

Development of Self-Healing Concrete using *Bacillus Subtilis* and Eggshell Powder as Partial Replacement of Cement

Dr. M. Madhuri¹, A. Sai Ganesh², B. SrinivasaRao³, P. Sailu⁴, S. Janaki Devi⁵

¹Associate Professor, Department of Civil Engineering, Sanketika Vidya Parishad Engineering College, Andhra Pradesh, India

^{2,3,4,5}B. Tech Students, Department of Civil Engineering, Sanketika Vidya Parishad Engineering College, Andhra Pradesh, India

Abstract - Cracks in concrete reduce durability and service life. This project investigates self-healing concrete using *Bacillus subtilis* bacteria and eggshell powder as a partial replacement of cement in M30 grade concrete designed as per IS 10262:2019 & IS 456:2000. Eggshell powder was used at 5%, 10%, and 15%, while the bacterial dosage was kept constant at 2% to promote Microbial Induced Calcite Precipitation (MICP) for crack healing. Five concrete mixes were prepared, including a control mix and a bacteria-only mix. Compressive strength tests were conducted at 7, 14, 21, and 28 days, along with water absorption and self-healing observation to evaluate strength, durability, and self-healing performance.

Key Words: Self-healing concrete, *Bacillus subtilis*, Microbial Induced Calcite Precipitation (MICP), Eggshell powder (ESP), Compressive strength

1. INTRODUCTION

Concrete is the most widely used construction material due to its high compressive strength and durability. However, the formation of micro-cracks in concrete is unavoidable and leads to reduced durability, permeability issues, and increased maintenance costs. Conventional repair methods are time-consuming and expensive. Self-healing concrete is an advanced material that can automatically repair cracks without external intervention. The use of *Bacillus subtilis* bacteria promotes Microbial Induced Calcite Precipitation (MICP), which results in the formation of calcium carbonate that seals cracks. Eggshell powder is a calcium-rich waste material and can be effectively used as a partial replacement of cement to enhance sustainability. This project focuses on developing self-healing and eco-friendly M30 grade concrete using bacteria and eggshell powder.

1.1 Scope of the Project

- The study is limited to M30 grade concrete only. Other grades of concrete are not considered in this investigation.
- Cement is partially replaced with eggshell powder at 5%, 10%, and 15% by weight. Replacement levels beyond 15% are not included in this study.

- A constant 2% *Bacillus subtilis* dosage is maintained for all concrete mixes. The effect of varying bacterial percentages is not considered.
- Workability is evaluated using slump test, while strength assessment is restricted to compressive strength testing.
- Durability performance is examined through water absorption test and self-healing observation only. Long-term durability tests are beyond the scope of this project.

1.2 Objectives

- To design and proportion M30 grade concrete in compliance with IS 10262:2019 & IS 456:2000.
- To develop self-healing concrete through the incorporation of *Bacillus subtilis* bacteria.
- To investigate the effect of eggshell powder as a partial replacement of cement on the performance of concrete.
- To evaluate the workability characteristics of fresh concrete using standard tests.
- To assess the compressive strength development at 7, 14, 21, and 28 days of curing.
- To examine the self-healing efficiency and durability characteristics of bacterial concrete.

2. LITERATURE REVIEW

Yeong Yu Tan et al. (2018) - Studied the utilization of eggshell powder (ESP) in concrete under different curing conditions. ESP was used as a partial replacement of cement at 5%, 10%, 15%, and 20%. The study revealed that strength and durability improved under proper curing conditions, and water absorption was reduced. However, higher percentages of ESP led to a reduction in strength, especially in aggressive environments. The optimum replacement level was found to be around 10% ESP.

Ashfaque Ahmed Jhatial et al. (2019) - Investigated the effect of eggshell powder as a supplementary cementitious material in concrete. ESP was added at 5%, 10%, and 15% replacement levels with different fineness (50 µm and 100 µm). The results showed that maximum compressive strength was achieved at 10% replacement. Finer particles of

ESP improved particle packing, resulting in better strength performance. Thus, 10% ESP was identified as the optimum value.

S. Mohd Arif et al. (2021) - Conducted an experimental study on high-strength concrete using eggshell powder. ESP was used at 0%, 5%, 10%, and 15% replacement levels. The results indicated that the highest compressive strength (68.4 MPa at 28 days) was achieved at 10% ESP. However, it was observed that workability decreased with an increase in ESP content. Therefore, 10% ESP was considered the optimum replacement level.

Safiuddin et al. (2022) - Carried out a study on self-healing concrete using Bacillus subtilis. The bacteria were added at 2%, 3%, 4%, and 6% dosages by weight of cement. The study found that crack healing occurred within 48 hours for 2% dosage and 32 hours for 3% dosage. Both compressive and tensile strengths improved with bacterial addition, but higher percentages were less effective. The optimum dosage was found to be 2–3% bacteria.

Adil et al. (2024) - Investigated self-healing concrete using Bacillus subtilis with bacterial solution dosages of 60 mL, 75 mL, and 90 mL per cube. The results showed that maximum compressive strength was achieved at 75 mL dosage, while better crack healing performance was observed at 90 mL. This indicates a trade-off between strength and healing efficiency, with 75 mL considered optimal for strength.

Balte et al. (2024) - Performed an experimental investigation on self-healing concrete using Bacillus subtilis at 3% and 6% dosages. The results showed that both mixes exhibited higher strength compared to the control mix. However, the 6% dosage, although increasing strength, negatively affected workability and increased cost. Therefore, 3% bacterial dosage was considered more practical and efficient.

3. METHODOLOGY



Flow Chart - 1: Methodology of the Project

3.1 Materials used:

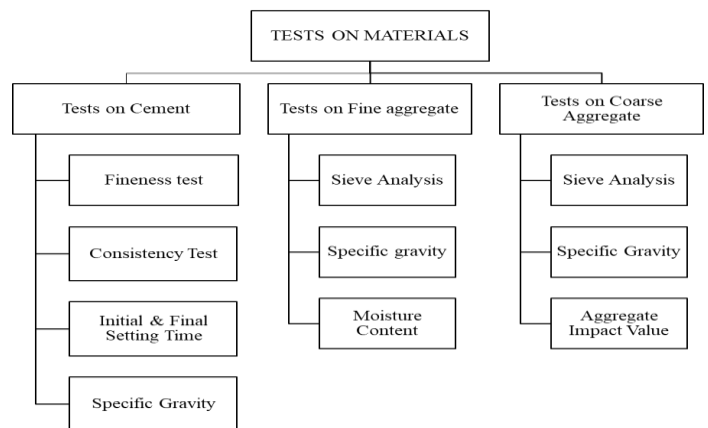
- Cement: OPC 53 grade cement was used as the primary binding material.

- Fine Aggregate: Clean natural river sand was used as fine aggregate.
- Coarse Aggregate: Crushed angular aggregates of 20 mm and 10 mm sizes were used.
- Eggshell Powder: Finely ground eggshell powder passing 75-micron sieve was used as partial replacement of cement.
- Bacillus subtilis: Bacillus subtilis bacteria was used as a bio-admixture for self-healing of cracks.
- Water: Potable water was used for mixing and curing of concrete.



Fig -1: Eggshell powder & Bacillus Subtilis

3.2 Tests on Materials:



Flow Chart - 2: Test on Materials

3.3 Mix Design:

Mix Design is carried out in B.I.S Method (Bureau of Indian Standards) As per IS 10262:2019 & IS 456:2000

MIX DESIGN PROCEDURE FOR THE CONCRETE OF GRADE M30:

1. Target Strength

$$f'_{ck} = (f_{ck} + k_s) \text{ or } (f_{ck} + x)$$

f_{ck} = Target mean compressive strength at 28 days

$K = 1.65$

$S = 5 \text{ N/mm}^2$ standard deviation (IS-10262- 2019, table-2

P. No:3)

X = factor based on grade of concrete as per table-1

X = 6.5 (IS-10262-2019, Table -2 P. No:3)

$f_{ck1} = 30 + (1.65 \times 5) = 38.25 \text{ N/mm}^2$

$f_{ck2} = 30 + 6.5 = 36.5 \text{ N/mm}^2$

$f_{ck1} > f_{ck2}$

$38.25 > 36.5 \text{ N/mm}^2$

$f_{ck} = 38.25 \text{ N/mm}^2$

2. Water cement ratio:

Using IS-456-2000, table - 3&5, P. No:20

Water cement ratio = 0.45 (severe range)

3. Water content:

Using IS-10262, Table-4, P. No:5

20 mm coarse aggregate = 186 kg (for 50 mm slump)

100 mm slump:

For every 25 mm -add 3% (IS-10262- 2019, cl:5.30)

$186 + 6\% = 197.16 \text{ kg}$

4. Calculation of cement content:

Water cement ratio = water content / cement content

Cement = water content / water cement ratio

Cement = $197.16 \text{ kg} / 0.45 = 438.13 \text{ kg}$

Minimum cement content = 320 kg (IS: 456:2000, P. No:20)

$437.78 > 320 \text{ kg}$

5. Aggregate proportion (coarse aggregate & fine aggregate):

IS-10262-2019, Table - 5, P. No:6, cl:5.51

Zone-2-0.62 (W/C-0.5)

Every 0.05 decrease increase 0.01

$(W/C-0.5) = (0.45-0.50) = 0$

$0.62 + 0.01 = 0.63 \text{ kg}$

Coarse aggregate = 0.630 kg

Volume of fine aggregate = $1 - 0.630 = 0.370 \text{ kg}$

Fine aggregate = 0.370 kg

6. Mix calculation:

a) Volume of concrete - 1 m^3

b) Volume of cement (mass / sp. gravity) $\times (1/1000)$
 $= 438.13 / (3.15 \times 1000) = 0.139 \text{ m}^3$

c) Volume of Water = $197.16 / (1 \times 1000) = 0.197 \text{ m}^3$

d) Volume of all in aggregate: $1 - (b + c) = 1 - (0.139 + 0.197) = 0.664 \text{ kg}$

e) Mass of coarse aggregate:

Volume of all in aggregate \times Volume of coarse aggregate \times Sp. Gravity of coarse aggregate $\times 1000 = 0.664 \times 0.630 \times 2.73 \times 1000 = 1142.01 \text{ kg}$

f) Mass of fine aggregate:

Volume of all in aggregate \times Volume of fine aggregate \times Sp. Gravity of fine aggregate $\times 1000 = 0.664 \times 0.370 \times 2.65 \times 1000 = 651.05 \text{ kg}$

7. Summary:

Cement = 438.13 kg/m^3

Water = 197.16 kg/m^3

Fine aggregate = 651.05 kg/m^3

Coarse aggregate = 1142.01 kg/m^3

Table -1: Material Proportions per m^3

Materials	CM	BC - 2%	ESP 5B	ESP 10B	ESP 15B
Cement	438.13	438.13	416.22	394.32	372.41
Eggshell Powder	0	0	21.91	43.81	65.72
Fine Aggregate	651.05	651.05	651.05	651.05	651.05
Coarse Aggregate	1142.01	1142.01	1142.01	1142.01	1142.01
Water	197.16	197.16	197.16	197.16	197.16
Bacteria	0	8.76	8.76	8.76	8.76

4. RESULTS

The results obtained from the experimental investigation carried out in this study. The results of tests conducted on materials, fresh concrete, and hardened concrete are presented in tabular form for better understanding and comparison.

4.1 Tests on Materials:

The properties of materials such as cement, fine aggregate, and coarse aggregate were determined through laboratory testing. The results obtained from these tests are presented below.

Table -2: Results of Materials Tests

Material	Test Conducted	Result
Cement	Fineness	9%
	Standard Consistency	32%
	Initial Setting Time	110 min
	Final Setting Time	220 min
Fine aggregate	Grading Zone	Zone II
	Specific Gravity	2.65
	Moisture Content	4.16%
Coarse aggregate	Sieve Analysis	Well- Graded
	Specific Gravity	2.73
	Aggregate Impact Value	9.83%
Eggshell Powder	Particle Size	Passed through 75 μm sieve

4.2 Tests on Fresh Concrete:

The workability of fresh concrete mixes was determined by conducting the slump test in accordance with IS 1199:1959. The test was carried out for all concrete mixes including control mix, bacterial concrete, and eggshell powder incorporated bacterial concrete.

Table -3: Slump Test Results

Mix Type	Slump Value (mm)	Workability
Control Mix (CM)	90	Medium
Bacterial Concrete (BC)	85	Medium
ESP 5% + 2% Bacteria	78	Medium
ESP 10% + 2% Bacteria	70	Medium
ESP 15% + 2% Bacteria	62	Medium

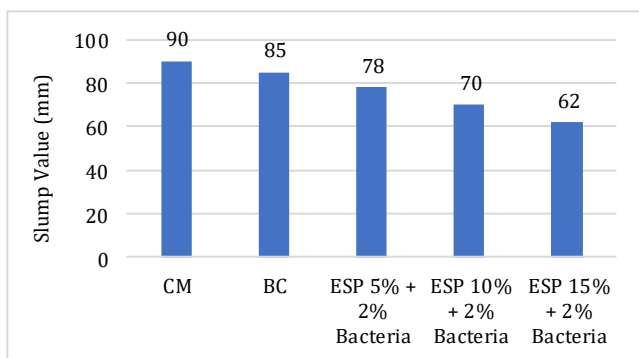


Chart -1: Workability of Concrete Mixes

Table -4: Compressive Strength Results

Mix	7 Days (MPa)	14 Days (MPa)	21 Days (MPa)	28 Days (MPa)
Control Mix	17.78	24.89	29.33	35.56
Bacterial Mix	16.44	23.11	28.88	34.22
ESP 5% + Bacteria	15.55	21.33	27.11	32.88
ESP 10% + Bacteria	16.88	24.88	33.77	38.66
ESP 15% + Bacteria	13.77	19.11	24.44	30.66

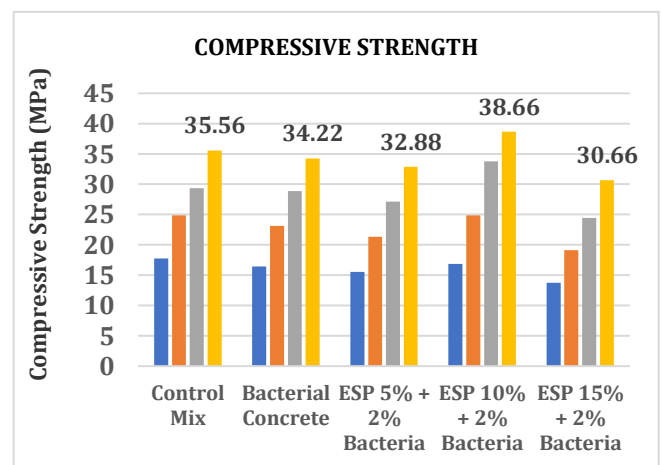


Chart -2: Compressive Strength of Concrete Mixes

4.3 Tests on Hardened Concrete:

The hardened properties of concrete were evaluated by conducting laboratory tests on cured concrete specimens. These tests were carried out to determine the strength and durability characteristics of the concrete mixes. The hardened concrete tests conducted in this study include compressive strength test, water absorption test, and self-healing observation. The results obtained from these tests are presented in the following sections.

a) Compressive Strength Test:

The compressive strength test was conducted on concrete cube specimens after 7, 14, 21 and 28 days of curing using a Compression Testing Machine (CTM) in accordance with IS 516:1959. The results obtained for different mixes are presented in the following table and bar chart.

b) Water Absorption Test:

The water absorption test was conducted on 28-day cured concrete cube specimens to evaluate the permeability characteristics of different concrete mixes. The test was performed for all mixes including control mix, bacterial concrete, and eggshell powder incorporated bacterial concrete in order to compare their water absorption behaviour.

The percentage of water absorption was calculated using the following formula:

$$\text{Water Absorption (\%)} = (W_2 - W_1) / W_1 \times 100$$

Table -5: Water Absorption Results

Mix Type	Oven Dry Weight (W ₁) (g)	Saturated Weight (W ₂) (g)	Water Absorption (%)
Control Mix (CM)	8050	8199	1.85
Bacterial Concrete (BC)	8020	8149	1.62
ESP 5% + Bacteria 2%	8000	8139	1.74
ESP 10% + Bacteria 2%	8030	8174	1.79
ESP 15% + Bacteria 2%	7980	8140	2.01

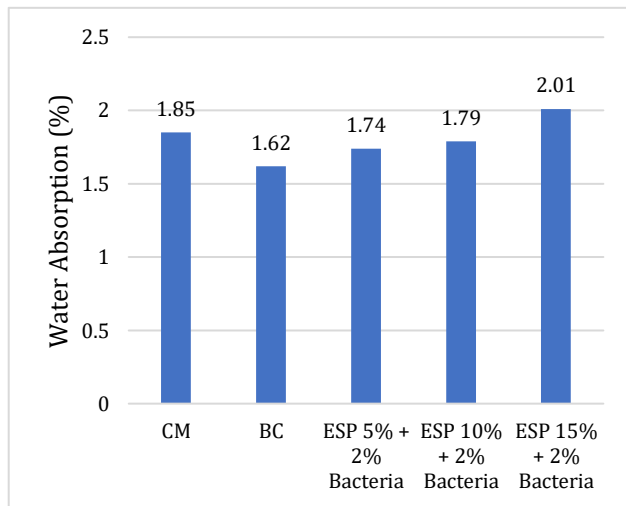


Chart -3: Water Absorption of Concrete Mixes

c) Self- Healing Observation Test:

Self-healing behaviour of concrete was observed by inducing cracks in cube specimens after 7 days of curing using a Compression Testing Machine (CTM). The crack locations were marked with paint to facilitate easy monitoring. The specimens were then kept under curing conditions and the crack healing process was visually observed at 7, 14, 21 and 28 days after crack induction.



Fig -2: Self- Healing Observation

5. CONCLUSIONS

This study focused on the development of self-healing concrete using Bacillus subtilis bacteria and eggshell powder as a partial replacement of cement. The experimental investigation was carried out to evaluate the fresh and hardened properties of concrete as well as the crack healing capability. The slump test results showed that the workability of concrete slightly decreased with the increase in eggshell powder content, but all mixes exhibited acceptable workability. The compressive strength results indicated that bacterial concrete showed strength comparable to the control mix, while the mix containing 10% eggshell powder with bacteria exhibited better strength among the modified mixes. The water absorption results revealed reduced permeability in bacterial concrete mixes, indicating improved durability. The self-healing observation confirmed that bacterial concrete was able to heal cracks over time due to calcium carbonate precipitation produced by bacterial activity. Overall, the incorporation of bacteria and eggshell powder enhances the self-healing capability of concrete and promotes sustainable construction by utilizing waste materials.

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