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Optimizing High-Strength Concrete Performance with Self-Healing Technologies

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ABSTRACT

This study focuses on optimizing high-strength concrete (HSC) by incorporating five mineral admixtures—quartz dust, fly ash, metakaolin, ultra-fine sludge, and rice husk ash—along with a third-generation superplasticizer to reduce water demand and enhance compaction density. Despite HSC's promising properties, its adoption is limited due to crack formation, which compromises durability. To address this, the research explores self-healing concrete using calcite-precipitating bacteria to automatically repair cracks, improving sustainability and longevity. Additionally, eco-friendly materials are integrated to reduce the environmental impact of cement production. The research is conducted in four phases, including material analysis, blend optimization, bacterial development, and mix design validation.

Keywords: High-strength concrete, Self-healing, Bacteria, Crack repair, Mineral admixtures.

INTRODUCTION

Concrete is the second most consumed material globally, after water. While lower-grade concrete sufficed historically, the demand for larger and more complex structures has driven the development of High-Strength Concrete (HSC). HSC is a high-performance concrete offering superior mechanical property, particularly in terms of compressive strength (typically 120–150 MPa, with some mixes exceeding 200 MPa) and durability. It is produced using high-grade cement (like OPC 53), silica fume, quartz sand, steel fibers, and advanced superplasticizers, optimizing the material's microstructure and strength. However, coarse aggregates can become weak links at such high strength levels, sometimes necessitating their removal for better consistency.

HSC also incorporates pozzolanic materials like silica fume and fly ash to enhance its density and strength, while minimizing environmental impact. Despite its benefits, HSC faces two challenges: the environmental footprint of large-scale cement production and the formation of cracks, which can reduce durability. To counter this, eco-friendly materials such as fly ash and slag partially replace cement. Additionally, self-healing technologies, which repair micro-cracks naturally or via healing agents, help improve HSC's resilience by preventing moisture and harmful substances from degrading the material, extending its service life.

Bacteria are classified into five types based on their fundamental shapes:

i) Spherical (Cocci)
ii) Comma-shaped (Vibrio's)
iii) Spiral (Spirilla)
iv) Rod-shaped (Bacilli)
v) Corkscrew-shaped (Spirochaetes)

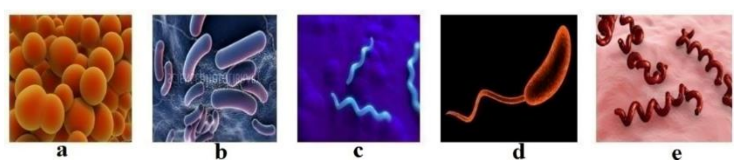

Figure 1 Classification of bacteria based on shapes.

The study by Lee et al. (2009) demonstrated the effectiveness of Reactive Powder Concrete (RPC) as a repair material for existing concrete structures. Their accelerated aging tests, including freeze-thaw cycles, revealed that RPC significantly improved compressive and flexural strength, maintaining durability even after 1,000 freeze-thaw cycles. RPC increased flexural strength by 150% and compressive strength by 200% compared to standard cement, confirming its suitability for repair and retrofitting.

In another study, Yanzhou Peng et al. (2010) explored the use of silica-rich pozzolans like steel slag, silica fume, and ultra-fine fly ash to enhance packing density in cementitious materials. The inclusion of these mineral admixtures in various combinations improved both packing density and concrete performance. Additionally, the study discussed the role of urease-induced hydrolysis in calcium carbonate precipitation in calcium-rich environments, such as caves and limestone, facilitating the formation of CaCO3 crystals.

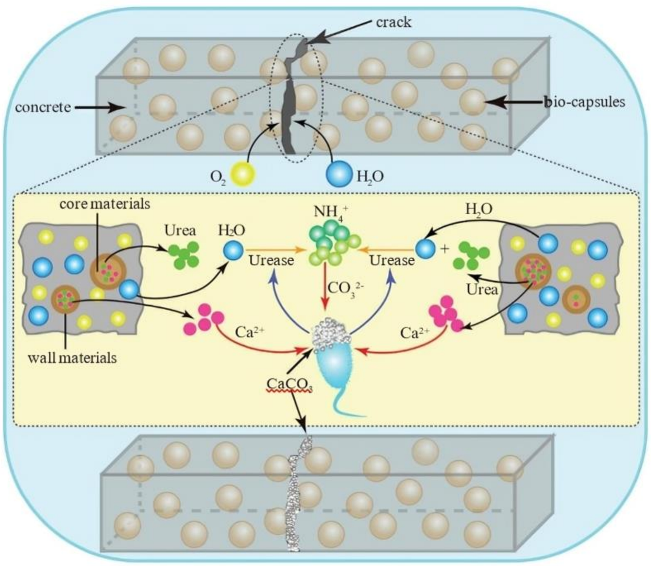

FIGURE 2: Mechanism of bio-capsule self-healing for cracks in concrete. This illustration is adapted from reference [35] with permission from Elsevier Ltd.

All three strains exhibited urease activity, promoting the precipitation of calcium carbonate through both biologically induced and organically influenced processes in optimal alkaline conditions.

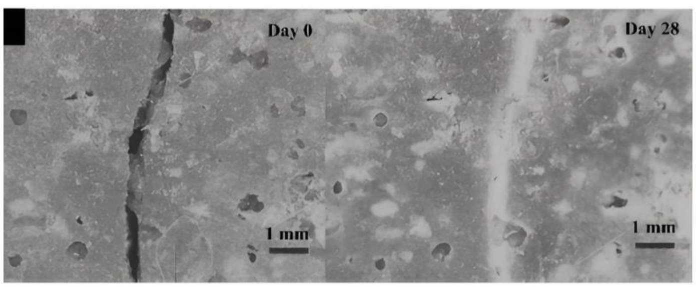

FIGURE 3: Self-healing of concrete after 28 days

The step-by-step flow methodology employed in this study is outlined as follows:

1.Acquisition of Raw Materials: Identify and collect the necessary raw materials for concrete production, including cement, Metakaolin, Quartz powder, aggregates, water, and bacterial culture.

2.Raw Material Characterization: Evaluate the physical and chemical properties of each raw material, focusing on factors such as particle size distribution, specific gravity, chemical composition, and fineness.

3.Mix Proportions Optimization: Perform experiments to refine the mix proportions for binary, ternary, and quaternary concrete mixtures to achieve optimal packing density. Adjust the ratios of cement, Metakaolin, Quartz powder, and aggregates while maintaining a consistent water-to-cement ratio.

4.Bacterial Isolation and Screening: Collect samples for bacterial isolation from suitable environments, such as soil, cementitious materials, or wastewater treatment facilities. Isolate and screen bacteria capable of precipitating calcium carbonate through culture-based assays and molecular techniques.

5.Concrete Sample Fabrication: Prepare concrete samples according to the optimized mix proportions, incorporating the selected bacterial culture at a specified concentration (e.g., 10^5 cells/ml). Cast concrete specimens in standard molds, such as cubes or cylinders, for subsequent testing.

6.Mechanical Properties Assessment: Conduct mechanical testing on the prepared concrete samples to evaluate their compressive strength, flexural strength, and tensile strength using standard testing methods. Assess the influence of bacterial incorporation and supplementary cementitious materials on these mechanical properties.

7.Porosity and Water Absorption Evaluation: Analyse the porosity and water absorption characteristics of the concrete samples using suitable techniques, such as mercury intrusion porosimeter or water absorption tests.

Bacterial Isolation and Confirmation:

Materials and Chemicals Needed

This section specifies the key chemicals and materials required for isolating Bacillus, with a focus on bacteria that promote calcite precipitation. It also lists the materials needed for optimizing mortar samples and their casting. Table 1 summarizes the culture media used for the specific microorganisms of interest.

Table 1: Chemical needed for isolation of bacteria

S. No.	Material & Chemical Name	Purpose
1	Sodium Bicarbonate ($NaHCO_3$)	Nutrient Media
2	Urea (CH_4N_2O)	Nutrient Media
3	Nutrient Broth	Nutrient Media
4	Ammonia Chloride (NH_4Cl)	Nutrient Media
5	Calcium Chloride two Hydrate ($CaCl_2.2H_2O$)	Nutrient Media
6	Agar ($C_{14}H_{24}0_9$)	Solidification of Nutrient Media
7	Soil and water sample from different locations	Isolation of bacteria

Table 2 includes a range of samples collected for the isolation of alkaliphilic bacteria, which are predominantly found in alkaline soils, sewage, and water sources. A total of twelve samples were gathered, consisting of six iron oxide- and lime-rich alkaline soil samples, as well as six sewage samples, sourced from various locations in the Bilaspur and Solan districts of Himachal Pradesh (H.P).

Table 2: Samples collected till date for the isolation of bacteria.

S. No.	Sample Type	Location
1.	Soil Sample 1	UltraTech cement limited, Salarpur khadar (U.P.)
2.	Soil Sample 2	J K Cement Factory limited, Gaziabad (U.P.)
3.	Soil Sample 3	Rama Universisty campus, mandhana (U.P.)
4.	Soil Sample 4	Iscon tample, kanpur (U.P.)
5.	Soil Sample 6	Kargil Park, kanpur (U.P.)
6.	Soil Sample 6	Ganga barrage, kanpur (U.P.)
7.	Bore well Water 1	UltraTech cement limited, Salarpur khadar (U.P.)
8.	Bore well Water 2	J K Cement Factory limited, Gaziabad (U.P.)
9.	River Water Sample	Ganga ji, Kanpur (U.P.)
10.	Lake Water Sample	Moti jheel, Kanpur (U.P.)
11.	Bore well Water 3	Rama Universisty campus, mandhana (U.P.)
12.	Bore well Water 4	Blue warld water park, Kanpur (U.P.)

Table 3 presents a compilation of the materials needed for testing cement, mortar, and concrete.

Table 3: Material used for cement, mortar and concrete testing.

S. No.	Material
1.	Cement (PPC-Fly Ash Based) for plastering
2.	Cement OPC (43/53 Grade)
3.	Benzene or Kerosene
4.	Bricks For Wall making
5.	Plastering with River Sand
6.	Metakoilin
7.	Fine Aggregates (FA)
8.	Coarse aggregates (CA)

This table outlines the chemicals necessary for performing urease activity tests on bacteria.

Table 4: Chemicals for Urease Activity Tests

S. No.	Materials
1.	Deionized Water
2.	Urease (CH_4N_2O)
3.	Phenol Red ($C_{19}H_{14}O_5S$)

Equipment Needed for Bacterial Isolation and Growth: This table details the essential equipment required for isolating and cultivating bacteria, along with their specific functions.

Table 5: Equipment's for Bacteria Isolation and Growth

S. No.	Equipment used	Purpose
1.	Laminar Airflow	Provides Sterilised Environment
2.	Autoclave	To Sterilised Media & Glass Plates
3.	Digital Weighing Balance (1-220 gm)	Weighing Materials
4.	Inoculating Loop	For Inoculating Bacteria
5.	BOD Incubator (@ 38°C)	For Growth of Bacteria
6.	Freezer (@ 4°C)	Prevent culture against over growth and contamination
7.	pH Meter	To measure pH value
8.	Conductivity Meter	To measure bacterial activities
9.	Microwave Oven	To use for melting Agar

Table 6: Glassware required for the preparation of bacteria culture.

S. No.	Equipment used	Purpose
1.	Petri Dish (90×15 mm)	To culturing Bacteria
2.	Conical Flask	Mixing Media
3.	Measuring Cylinder	Measuring Media & Distilled Water
4.	Centrifuge Tubes (2 ml, 20 ml and 50 ml)	For Centrifuge Cells.
5.	Test Tube	For making Slants & Growing Bacteria

Table 7: Equipment and apparatus that are required for testing of Cement, concrete and Mortar samples

S. No.	Equipment	Purposes
1	Vicat Apparatus	Consistency, Initial Setting Time and Final setting Time
2	90-micron sieve	Fineness of cement
3	Le-chatelier Flask	Cement specific gravity
4	Le-chatelier Mould	Soundness
5	Digital weight machine	Weighting sample
6	Pycnometer	Specific Gravity of sand

Biological Mechanisms of Microbial-Induced Calcite Precipitation (MICP)

The precipitation of calcium carbonate is influenced by various types of bacteria and abiotic factors, including salinity, pH, temperature, and nutrient composition across different environments (Knorre and Krumbein, 2000; Rivadeneyra et al., 2004). Critical factors that regulate MICP encompass calcium concentration, dissolved inorganic carbon levels, pH, and the availability of nucleation sites (Hammes and Verstraete, 2002).

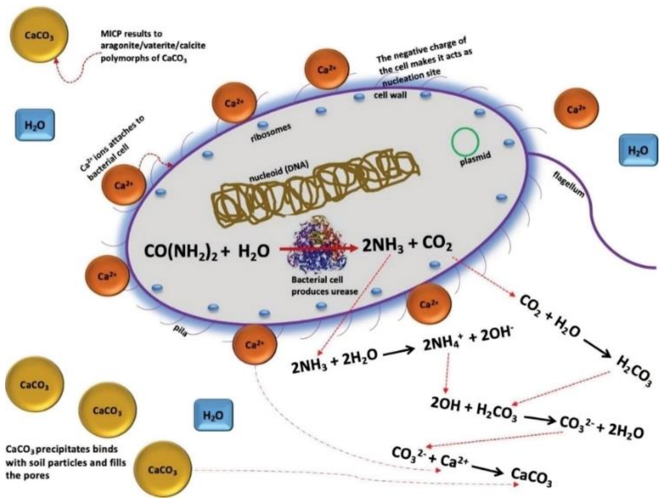

FIGURE 3: Overview of bio-mediated calcite precipitation using ureolysis. Reproduced from ref. [36] with permission of the Korean Society of Environmental Engineers.

Urease enzymes generated by bacteria break down urea into ammonium and carbonate ions, kickstarting the precipitation process.

$$CO(NH_2)_2 \rightarrow 2NH_4{}^{+} + CO_3{}^{2-} \qquad (1)$$

$$Ca^{2+} + CO_3{}^{2-} \rightarrow CaCO_3 \qquad (2)$$

The released ammonium ions raise the local pH, promoting the precipitation of calcium carbonate. In anaerobic environments, denitrifying bacteria oxidize organic carbon using nitrate, resulting in elevated levels of CO32- and HCO3- ions. These ions subsequently react with Ca2+ to produce calcium carbonate (Lee and Park, 2018).

$$5HCOO^{-} + 2NO_3{}^{-} \rightarrow 3HCO_3{}^{-} + 2CO_3{}^{2-} + H_2O + N_2 \qquad (3)$$

$$HCO_3 + H^{+} \rightarrow CO_3{}^{2-} \qquad (4)$$

Moreover, bacteria act as nucleation sites for the crystallization of calcium carbonate by drawing in Ca2+ ions and encouraging the deposition of crystals on their cell walls, which in turn aids in the growth of additional crystals.

CONCLUSION

The findings from this study indicate that microbial cells can effectively serve as crack healers for both macro and micro cracks in concrete. During the isolation phase, 11 bacterial cultures with potential were identified, but further screening narrowed this number down to just 2. This reduction is attributed to the highly alkaline environment of concrete, which makes it challenging for most bacterial groups to survive. Therefore, it is essential to isolate and select only those bacteria that can thrive in high pH conditions for use in concrete applications.

Tests conducted on concrete demonstrated that samples containing microorganisms exhibited greater strength and improved characteristics compared to control samples (without bacteria). This enhancement is attributed to the presence of calcite-precipitating bacteria, which filled the pores within the concrete matrix and formed thin calcium carbonate crystals on the surface cracks. These bacteria are unique in their ability to precipitate calcium carbonate when supplied with nutrients, such as calcium-rich sources and moisture.

The moisture and nutritional requirements of these bacterial colonies are minimal, as they can be satisfied by the moisture in the air and tiny food particles present in the atmosphere. During visual inspections conducted at 7 days post-casting, whitish-yellow crystals were observed near the crack surfaces. Further investigations over 28 days revealed that the highest level of crack healing occurred in the standard concrete system compared to both isolated and control concrete samples.

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