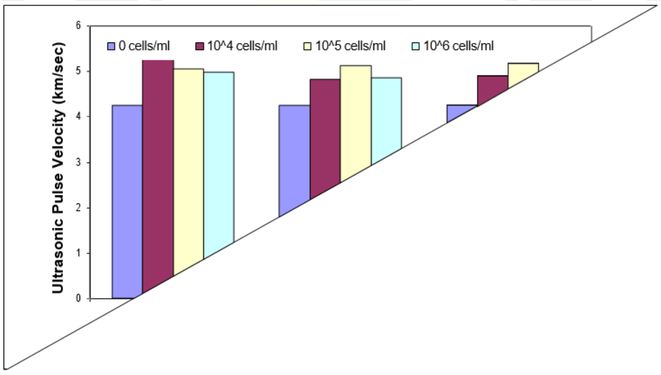

Figure -21: Influence of various types of bacteria on ultrasonic pulse velocity of M20 grade bacterial concrete mixes at 28 days

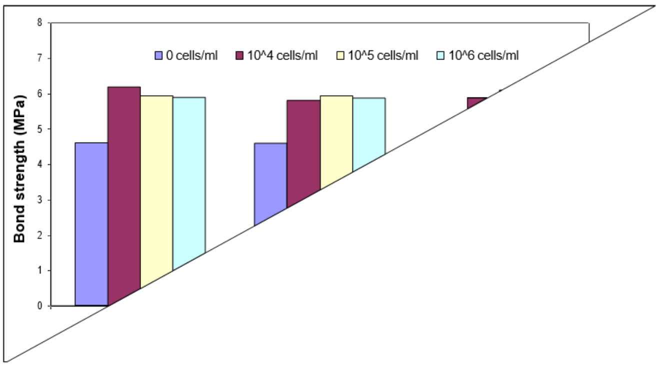

Figure -22: Influence of various types of bacteria on bond strength of M20 grade bacterial concrete mixes at 28 days

5.2 Result and Discussion of Durability Characteristics

5.2.1 Saturated Water Absorption

The influence of bacteria on the water absorption of concrete mixes withdifferent cell concentration of bacteria is shown in Figures 23 and 24.

5.2.2 Porosity

From the test results, it is observed that the effective porosity of bacterial concrete mixes was found to be lower when compared with the porosity of control concrete. It is also seen that the optimum dosage of cell concentration for Bacillus Megaterium, Bacillus Subtilis and PseudomonasAeruginosa bacteria was found to be 10^4, 10^5 and 10^6 cells/ml respectively for achieving the lower value porosity at the age of 28 days and 90 days from the experimental results. It is also noted that the bacterial concrete mixes at the age of 28 days showed porosity value of about 53 to 68 percent less than control concrete mix.

5.2.3 Sorptivity

The influence of bacteria on the sorptivity of concrete mixes with different cell concentration of bacteria is shown in Figures 25 and 26.

5.2.4 Permeability

Permeability is the principal factor that affects durability. Lowpermeability is the primary requirement to produce durable concrete. Tests for permeability were carried out as per the procedure given in IS: 3085-1965 using concrete permeability apparatus. Concrete cubes of 150 mm size were subjected to a water pressure of 10 kg/cm^2 for 100 hours. The results of the permeability tests of various concrete mixes at the age of 28 and 90 days are presented in and the influence of bacteria on the permeability of concrete mixes with different cell concentration of bacteria is shown in Figures 27 and 28.

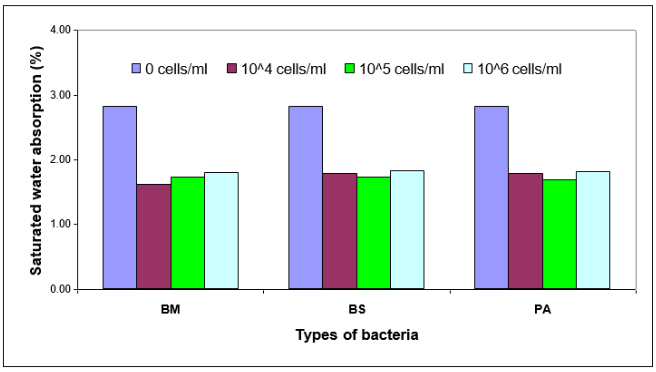

Figure -23: Influence of various types of bacteria on saturated water absorption of M20 grade bacterial concrete mixes at 28 days

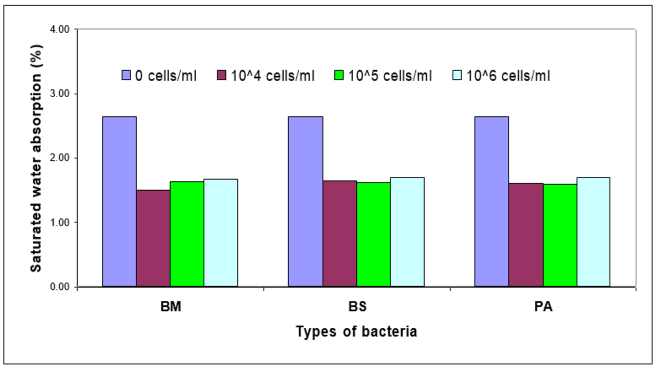

Figure -24: Influence of various types of bacteria on saturated water absorption of M20 grade bacterial concrete mixes at 90 days

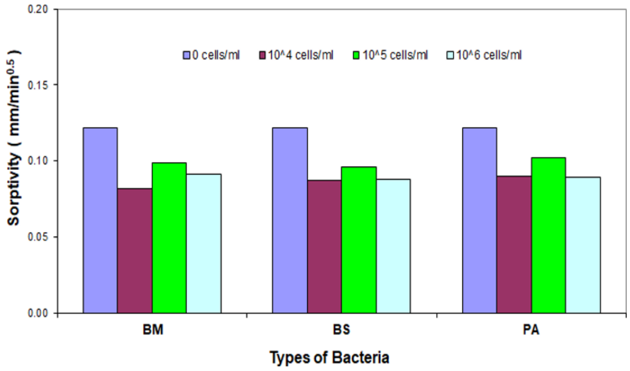

Figure -25: Influence of various types of bacteria on sorptivity of M20 grade bacterial concrete mixes at 28 days

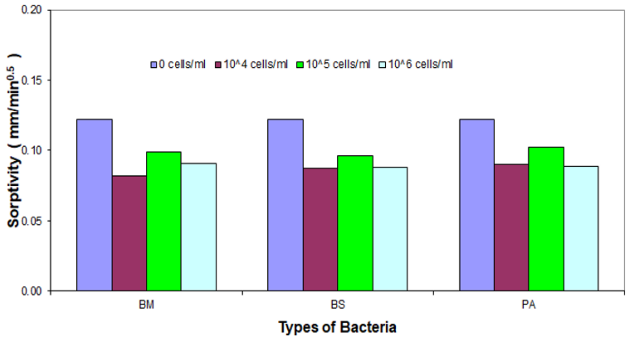

Figure -26: Influence of various types of bacteria on sorptivity of M20 grade bacterial concrete mixes at 90 days

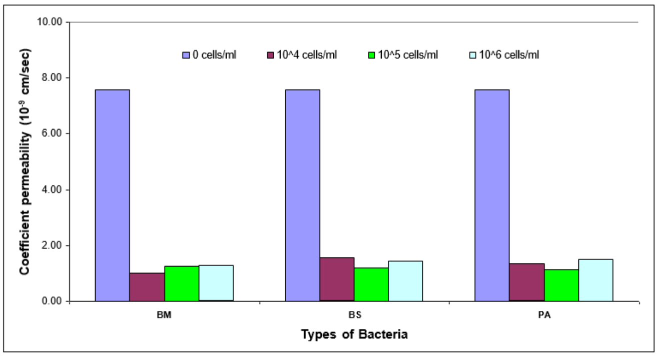

Figure -27: Influence of various types of bacteria on permeability of M20 grade bacterial concrete mixes at 28 days

5.2.5 Acid resistance

The results of the acid resistance tests of various concrete mixes at the age of 28 days and 90 days and the average percentage loss of weight and compressive strength for the bacterial concrete mixes were found to be less, whereas for the control concretemix the average percentage loss of weight and compressive strength was more. That is, the addition of bacteria into concrete showed lesser loss of weight of concrete. The average percentage weight loss of bacterial concrete in H_2SO_4 was greater compared to the average percentage weight loss of bacterial concrete in HCl. Thus, from the test results, it is observed that the attack of acidon bacterial concrete is less when compared to control concrete.

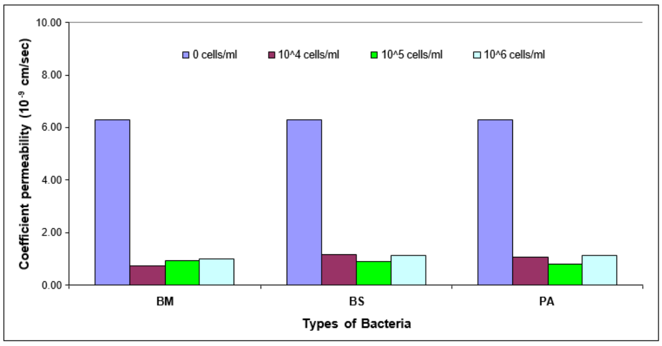

Figure -28: Influence ofvarious types of bacteria on permeability of M20 grade bacterial concrete mixes at 90 days

5.2.6 Sea Water Resistance

The results of the sea water resistance tests of various concrete mixes at the age of 28 days and 90 days and the influence of bacteria on the sea water resistance with different cell concentration of bacteria is shown in Figures 29 and 30.

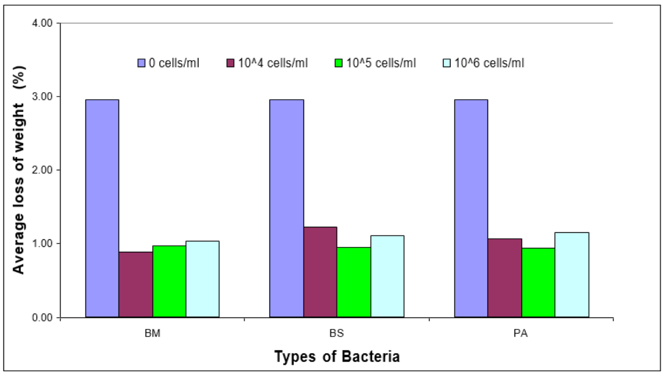

Figure -29: Influence of various types of bacteria on sea water resistance of M20 grade bacterial concrete mixes at 28 days

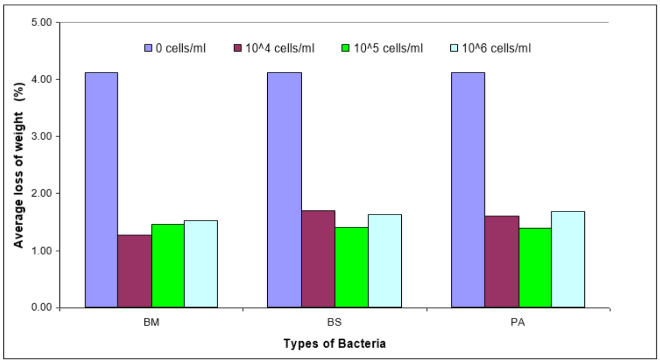

Figure -30: Influence of various types of bacteria on sea water resistance of M20 grade bacterial concrete mixes at 90 days

5.2.7 Impact Strength

The results of the impact strength tests of various concrete mixes at the age of 28 days and the influence of bacteria on the impact strength and the variation of impact strength with different cell concentration of bacteria is shown in Figure 31. The impact strength of control concrete mix and bacterial concrete mixes (CS, BM1, BM2, BM3, BS1, BS2, BS3, PA1, PA2 and PA3) at the age of 28 days was around 1677, 2303, 2121, 2101, 2040, 2182, 2081, 2101, 2222 and 2060 N-m respectively. From the test results, it is observed that the impact strength of bacterial concrete mixes was found more when compared with control concrete mix (CS). It is also understood that the induction of bacteria into concrete enhances the impact strength of concrete. This is due to the deposition of large quantity of stable MICP crystals in bacterial concrete.

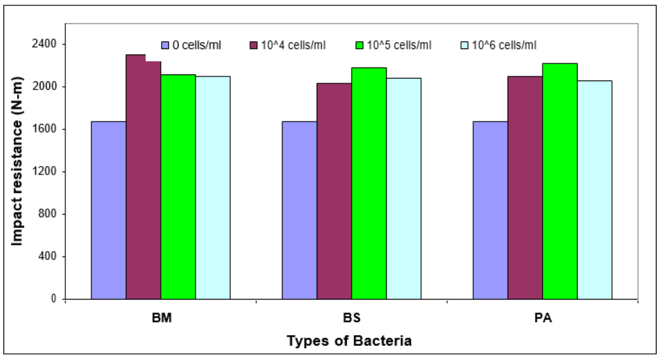

Figure -31: Influence of various types of bacteria on impact strength of M20 grade Bacterial concrete mixes at 28 days

5.2.8 Rapid Chloride Penetration Test

The results of the rapid chloride penetration tests of various concrete mixes at the age of 28 days and the chloride ion penetration of control concrete mix and bacterial concrete mixes (CS, BM1, BM2, BM3, BS1, BS2, BS3, PA1, PA2 and PA3) at the age of 28 days was around 2085, 329, 338, 345, 368, 345, 355, 378, 341 and 374 coulombs respectively. The initial current readings for all the bacterial concrete specimens were found less than the control concrete specimen (CS). From the test results, it was found that, significantly lower chloride permeability is observed in all bacterial concrete specimens than control specimen. It is also noted that the optimum dosage of cell concentration for Bacillus Megaterium, Bacillus Subtilis and Pseudomonas Aeruginosa bacteria was found to be 10^4, 10^5 and 10^6 cells/ml respectively for achieving the lower value of chloride ion penetration at the age of 28 days. It is also viewed that the bacterialconcrete specimens showed 82 to 85 percent reduction in chloride ion penetration than control concrete specimen at the age of 28 days. It is due to the fact that the presence of bacteria induced formation of MICP (Microbiologically Induced Calcite Precipitation) crystals in the pores of concrete using built-in bacteria, seals the pores in hardened concrete there by leading to lesser voids and hence lesser chloride ion penetration.

The maximum reduction in chloride penetration of specimens treated with Bacillus Megaterium bacteria is found as 85 percent in control concrete specimen at the age of 28 days. As per ASTM C-1202-12, the control concrete sample falls under the category of "Moderate" degree of chloride ion penetrability and all bacterial concrete samples fall under the category of "VeryLow" degree of chloride ion penetrability. That means, in the present study the bacterial concrete specimen showed much higher penetration resistance and therefore greater amount of reduction in the magnitude of charge passed than the normal conventional cement concrete.

5.2.9 Accelerated Electrolytic Corrosion

In the accelerated electrolytic corrosion test, constant voltage studies were carried out on M20 grade control concrete and bacterial concrete specimens. The accelerated electrolytic corrosion test results of the various concrete mixes at the age of 28 days are given in Table 11.

Table -11: Accelerated electrolytic corrosion results of bacterial concrete mixes at 28 days

Type of Specimen	**Mix Designation**	**Cell concentration(cells / ml)**	**AverageIapp (Amps)**	**Initial weight(gm)**	**Final weight(gm)**	**Weightloss (gm)**	**Theoretical weight loss (gm)**	**Weightloss (%)**	**Theoretical weight loss (%)**	**Equivalent corrosion current, Icorr (Amps)**
Control Specimen	CS	-	1.26	2822	2676	146	158.17	5.17	5.60	1.17
Bacillus Megaterium	BM1	10^4	0.82	2861	2781	80	102.14	2.80	3.57	0.64
	BM2	10^5	0.72	2836	2768	68	89.60	2.40	3.16	0.54
	BM3	10^6	0.76	2809	2734	75	95.05	2.67	3.38	0.60
BacillusSubtilis	BS1	10^4	0.77	2842	2765	77	95.67	2.71	3.37	0.62
	BS2	10^5	0.75	2854	2775	79	93.63	2.77	3.28	0.63
	BS3	10^6	0.86	2850	2764	86	107.69	3.02	3.78	0.69
Pseudomonas Aeruginosa	PA1	10^4	0.86	2862	2774	88	107.38	3.07	3.75	0.70
	PA2	10^5	0.77	2857	2776	81	96.35	2.84	3.37	0.65
	PA3	10^6	0.90	2826	2737	89	112.29	3.15	3.97	0.71

5.2.10 Alkalinity measurement

The pH values of the aqueous solutions prepared from the powder samples of control concrete mix and bacterial concrete mixes at the age of 28 days and 90 days are given in Tables 12 and 13.

Table -12: Alkalinity results of bacterial concrete mixes at 28 days

			pH value of samples

Mix designation	Type of bacteria	Cell concentration (cells / ml)	pH meter	pH indicating papers
CS	-	-	13.25	>13
BM1	Bacillus Megaterium	10^4	13.40	>13
BM2		10^5	13.42	>13
BM3		10^6	13.42	>13
BS1	Bacillus Subtilis	10^4	13.36	>13
BS2		10^5	13.38	>13
BS3		10^6	13.41	>13
PA1	Pseudomonas Aeruginosa	10^4	13.35	>13
PA2		10^5	13.36	>13
PA3		10^6	13.38	>13

Table -13: Alkalinity results of bacterial concrete mixes at 90 days

Mix designation	Type of bacteria	Cell concentration (cells / ml)	pH value of samples	
			pH meter	pH indicating papers
CS	-	-	13.30	>13
BM1	Bacillus Megaterium	10^4	13.42	>13
BM2		10^5	13.44	>13
BM3		10^6	13.44	>13
BS1	BacillusSubtilis	10^4	13.38	>13
BS2		10^5	13.38	>13
BS3		10^6	13.40	>13
PA1	Pseudomonas Aeruginosa	10^4	13.38	>13
PA2		10^5	13.40	>13
PA3		10^6	13.41	>13

6. CONCLUSIONS

The following conclusions are made based on the experimental investigations carried out on concrete mixes with and without bacteria.

6.1 Strength Properties of Bacterial Concrete

Based on the experimental investigations carried out on the strength and micro structural characteristics of bacterial concrete mixes, the following conclusions are arrived at:

- Workability: The workability of bacterial concrete is not affected with the induction of bacteria into concrete.
- Cube compressive strength: There was an increase of only 7 to 10 MPa in the compressive strength between 28 days and 90 days for concrete mixes without bacteria while this increase was in the range of 10 to 16 MPa for bacterial concrete mixes. This could be advantageously used for design of structures such as bridge piers, abutment walls and other mass concrete structural elements where early strength is not a criterion.
- Cylindrical compressive strength: The bacterial concrete mixes have shown higher values of cylinder compressive strength than control concrete mix at the age of 28 days. The maximum cylinder compressive strengths were obtained for bacterial concrete specimens BM1, BS2 and PA2 as 26.95 MPa, 26.38 MPa and 26.62 MPa respectively. The ratio between cylinder and cube compressive strengths is found to be 0.81.
- Splitting tensile strength: The maximum splitting tensile strengths were obtained for bacterial concrete specimens BM1, BS2 and PA2 as 2.64 MPa, 2.54 MPa and 2.60 MPa respectively at the age of 28 days. The splitting tensile strength increases along with increase in compressive strength. The splitting tensile strength of bacterial concrete is about 7 to 8

percent of cube compressive strength. The maximum increase in splitting tensile strength of 24.53 percent is obtained for BM bacterial concrete.

- Flexural Strength: The maximum flexural strengths were obtained for bacterial concrete specimens BM1, BS2 and PA2 as 4.93 MPa, 4.74MPa and 4.80 MPa respectively at the age of 28 days. The flexural strength of bacterial concrete is about 15 percent of cube compressive strength. The maximum increase in flexural strength of 25.76 percent is obtained for BM bacterial concrete. The flexural strength of concrete at the age of 28 days is higher than the value calculated by the expression 0.7 √fck as specified in IS : 456 - 2000. The code IS : 456 - 2000 underestimates the value of flexural strength of bacterial concrete.
- Modulus of Elasticity: The maximum values of Ec were obtained for bacterial concrete specimens BM1, BS2 and PA2 as 33.02 GPa, 31.88 GPa and 32.25 GPa respectively at the age of 28 days. The maximum increase in modulus of elasticity of 25.03 percent is obtained for BM bacterial concrete. The modulus of elasticity of concrete at the age of 28 days was more than the value calculated by the expression 5000 √fck as specified in IS : 456-2000.
- Flexural Behaviour: The deflection is also less for bacterial concrete specimens. The average maximum ultimate load of 49 kN is found in BM and BS bacterial concrete specimens.
- Ultrasonic Pulse Velocity: The maximum pulse velocities were obtained for the bacterial concrete specimens BM1, BS2 and PA2 as 5.35 km/sec, 5.12 km/sec and 5.18 km/sec respectively at the age of 28 days. Out of all the bacterial specimens the high pulse velocity is found to be 5.35 km/sec for BM bacteria at the age of 28 days. The UPV value of all the bacterial concrete specimens fall under "Excellent" category as per the guidelines given in IS : 13111 (Part 1) -1992 whereas the UPV values of control concrete specimens fall under "Good" category.
- Bond Strength: The maximum value of bond strengths were obtained for bacterial concrete specimens BM1, BS2 and PA2 as 6.20 MPa, 5.95 MPaand 6.10 MPa respectively at the age of 28 days. The increase in bond strength is due to the accumulation of the pores inside the bacterial concrete induced precipitation of CaCO3.

6.2 Durability Properties of Bacterial Concrete

Based on the experimental investigations carried out on the durability characteristics of bacterial concrete mixes, the following conclusions are arrived at:

- Saturated Water Absorption (SWA), Porosity and Sorptivity: The bacterial concrete specimens showed 35 to 43 percent and 36 to 43 percent reduction in water absorption than control concrete specimen at the age of 28 days 90 days respectively. This means that the time taken for the water rise by capillary action in bacterial concrete is longer and thus proved that this concrete is less porous compared to control concrete. The specimens showed porosity value of about 53 to 68 percent less than the control concrete and sorptivity found to be lower when compared with the sorptivity of the control concrete specimen at the age of 28 days and 90 days also.
- Permeability: The maximum reduction in water permeability of specimens treated with BM is about 87 percent and 88 percent in control concrete specimen at the age of 28 days and 90 days respectively. Hence, the addition of bacteria in concrete mixes makes the concrete denser and more impermeable.
- Acid Resistance and Sea Water Resistance: The addition of bacteria into concrete mixes showed lesser loss of weight of concrete. Hence, it can be concluded that the bacteria concrete mixes are more resistible against acid attack and sea water attack.
- ImpactStrength: It is understood that the induction of bacteria into concrete enhances the impact strength of concrete. This is due to the deposition of large quantity of stable MICP crystals in bacterial concrete.
- Rapid Chloride Penetration Test (RCPT): The maximum reduction in chloride penetration of specimens treated with BM bacteria is found to be 85percent in control concrete specimen at the age of 28 days. As per ASTM C-1202-12, the control concrete sample falls under the category of " Moderate " degree of chloride ion penetrability and all bacterial concrete samples fall under the category of " Very Low " degree of chloride ion penetrability. That means, in the present study, the bacterial concrete specimen showed much higher penetration resistance and therefore greater amount of reduction in the magnitude of charge passed than the conventional cement concrete.
- Accelerated Electrolytic Corrosion: The concrete mixes containing higher dosage of cell concentration of bacteria have shown less corrosion and hence addition of bacteria in concrete increases the corrosion resistance.
- Alkalinity Measurement: Due to the fact that during the process of MICP there is an increase in pH due to subsequent increase in ammonia which leads to the precipitation of insoluble CaCO3. Hence, bacterial concrete mixes provide sufficient alkaline environment to the embedded steel and protect the steel from corrosion.

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