Parametric Study of Mechanical and Durability Properties of Bacterial Concrete by Incorporating Ceramic Tiles Waste

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1. Abstract

Concrete is a highly used construction material in the world. The use of concrete is increased by about 2.5% yearly. Concrete has high compressive strength, but it is weak in carrying tension. Shrinkage stresses, temperature stresses, corrosion of reinforcement bar, etc., can crack the concrete. With the effect of external loading, small cracks can create a network of cracks. Hazardous gases and moisture can easily penetrate the cracks, and concrete deterioration and steel corrosion will start. Ultimately the strength of concrete and the durability of the entire structure will reduce. One possible way to improve the strength and durability of the concrete is to use Microbial Induced Mineral Precipitation (MIMP). The concrete can be made by embedding a biochemical solution in the concrete to take advantage of microbial-induced mineral precipitation, and it is also called bacterial concrete.

Cement is a crucial component of concrete. During the manufacture of 1 tonne of cement, there is an approximate emission of one tonne of carbon dioxide. Around 2.5% yearly growth is seen in cement use around the world. Thus, there is a need to utilise supplementary cementitious materials (SCMs) as a halfway substitution of cement in concrete. Using SCMs decreases the utilisation of ordinary Portland cement and, in this manner, reduces the energy utilisation and ozone-depleting substance releases during concrete production. This study explores the possibility of replacing cement in concrete with Ceramic tiles powder (CTP). India accounts for 7% of the global production of ceramic tiles, making it the world's second-largest manufacturer of ceramic tiles. The tiles industry has about 2.5% of tiles waste material generated during the tiles' manufacturing, handling, and transportation. The tile's broken pieces have been stored in the industry's backyard or dumped nearby the industry on open land.

The method of Calcite Precipitation by bacteria in concrete is more desirable because it is pollution-free and natural. However, disposing of ceramic tiles waste is a problem for the ceramic industry, the environment, and human health. Therefore, this study used different concentrations of Bacillus Megaterium-10086(MTCC) bacteria (10^3, 10^5, 10^7, and 10^9) and different percentages of ceramic tiles waste powder (5%, 10%, 15%, and 20%). The experimental investigations have determined the bacteria's ideal concentration and cement replacement rate with CTP.

The parametric study of mechanical and durability properties of bacterial concrete by incorporating ceramic tiles waste shows improvement in the quality of concrete compared

to control concrete. The petrographic analysis displays a better surface and element composition in concrete by 10% replacement of cement with CTP in bacterial concrete. The SEM images of bacterial concrete show a higher amount of calcite precipitation and a lower amount of void formation than the control concrete. The EDS report shows that no impurities/foreign material is available in the sample. It has been concluded that 10^5 cells/ml is an ideal concentration of microbes, and 10% replacement of cement with CTP is the best proportion, which together has a beneficial effect on the strength and durability of concrete.

2. Brief description of the state of the art of the research topic

There are national and international level researchers who have published a paper on bacterial concrete. The majority of researchers believe that adding microorganisms to concrete can boost its strength and durability. The procedure and the biochemical reactions required during calcite precipitation were clarified by Ramachandran et. al.[1]. Table 1 shows the facts of various kinds of microscopic organisms utilised by the authors to develop the quality of the concrete. The proportion of progress in the quality of the concrete may change depending upon the concentration of the bacteria. Fig.1 gives the details of profoundly utilised microbes by analysts to enhance the strength of concrete.

Table-1: Different kinds of microorganisms with changes in concentration utilised by researchers to improve the quality of concrete.

Sr. No.	Author & Journal Detail	Bacteria used	Bacterial concentration	Increased in Compressive strength
1	Varenyam Achal et. al. [2]	Bacillus sp. CT-5	OD (600 nm) of 1.0.	36%
2	Varenyam Achal et. al. [3]	Bacillus sp. CT-5	5×10^7 cells /mm^3	40%
3	Kunal et. al. [4]	Bacillus sp. Strain KG1	OD of 0.8 at 600	26%
4	Ramin Andalib et. al. [5]	Bacillus megaterium	30×10^5 cfu /ml	24%
5	Varenyam Achala et. al. [6]	B. megaterium ATCC 14581	5×10^7 cfu /ml	19%
6	S. Krishnapriyaa et. al. [7]	B. megaterium MTCC [illegible]	10^5 cells/ml	16%
7	Leena Chaurasia et. al. [8]	B. megaterium MTCC [illegible]	3×10^7 cells /ml	40%
8	Gurvinder Kaur et. al. [9]	Bacillus megaterium (SS3)	$OD_{600} = 1.5$	56%
9	Wasim Khaliq et. al. [10]	Bacillus subtilis	2.8×10^8 cells /ml	12%
10	Sunil Pratap Reddy et. al. [11]	Bacillus subtilis	10^5 cells/ml	14%
11	Park, Sung-Jin et. al. [12]	B. subtilis 168	(OD) of 0.8 at 600	19%
12	Rafat Siddique et. al. [13]	Bacillus aerius	10^5 cells/ml	12%
13	Rafat Siddique et. al. [14]	Bacillus aerius Strain - AKKR5	10^5 cells/ml	11%
14	S. K. Ramchandran et. al. [15]	S.pasteurii or Bacillus pasteurii	10^5 cells/ml	35%
15	Navneet Chahal et. al. [16]	S.pasteurii or Bacillus pasteurii	10^5 cells/ml	20%

16	Navneet Chahal et. al. [17]	S.pasteurii or Bacillus pasteurii	10^5 cells/ml	38%
17	V. Achal et. al. [18]	S.pasteurii NCIM 2477	OD_{600}	17%
18	S.A. Abo-El-Enein et. al. [19]	S.pasteurii NCIMB 8841	OD at 600 nm of 0.5, 1.0 and 1.5	33%
19	V. Ramakrishnan et.al. [20]	Sporosarcina pasteurii	10^7 cells/ml	10%
20	Nafise Hosseini Balam et. al. [21]	Sporosarcina pasteurii	10^6 cells/ml	20%
21	Leena Chaurasia et. al. [8]	B. pasteurii MTCC 1761	3 x 10^7 cells /ml	37%
22	S. Maheswaran et al. [22]	B. pasteurii	10^5 cells/ml	29%
23	Peihao Li et. al. [23]	Sporosarcina pasteurii	2.8 × 10^7 cfu/ml	15%
24	Yousef Al-Salloum et. al. [24]	S. pasteurii (ATCC 6453)	10^8 cells/ml	24%
25	P. Ghosh et. al. [25]	Shewanella Species	10^5 cells/ml	25%
26	Farzaneh Nosouhian et. al. [26]	S.pasteurii with B.subtilis	2 x 10^9 cells /ml	20%
27	G. Mohan Ganesh et. al. [27]	Bacteria isolate from Cement godown	Bacteria in NB 38.32 Lit./m^3	23%
28	Kunal et. al. [28]	Bacillus halodurans strain KG1	OD1.0 = 10^8 cells/ml	26%
29	Zhigang Zhang et al. [29]	Bacillus halodurans DSM 497	10^7 to 10^8 cells/ml	19%
30	Zhigang Zhang et al. [29]	Mutant one based on Bacillus halodurans DSM 497	10^7 to 10^8 cells/ml	26%
31	Leena Chaurasia et. al. [8]	B. cohnii MTCC 10,221	3 x 10^7 cells /ml	25%
32	Peihao Li et. al. [30]	Acinetobacterjohnsonii	4 × 10^7 cfu /ml	21%
33	Peihao Li et. al. [31]	Acinetobacterjohnsonii	4 × 10^7 cfu /ml	20%
34	S. Maheswaran et. al. [22]	Bacillus cereus	10^6 cells/ml	38%
35	Park, Sung-Jin et. al. [12]	B. cereus KCTC3624	(OD) of 0.8 at 600	14%
36	Pitcha Jongvivatsakul et. al. [32]	Bacillus sphaericus (LMG 22257)	1.8 x 10^{12} cells/ml	43%
37	Gurdeep Kaur et. al. [33]	Eupenicillium crustacean (Fungal)	1.7 x 10^7 cells/ml	24%
38	Mousumi Biswas et. al. [34]	Thermo an Aerobacter	10^5 cells/ml	25%
39	Yousef Al-Salloum et. al. [24]	E. coli DH5a (ATCC 53868)	10^8 cells/ml	02%

According to the information presented in Table 1 and Figure 1, about 16 distinct bacterial species have been utilised to improve concrete quality [2-34]. Bacillus pasteurii and Bacillus megaterium are commonly used to enhance the quality of concrete [5-9], [15-26]. Another observation was that no one had simultaneously evaluated the impact of different concentrations of bacteria on higher and lower grades of concrete. The current study is based on different concentrations of Bacillus Megaterioum because it has been observed that B. Megaterioum is more effective on concrete strength and durability than B.Pasturium. As a result, we studied the effect of different concentrations of Bacillus Megaterium bacteria on the higher and lower-graded concrete.

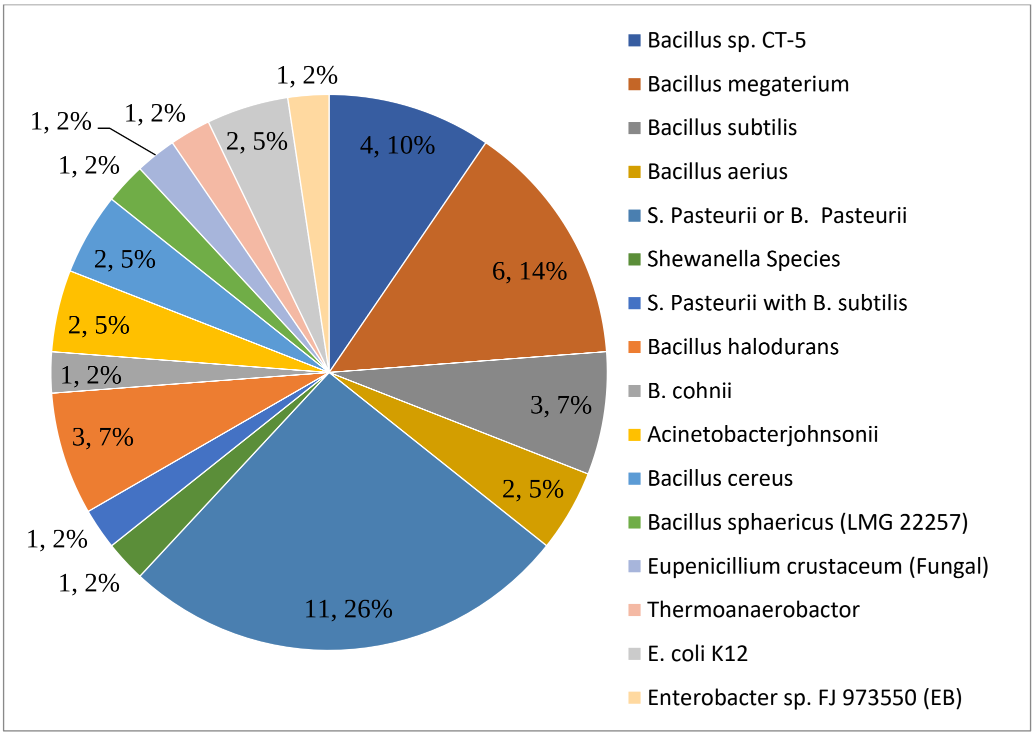


Fig.1 Highly used microbes enhance the concrete's compressive strength [35].

India is the second-largest ceramic tile manufacturer in the world. It is a common building material used all around the world. Approximately 2.5 per cent of the total tile quantity is lost or squandered when it is manufactured, handled, or transported. Therefore, the disposal of ceramic tile waste powder (also known as CTP) in landfills will harm the environment. The waste powder from ceramic tiles primarily consists of the chemical oxides silica dioxide (SiO_2) and aluminium oxide (Al_2O_3). To create environmentally friendly concretes, CTP has the potential to be used as a partial replacement for cement. Other researchers had noted in past investigations that ceramic waste materials might be used to replace concrete elements like cement and aggregate [36]–[41]. Using a limited amount of CTP instead of cement has no negative impact on the concrete's strength and durability.

3. Definition of the Problem

Concrete is the second-most-used substance in the world after water. Concrete use is growing every day, and it's about 2.5% yearly [42]. Concrete can be moulded into any shape and is a versatile material. It has high compressive strength but is weak in tension because it is a brittle material. Due to external loading, shrinkage, temperature stresses, etc., concrete can crack. Small cracks have the potential to grow into a network of cracks when subjected to external loading. The moisture and harmful gases can quickly enter the microcracks available in the concrete. As a result, concrete deterioration and steel corrosion will begin. In the end, the overall structure's durability and the strength of the concrete would decline.

Therefore, it is essential to increase the concrete's strength and durability. The microbial-induced mineral precipitation (MIMP) is a novel technique that can improve the strength and durability of concrete structures.

Bacterial concrete is produced by incorporating bacteria into the concrete. The metabolic activity of bacteria present in biochemical solution has calcite in the form of extract. When the materials for the concrete are mixed, bacterial spores and their food are added. Bacterial spores are in dormant mode at the time of mixing. Once supersaturation level is achieved by various nucleation on the microorganism cell wall, the precipitation of calcite crystals starts. As crystal produces inside the concrete, precipitated calcite densifies it by filling micro-cracks and porous available in the concrete. Thus, the MIMP technique can potentially improve the strength and durability of concrete.

India is the second-largest producer and consumer of cement in the world. The growth of long-term cement demand is estimated to be 1.2 times India's GDP growth rate [43]. Cement is being used more and more frequently, and cement manufacture adds CO_2 to the atmosphere. Therefore, a cement substitute must be developed without sacrificing the durability and strength of concrete. This investigation used ceramic tile powder instead of cement to make concrete.

Fig.2 Wastage of Ceramic Tiles dumped nearby the industry

When it comes to ceramic tiles, India is the world's number two producer after China. About 2.5% of all tiles are discarded as waste during production, storage, and shipment. The tiles that have been cracked are either kept in the back yard of the factory or dumped on open land close by. The land, the air, and the water all get contaminated as a result of these activities. Because of this, it poses a threat to both the health of people and the environment. Using such industrial waste in the production of concrete is one of the possibilities that may be pursued to protect both the health of people and the environment. CTP is a reactive pozzolanic material due to its surface fineness and high silica content; it can react with calcium hydroxide and produces additional Calcium Silicate Hydrate (CSH) gel.

MIMP is an innovative technique used to enhance the quality of concrete by precipitation of calcium carbonate. The method of Calcite Precipitation by microorganisms in concrete is more desirable because it is pollution-free and natural. The disposal of ceramic tiles waste is a problem for the ceramic industry and creates air, water, and land pollution. The partial replacement of cement with a CTP is one of the ways to utilise ceramic tiles' waste material in the bacterial concrete. This study helps to solve the problem of environmental pollution and improve the strength and durability of the concrete.

4. Objective and Scope of work

4.1. Objectives of the research work

The primary goal is to investigate the impact of different concentrations of microorganisms on the concrete's Engineering and Durability parameters by replacing cement with varying percentages of ceramic tiles powder and verify the results by petrographic analysis.

4.2. Scope of the research work

- Perform a literature survey to learn about the different types of bacteria and their application in civil engineering.
- To know about the different methods used to classify the bacteria and the process for the revival of bacteria
- Perform Gram staining and Schaeffer Fulton method for the classification and count the concentration of the bacteria
- Perform Research project Phase-1 to determine the ideal concentration of bacteria to be added to the concrete
- Perform Research project Phase-2 to determine the ideal percentage of replacement of cement with ceramic tiles powder
- Perform Research project Phase-3 for parametric study of the Bacterial concrete by replacement of cement with ceramic tiles waste

5. Original contribution by the thesis

- The strength and durability of concrete are enhanced by adding biochemical solutions to the concrete.
- The utilisation of cement is reduced in concrete by replacing cement with ceramic tiles waste powder.

- The process of microbial-induced mineral precipitation is more desirable because it is environmentally friendly.
- The partial replacement of cement with ceramic tiles waste powder helps reduce the concrete's overall cost and supports the environment by lessening air, water, and land pollution.

6. Methodology of Research, Results / Comparisons

The entire research work has been carried out in two parts. Part-I is a pilot project performed to know the ideal concentration of bacteria to be added to the concrete. The pilot project aims to reduce the number of tests. The part-II is about the parametric study of Bacterial Concrete by replacement of cement with CTP. The bacterial concrete in part II has been prepared by utilising the ideal concentration of the bacteria.

6.1. Determine the ideal concentration of bacteria

The concentration of bacteria is a significant factor that affects the quality of the bacterial concrete. The different concentrations of biochemical solutions that the earlier researcher used are shown in Table 1. The range of 10^3 to 10^9 cells/ml concentration of bacteria has been selected from the literature survey. The tests have been performed to know the effect of 10^3, 10^5, 10^7, and 10^9 cells/ml concentration of Bacillus Megaterium-10086(MTCC) bacteria on the properties of concrete. The influence of different concentration of bacteria on higher and lower grade of concrete have been studied. It was decided that the M30 of concrete would be used for the lower grade, while the M70 of concrete would be used for the higher grade. Compressive strength, tensile strength, water permeability test, RCPT, Chemical attack test, and microstructure analysis SEM and EDS test have been performed. The concentration of four distinctive cells of microorganisms has been used to make ten series of concrete mixes.

6.1.1. Mix design

M30-grade and M70-grade concrete cube and cylinder samples were cast with and without the addition of bacteria by utilising OPC 53-grade cement. The water to cement ratio was 0.48 and 0.29 for concrete grades M30 and M70, respectively. Cement-FA-CA ratio was 1:1.76:3.15 for M30 grade and 1:1.17:2.82 for M70 grade concrete. Concrete cube specimens measuring 150 x 150 x 150 mm were tested to determine the concrete's compressive strength, and concrete cylinder specimens measuring 150 x 300 mm were tested to determine the concrete's split tensile strength. Concrete cylinder specimens of 150 x 150 mm were tested by IS 3085:1965 to ensure the concrete's water permeability [44]. Normal specimens were prepared using water, while bacterial concrete samples were cast by replacing 10% of bacteria cultured with tap water. A sum of five series of concrete mixes of M30 grade and five series of concrete mixes of M70 grade have been considered in this investigation.

The first series was a control mix (M1) prepared using regular tap water for M30 grade concrete. The second, third, fourth, and fifth series were like the first series concerning the all ingredients used in concrete; however, in this, 10% water was replaced with B. Megaterium MTCC 10086 grown in NB with a cell concentration of 10^3(M2), 10^5(M3), 10^7(M4) and 10^9(M5) cells/ml individually. The sixth series was a control mix (M6) prepared using ordinary tap water for M70 grade concrete. The seventh, eighth, ninth, and tenth series were like the sixth series concerning all ingredients used in concrete; however, in this, 10% water was replaced with B. Megaterium MTCC 10086 grown in NB with a cell concentration of 10^3(M7), 10^5(M8), 10^7(M9), 10^9(M10) cells/ml individually.

Table-2: Concrete mix design as per IS:10262 [45] **method**

Concrete Mix	**Grade of Concrete**	**Cement in kg/m^3**	**Fly Ash in kg/m^3**	**Silica Fume in kg/m^3**	**Coarse Agg. in kg/m^3**	**Fine Agg. in kg/m^3**	**w/c or w/cm**	**Admixture in kg/m^3**	**Water in kg/m^3**	**Bacteria**	
										Content in ltr/m^3	**Concentration in cells/ml**
M1	M30	387	-	-	1222	681	0.48	-	199	-	-
M2	M30	387	-	-	1222	681	0.48	-	179	19.90	10^3
M3	M30	387	-	-	1222	681	0.48	-	179	19.90	10^5
M4	M30	387	-	-	1222	681	0.48	-	179	19.90	10^7
M5	M30	387	-	-	1222	681	0.48	-	179	19.90	10^9
M6	M70	429	80.45	26.82	1208	502	0.26	2.67	152	-	-
M7	M70	429	80.45	26.82	1208	502	0.26	2.67	137	15.24	10^3
M8	M70	429	80.45	26.82	1208	502	0.26	2.67	137	15.24	10^5
M9	M70	429	80.45	26.82	1208	502	0.26	2.67	137	15.24	10^7
M10	M70	429	80.45	26.82	1208	502	0.26	2.67	137	15.24	10^9

6.1.2. Results of Compressive strength

Impact of different concentrations (10^3, 10^5, 10^7, and 10^9 cells/ml) of B. Megaterium MTCC 10086 microorganisms on the 7-day, 28-day, and 56-day compressive and tensile strength of M-30 grade (standard) and M-70 grade (high strength) concrete cube samples have shown in Fig.3 to 6.

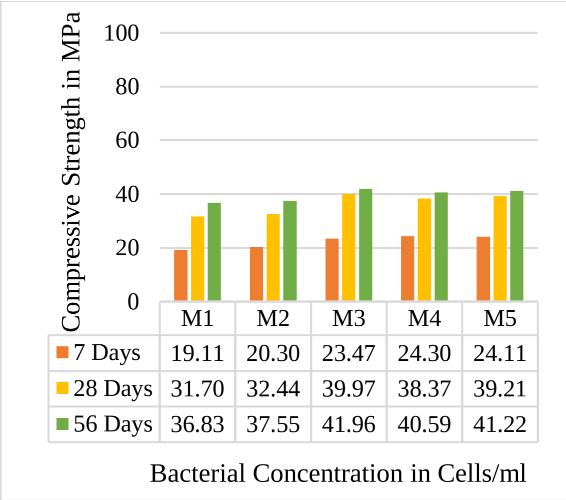


Fig.3 Compressive Strength of M30 grade concrete with Different Concentrations of Bacteria

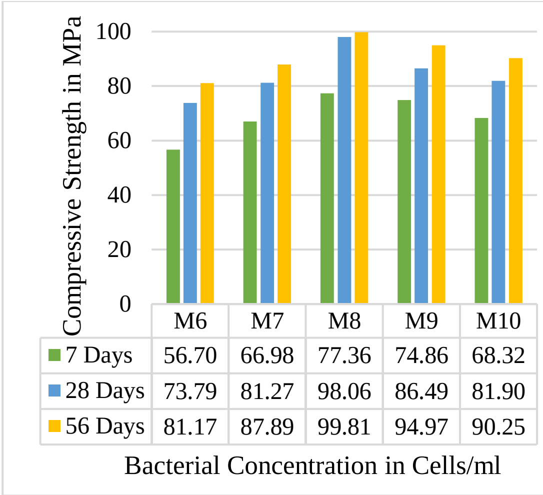


Fig.4 Compressive Strength of M70 grade concrete with Different Concentrations of Bacteria

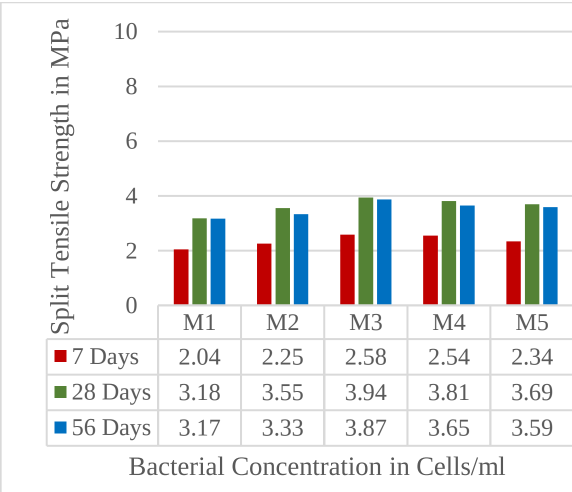


Fig.5 Tensile Strength of M30 grade concrete with Different Concentrations of Bacteria

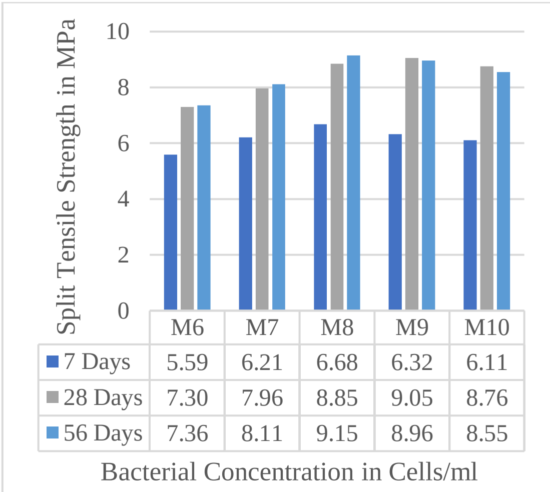


Fig.6 Tensile Strength of M70 grade concrete with Different Concentrations of Bacteria

6.1.3. Results of Water permeability test

Fig.7 Water permeability test apparatus

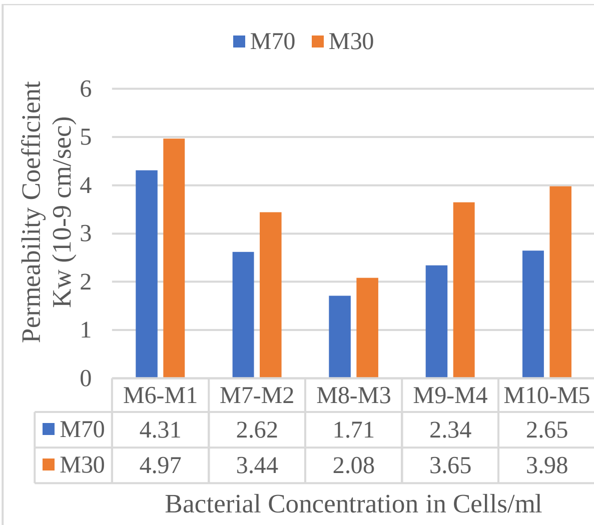


Fig.8 Water Permeability Coefficient of concrete with different Concentrations of Bacteria

The test was performed, and the water permeability coefficient Kw was estimated as IS 3085:1965 [44]. The impact of various concentrations (10^3, 10^5, 10^7, 10^9 cells/ml) of B. Megaterium MTCC 10086 microscopic organisms on the 28-day water permeability test of M-30 grade and M-70 grade concrete specimens has shown in fig.

6.1.4. Results of Rapid Chloride Permeability Test (RCPT)

The specimens were prepared as per the test procedure developed by the researcher of AASHTO T277 and ASTM C1202. The prepared sample was 100 mm in diameter and 50 mm in length. Fig.9 shows the image of the concrete cylindrical specimen after demolding.

Fig.11 Filling of RCPT cell with a solution

Fig.9 Casting and demolding of RCPT test mold

Fig.10 Used silicon sealant to seal the gap between the concrete specimen and cell wall

The RCPT test was performed after completing the curing period of 28 days. After 28 days of curing, the sample was stored at room temperature for an hour. Put the material in the RCPT cell with one end in NaCl and the other in NaOH. Used silicon sealant to fill the space between the cell walls and the concrete specimen, as illustrated in fig. 10, and then allowed it to cure. As shown in fig. 11, the test cell's left side (-) is filled with a 3 per cent NaCl solution, and its right side (+) is filled with a 0.3 N NaOH solution. After connecting the gadget, a continuous 60-volt potential is provided for the next six hours. The reading of current passes from the specimen has been noted every 30 minutes. After 6 hours, the sample was removed from the cell, and the charge passed through the specimen was calculated.

Table-3: Calculation of charge passes from the control and bacterial concrete specimen

Sr. No.	TIME	CH-1	CH-2	CH-3	CH-1	CH-2	CH-3
		Control Concrete Specimen			Bacterial Concrete Specimen		
I_{0}	11.00.00 AM	49.6	50.2	51.2	43.6	42.8	46.9
I_{30}	11.30.00 AM	50.3	51.4	52.1	44.3	44.0	47.8
I_{60}	12.00.00 PM	51.7	53.1	53.2	45.7	45.7	48.9
I_{90}	12.30.00 PM	52.9	54.7	54.0	46.9	47.3	49.7
I_{120}	01.00.00 PM	53.6	55.6	54.9	47.6	48.2	50.6
I_{150}	01.30.00 PM	54.4	56.1	55.7	48.4	48.7	51.4
I_{180}	02.00.00 PM	55.3	56.8	56.4	49.3	49.4	52.1
I_{210}	02.30.00 PM	56.1	57.1	57.2	50.1	49.7	52.9
I_{240}	03.00.00 PM	57.0	58.0	58.1	51.0	50.6	53.8
I_{270}	03.30.00 PM	57.6	58.2	58.6	51.6	50.8	54.3
I_{300}	04.00.00 PM	57.9	58.4	59.1	51.9	51.0	54.8
I_{330}	04.30.00 PM	58.2	58.7	59.6	52.2	51.3	55.3
I_{360}	05.00.00 PM	58.5	59.2	60.0	52.5	51.8	55.7
Charge passed in Coulomb		1186.3	1211.0	1214.1	1057.0	1051.2	1121.7

The avg. Current passes from Control concrete specimen were – 1203.8 coulombs.

The avg. Current passes from the Bacterial concrete specimen were – 1076.6 coulombs.

The reduction in Chloride ion permeability was 11%.

6.1.5. Durability analysis for normal and aggressive environment conditions

The concrete cubes are cast, demold, and cured in water. After 28 days, cubes were removed, and the initial weight was taken.

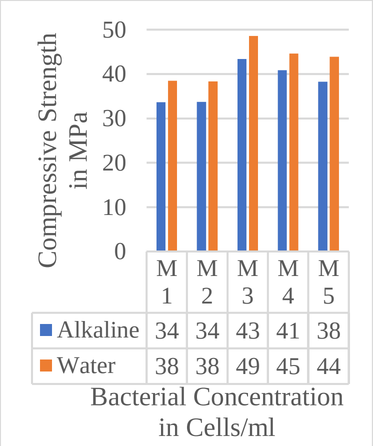


Fig.12 Effect of Alkaline water on the compressive strength of bacterial concrete

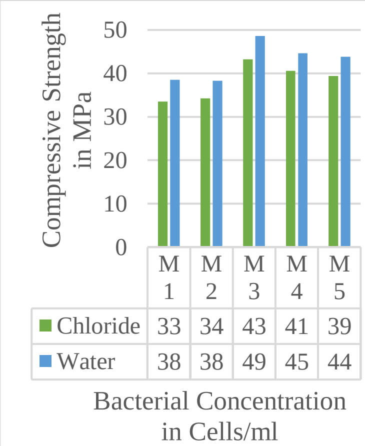


Fig.13 Effect of Chloride water on the compressive strength of bacterial concrete

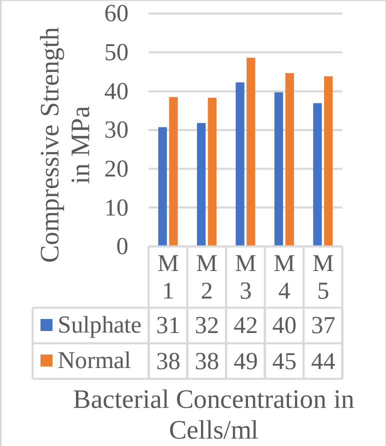


Fig.14 Effect of Sulphate attack on the compressive strength of bacterial concrete

The cubes have been immersed in alkaline water for 56 days to perform the alkali attack test. Alkaline water is made of NaOH (5% of wt. of water), and the alkalinity of water was maintained by measuring their Ph values. The Ph value of alkaline water was 12. Next, in the chloride resistance test, the cubes have been immersed in Chloride water; the Chloride water is made of Na_2Cl (5% of wt. of water). Finally, the sulfate attack test dipped the cubes in Sulphate water. Sulfate water is made of Na_2SO_4 and $MgSO_4$ (5% of water). After 56 days, the concrete cubes have been taken out. The specimens were then put to the compressive strength test.

6.1.6. Results of SEM analysis

Scanning Electron Microscope (SEM) analysis imagines the presence of calcite crystals precipitated by bacteria and voids inside concrete specimens. The broken parts of concrete cube samples collected from the compressive strength test have been used for SEM analysis. The samples were dried at 60°C in an oven for three days and gold coated with a sputter coating before being subjected to SEM analysis. The figure shows the 50µm and 5µm microscopic images of the control and bacterial concrete specimen. The image shows the content of voids and calcite precipitated by the bacteria. It shows a higher amount of calcite precipitated in bacterial concrete than in control concrete, and the content of voids is increased in control concrete than in bacterial concrete.

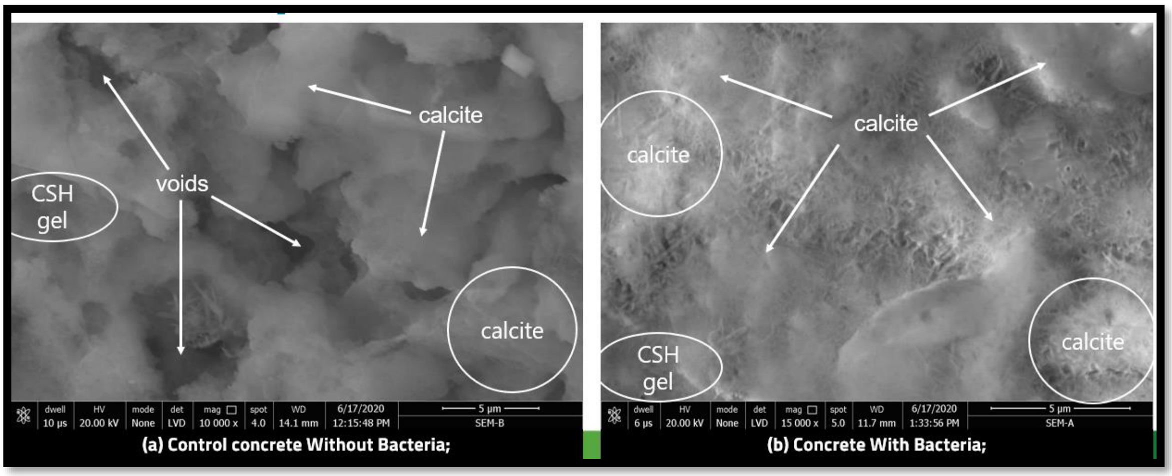
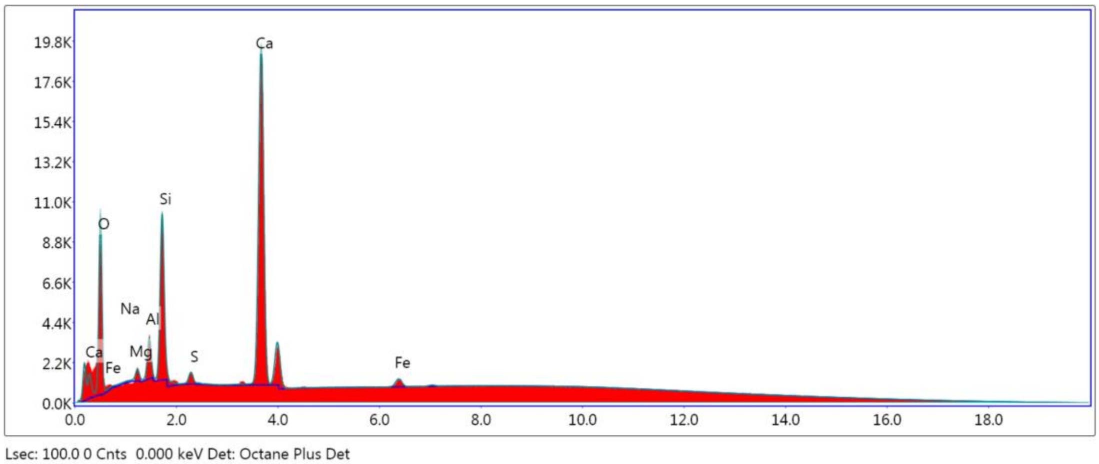
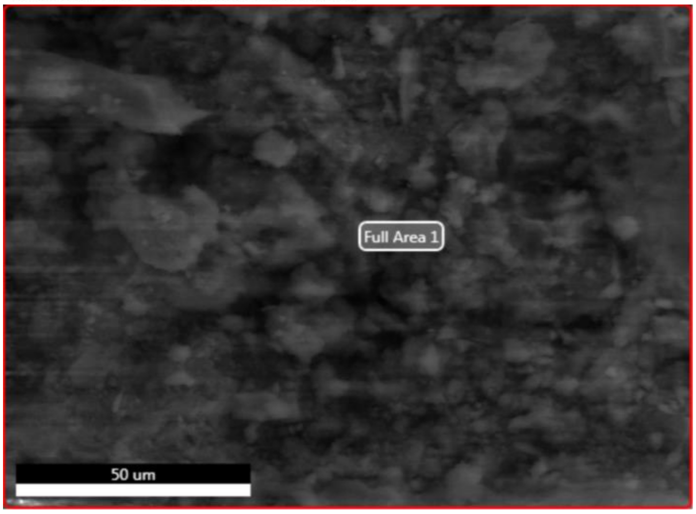


Fig.15 5µm size SEM image (a) Control concrete (b) Bacterial concrete

6.1.7. Results of EDS – Analysis

It is a chemical technique employed in conjunction with SEM. Prepare a sample and put it into the EDX machine. High-energy electrons have been transferred to the sample. These electrons will collide with the atoms of the element present inside the sample. Due to this collision, the electron of the particles has been removed from its near orbit. As a result, the electron from the upper orbit will jump toward the lower orbit by releasing some energy to fill this gap. The released energy has been recorded by the EDX machine [47].

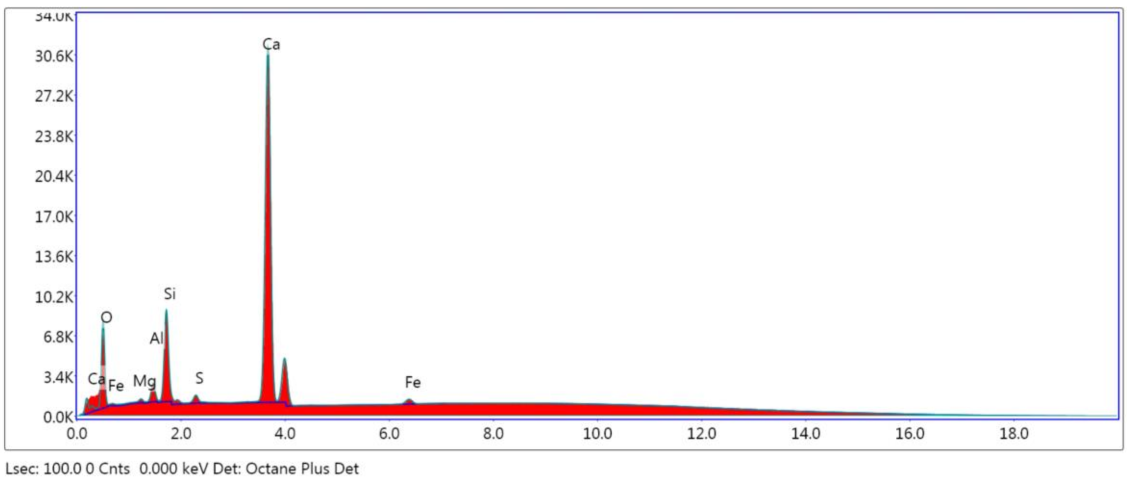


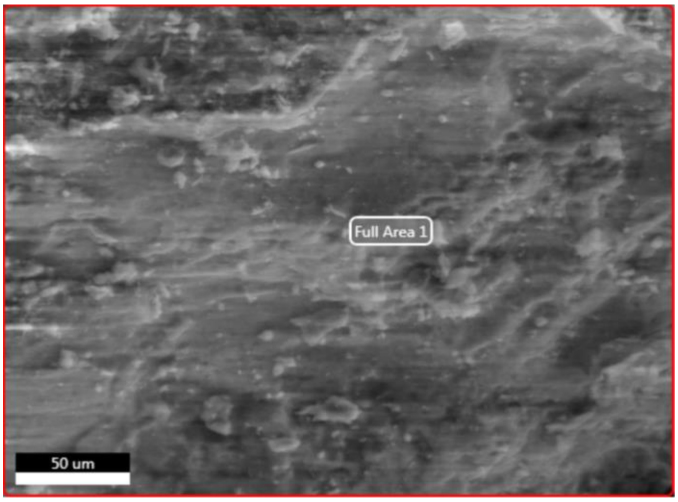


Element	Weight %	Atomic %
O K	50.97	70.26
NaK	0.07	0.07
MgK	0.81	0.73
AlK	2.41	1.97
SiK	8.74	6.86
S K	0.7	0.48
CaK	34.11	18.77
FeK	2.19	0.86

Fig.16 EDS Spectrum for control concrete specimen

During EDX, different areas were focused, and the corresponding peaks are shown in the figure. CaO, SiO_2, Fe_2O_3, Al_2O_3, etc., can be seen in the synthesised concrete specimen in the EDS spectrum. In the EDS spectrum, X-axis shows the energy released from C, O, Na, Mg, Al, Si, Ca, Fe, etc. elements according to their atomic number. The vertical axis shows the energy released during the movement of electrons.





Element	Weight %	Atomic %
O K	42.3	63.5
Mg K	0.3	0.29
Al K	1.43	1.27
Si K	6.3	5.39
S K	0.59	0.44
Ca K	47.32	28.35
Fe K	1.77	0.76

Fig.17 EDS Spectrum for Bacterial concrete specimen

6.2. Parametric Study of Bacterial Concrete by Incorporating CTP

The first series was bacterial concrete (BC1) prepared by replacement of 10% of water with B. Megaterium MTCC 10086 grown in NB with a concentration of 10^5 cells/ml. The second (BC2), third (BC3), fourth (BC4), and fifth (BC5) series were similar to the first series (BC1) in terms of all ingredients used in concrete, but 5%, 10%, 15%, and 20% cement were replaced with CTP, respectively.

Table-4 Concrete mix design

Type of Mix	Grade of Concrete	Cement (kg/m^3)	CTP (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	w/c or w/cm	Water (kg/m^3)	Bacteria	
								Content in ltr./m^3	Concentration in cells/ml
BC1	M30	387.50	-	1222.70	681.61	0.48	179.13	19.90	10^5
BC2	M30	368.13	19.37	1222.70	681.61	0.48	179.13	19.90	10^5
BC3	M30	348.76	38.75	1222.70	681.61	0.48	179.13	19.90	10^5
BC4	M30	329.39	58.12	1222.70	681.61	0.48	179.13	19.90	10^5
BC5	M30	310.02	77.50	1222.70	681.61	0.48	179.13	19.90	10^5

6.2.1. Results of Compressive and tensile strength

The figure shows the effect of different percentages of CTP on the compressive and tensile strength of M-30 grade bacterial concrete cube samples at 7 days, 28 days, and 56 days. As the amount of CTP was increased up to 10% cement replacement, the compressive and tensile strength of bacterial concrete increased; however, at 15% and 20% cement replacement, it decreased. At 7-day, 28-day, and 56-day M-30 grade bacterial concrete with 10% replacement of cement with CTP, 22.9%, 24.57%, and 25.57% improvement in compressive strength have been achieved individually, compared with the compressive strength of the control concrete. It was observed that at 7-day, 28-day, and 56-day M-30 grade bacterial concrete with 10% replacement of cement with CTP, 23.39%, 23.38%, and 20.36% improvement in tensile strength, respectively.

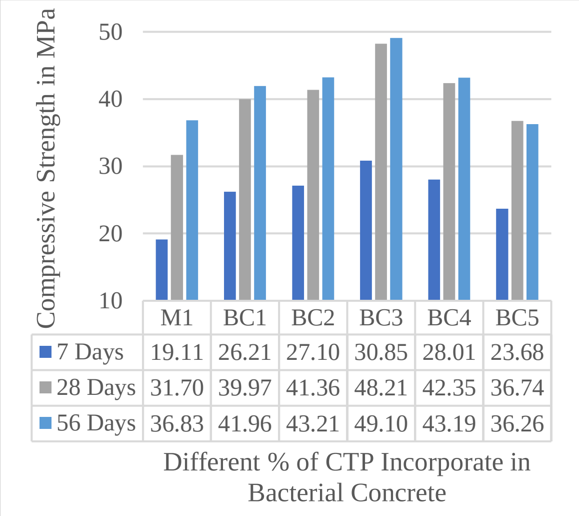


Fig.18 Compressive Strength of M30 grade bacterial concrete with Different % of cement replaced CTP

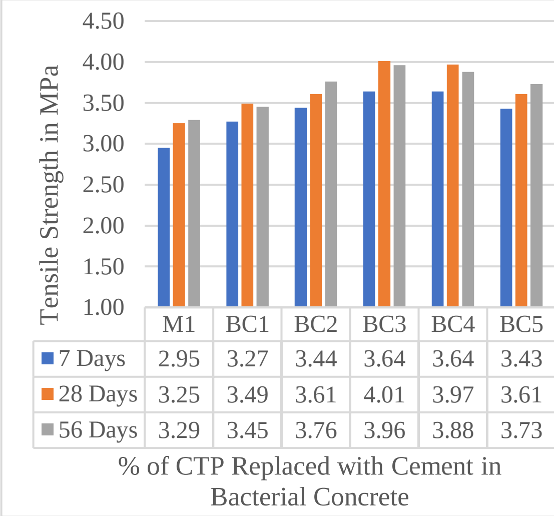


Fig.19 Tensile Strength of M30 grade bacterial concrete with Different % of cement replaced CTP

6.2.2. Results of Water permeability of concrete

It was found that at 10% cement replacement with CTP, the lowest value of water permeability coefficient has been achieved, and it's 2.27 at 28days. When the CTP concentration was increased from 5% to 10%, the value of Kw for the Control concrete decreased. When the CTP concentration was increased to 15% and 20%, the value of Kw for the Control concrete was increased. The percentage of reduction in water permeability at 28 days was 54.32%.

6.2.3. Results and discussion of RCPT test

The table-4 shows a higher percentage of charge passed from the specimen in controlled concrete than bacterial concrete when CTP partly replaces cement. It was observed that as you increase the % of CTP replacement with cement, the permeability of bacterial concrete was reduced up to 15% replacement of CTP with cement. The maximum reduction in the chloride ion permeability was observed at 15% cement replacement with CTP. The charges passed from the control concrete were 1204 coulombs, while it was 951 coulombs for bacterial concrete by 15% replacement of cement with CTP. There was a 21% reduction in chloride ion permeability observed.

Table-5 Charge passes from the bacterial concrete specimen by replacement of cement with CTP

Sr. No.	Concrete of Mix	Charges measured in Coulomb	Average Charges in Coulomb	Chloride Permeability	Reduction in Chloride ion permeability
1	BC1	1057	1076	Low	11%

2		1051			
3		1121			
4	BC2	988	1002	Low	17%
5		981			
6		1038			
7	BC3	976	979	Very Low	19%
8		984			
9		977			
10	BC4	961	951	Very Low	21%
11		948			
12		945			
13	BC5	978	993	Very Low	18%
14		998			
15		1002			

6.2.4. Chemical attack test

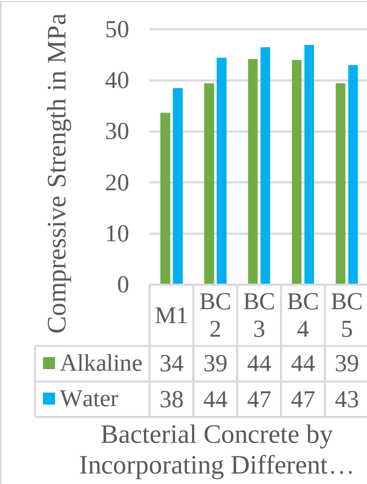


Fig.20 Effect of Alkali attack on the compressive strength of M30 grade bacterial concrete by replacement of cement with CTP

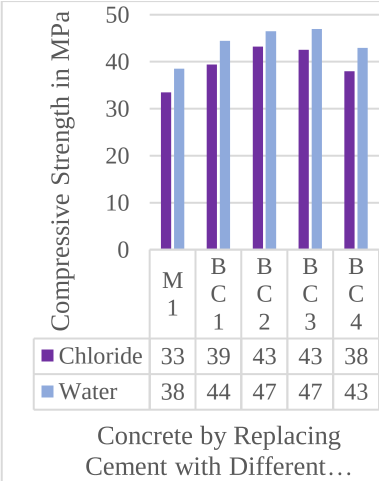


Fig.21 Effect of Chloride attack on the compressive strength of M30 grade bacterial concrete by replacement of cement with CTP

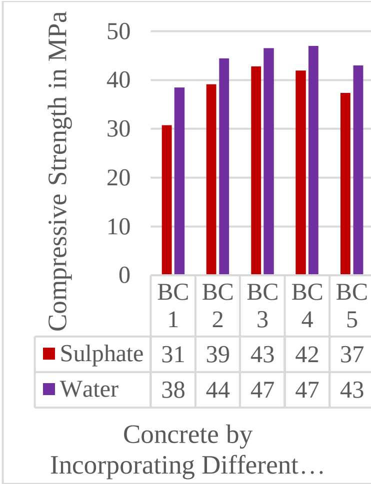


Fig.22 Effect of Sulphate attack on the compressive strength of M30 grade bacterial concrete by replacement of cement with CTP

6.2.5. Results and discussion - SEM analysis

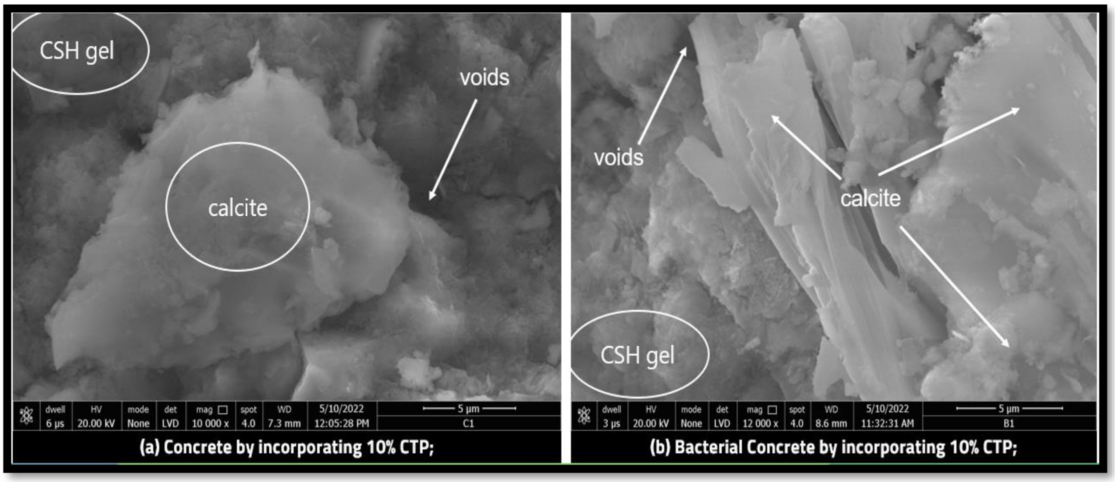


Fig.23 5µm size SEM image after 56-days (a) Concrete by 10% replacement of cement with CTP (b) Bacterial Concrete by 10% replacement of cement with CTP

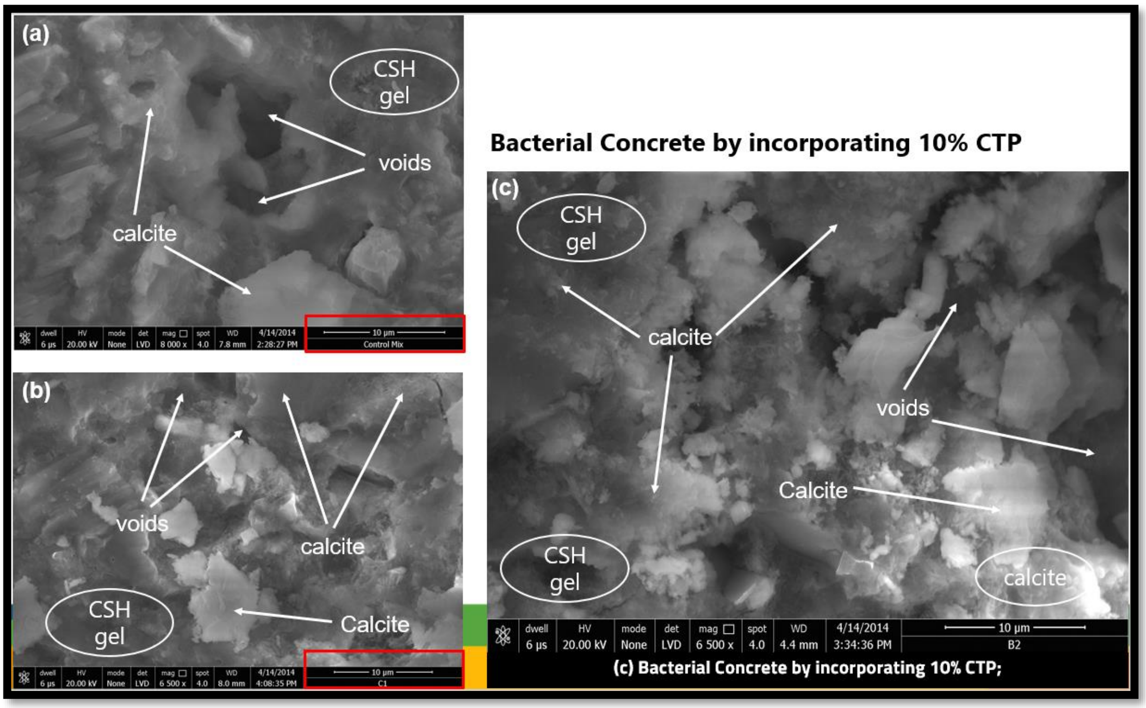
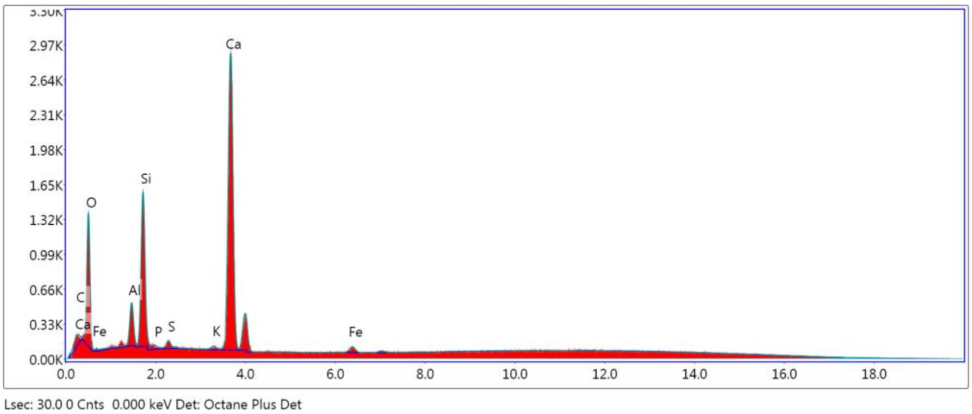
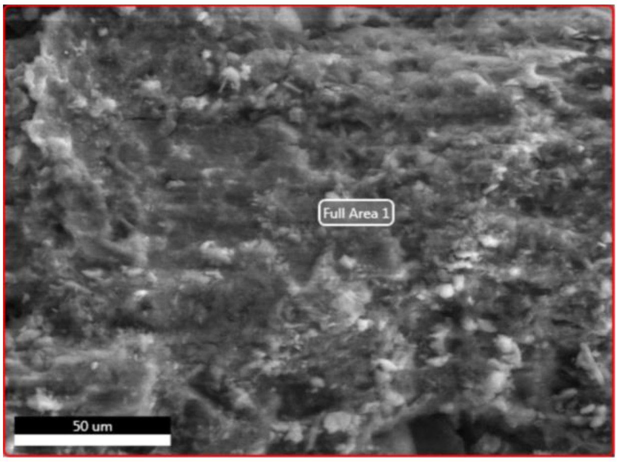


Fig.24 10µm size SEM image after 28-days (a) Control concrete (b) Concrete by 10% replacement of cement with CTP (c) Bacterial Concrete by 10% replacement of cement with CTP

6.2.6. EDS/EDX – Energy Dispersive X-ray Spectroscopy





Element	Weight %	Atomic %
C K	3.34	6.1
O K	46.05	63.23
Mg K	0.38	0.34
Al K	2.45	2
Si K	10.62	8.31
S K	0.36	0.24
K K	0.22	0.12
Ca K	33.94	18.61
Fe K	2.65	1.04

Fig.25 EDS Spectrum for Bacterial Control concrete specimen by incorporating 10% CTP @ 56 Days

The content of each element present in the specimen has been verified. Furthermore, comparing elements of the EDS spectrum from two different areas, a uniform distribution of all elements has been found.

7. Achievement and Conclusion

The following conclusions have been derived from the findings of this study.

- It was concluded that the compressive strength of the control concrete increased with an increase in the concentration of microscopic organism cells up to 10^5 cells/ml, accompanied by a decrease in strength at 10^9 cells/ml. The highest compressive strength rate attained at 28-day in M30 grade bacterial concrete was 26.07%, while for M70 grade bacterial concrete, it was 32.88% at 10^5 cells/ml bacterial concentration compared to control concrete. The 10^5 cells/ml bacterial concentration indicates a maximum increase in tensile strength; it was 23.90% for M30 grade and 21.24% for M70 grade bacterial concrete at 28-days.
- The significant decrease in water permeability coefficient Kw was 58.14% and 60.32% for M30 grade and M70 grade bacterial concrete (10^5 cells/ml) at 28 days. During the RCPT test, it was observed that the average charge passes from the control concrete specimen was 1204 coulomb, while it was 1076 coulomb in bacterial concrete. So, the chloride ion permeability is reduced by 11% in bacterial concrete.
- It was observed in Alkali attack, Chloride attack, and Sulphate attack tests that the % loss in compressive strength of bacterial concrete at 10^5 cells/ml bacteria concentration is less than control concrete.
- The maximum compressive and tensile strength of bacterial concrete by incorporating 10% CTP was 24.57% and 23.38%, respectively, at 28-day compared to control concrete. The increased strength is due to microbial-induced mineral precipitation that filling the pores within the concrete cube specimen.
- The significant reduction in water permeability coefficient Kw by incorporating 10% CTP was 54.33% at 28 days. During the RCPT test, it was observed that the average charge passes from the control concrete specimen was 1204 coulomb, while it was 979 coulombs in bacterial concrete by incorporating 10% CTP in the concrete. Compared to control concrete, the chloride ion permeability is reduced by 18.68% in bacterial concrete. This shows that microscopic organisms could have blocked the voids of the concrete matrix because of calcite precipitation.

- It was observed in Alkali attack, Chloride attack, and Sulphate attack tests that the % loss in compressive strength of bacterial concrete by incorporating CTP is less than control concrete.
- A higher amount of calcite precipitation and a lower amount of void formation have been observed in SEM images of the bacterial concrete specimen with 10^5cells/ml concentration. From the EDS report, it has been found that no impurities/foreign material is available in the sample, and the elements present in the concrete sample are verified using the EDS spectrum.

The 10^5 cells/ml is the ideal concentration of bacteria to be added to the concrete to improve its strength and durability. In the case of lower (10^3cells/ml) and higher (10^9cells/ml), bacterial cell concentrations compete with each other and prevent growth due to hunger or nutrient competition. The ideal concentration of bacteria positively influences the higher-grade concrete compared to lower-grade concrete. The CTP can be used in the future as a green construction material to enhance concrete quality. The low-cost, natural and durable concrete can be prepared by 10% replacement of cement with CTP in bacterial concrete with its ideal concentration.

8. List of all publications arising from the thesis

[1] K. B. Vaghela and J. R. Pitroda, "Microbial Mineral Precipitation to Develop the Properties of the Concrete – A Review," Int. J. Emerg. Technol., vol. 10, no. 4, pp. 335–344, 2019.

[2] K. B. Vaghela and J. R. Pitroda, "To Investigate The Impact of Ceramic Tile Powder On Concrete Properties," Int. J. Eng. Trends Technol., vol. 69, no. 8, pp. 11–16, 2021, DOI: 10.14445/22315381/IJETT-V69I8P202.

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