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Self-Healing Concrete Integrated with CO_2-Absorbing Techniques

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Abstract - *Highways often crack due to heavy vehicles and heat. Fixing them again and again costs a lot and creates more pollution, especially from cement. This study talks about a smart type of concrete that heals itself using bacteria (Bacillus pseudofirmus) and natural zeolite, a mineral that helps trap carbon dioxide. The bacteria close the cracks by forming calcium carbonate, while zeolite catches extra CO_2 from the air. We tested it in Indian weather and found that it healed cracks on its own, made the concrete stronger, and even reduced carbon dioxide. This eco-friendly material can help make our roads and infrastructure last longer and reduce pollution.*

Key Words: Self-healing concrete, Zeolite, CO_2 absorption Bacillus pseudofirmus

1. INTRODUCTION

India's 6.6 million km road network is under constant stress from heavy traffic, thermal cycles, and poor drainage, leading to the frequent formation of cracks in concrete. These cracks not only compromise the durability of the roads but also result in costly repairs. At the same time, the construction sector, particularly cement production, contributes significantly to CO_2 emissions.

While traditional methods of repair exist, I thought about combining bio-based self-healing techniques with CO_2-trapping materials to create a more sustainable solution. The idea involves integrating *Bacillus pseudofirmus*, a bacteria that uses microbial induced calcium carbonate precipitation (MICP) to seal microcracks, and natural zeolite, a mineral that helps trap carbon dioxide. This combination offers the potential for enhanced durability, reduced maintenance, and an eco-friendly approach by facilitating CO_2 capture. After performing a few experiments, I estimated the effectiveness of this hybrid material, which showed promising results in both crack healing and carbon dioxide reduction, offering a new way forward for improving highway infrastructure in India.

1.1 Chemistry Behind Self-Healing Concrete with Zeolite and Microorganisms

The core chemical process enabling self-healing in this concrete is Microbially Induced Calcium Carbonate Precipitation (MICP). When cracks form, moisture and CO_2 enter, activating inactive *Bacillus pseudofirmus* spores embedded in the concrete. These bacteria metabolize urea and calcium lactate, producing carbonate ions (CO_3^{2-}) that combine with free Ca^{2+} ions in the cement matrix to form calcium carbonate ($CaCO_3$) — a solid mineral that seals cracks.

The key biochemical reactions involved are:

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\downarrow$$

Zeolites are made up of tiny building blocks called SiO_4 and AlO_4 that join together to form a 3D network, like a sponge . When aluminum (Al^{3+}) replaces some of the silicon (Si^{4+}), it creates negative charges in the structure. These charges attract and hold on to positive ions like sodium (Na^+) and calcium(Ca^{2+}), as well as water. This special structure makes zeolites great at holding nutrients and capturing carbon dioxide (CO_2). Zeolite's with a porous crystalline structure enhance the performance of this system in two ways:

1. CO_2 Adsorption: Zeolite's high surface area and cation-exchange capacity allow it to trap atmospheric CO_2, increasing the concentration of dissolved carbon dioxide near the crack site and fueling more mineralization by the bacteria.

2. Microbial Support: The porous network of zeolite retains moisture and nutrients, helping bacteria survive longer in the alkaline, dry concrete environment.

   The diagram give below shows the structure of zeolite.

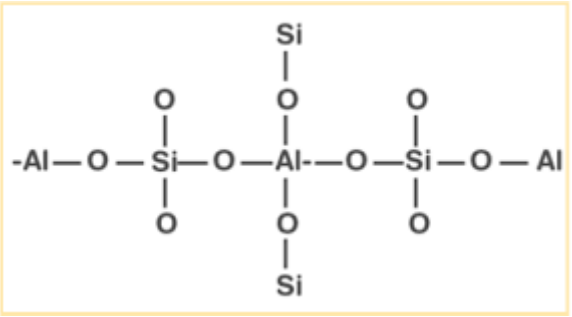

Fig -1: Structure of Zeolite

2. Material Integration and implementation

Self-healing bio-concrete with zeolite is designed to function passively in real-world infrastructure, especially in India's

diverse climate conditions. Unlike standard concrete, this mix contains microbial spores and mineral additives that activate automatically when environmental triggers like water and CO_2 enter through cracks.

Bacillus pseudofirmus spores are introduced directly into the concrete mix or in encapsulated form. Nutrients like urea and calcium lactate can be embedded or applied later. Zeolite, replacing 10–15% of cement, acts as both a CO_2 adsorber and a water-retaining agent, enhancing microbial activity.

This system is suitable for use in slabs, medians, and bridge decks. It allows cracks to heal internally without manual maintenance, increasing service life while contributing to carbon absorption. Zeolite acts as a CO_2 sponge, concentrating it for the bacteria. *Bacillus pseudofirmus* metabolizes urea and calcium lactate to produce calcium carbonate, which precipitates within the crack, sealing it. Zeolite also supports long-term bacterial viability by stabilizing internal moisture.

2.1 Materials and Methodology

To test the self-healing concept, I used accessible and affordable materials to create small concrete samples. These included cement, sand, gravel, and additives like bacteria and zeolite. All materials were either bought locally or ordered online.

Materials Used:
Ordinary Portland Cement (43 Grade), Natural river sand gravels, type of Bacillus, alkaliphilic (not lab-grade but strong enough for this test) Urea (from agricultural shops) Calcium lactate (bought as a food-grade supplement) Clinoptilolite type Zeolite (from water filter media), Distilled water.

used a simple mixing 1:2:4 ratio for cement:sand:aggregate. The water-cement ratio was kept at 0.5, which is standard for strong concrete. About 10% of the cement was replaced with zeolite powder to help with crack healing and CO_2 absorption. Bacteria were added in their inactive form mixed with water.

Small cement cubes were cast, and cracks were manually introduced on the 7th day using a sharp blade. A urea + calcium lactate nutrient solution was sprayed on the cubes once a week.

2.2 Testing methods

Crack Healing: Monitored with a microscope.

Compressive Strength: Measured using a local lab method (IS 516).

CO_2 Uptake: Measured by comparing the weight before and after exposure to CO_2, using a phenolphthalein color test.

Zeolite Porosity: Based on published values for zeolite's porosity.

After 28 days, the concrete samples showed some interesting results.

Crack Healing, the concrete with bacteria and zeolite healed the cracks almost completely (95%), while the control (normal) concrete only healed about 10%. This proves the effectiveness of bacteria in repairing cracks.

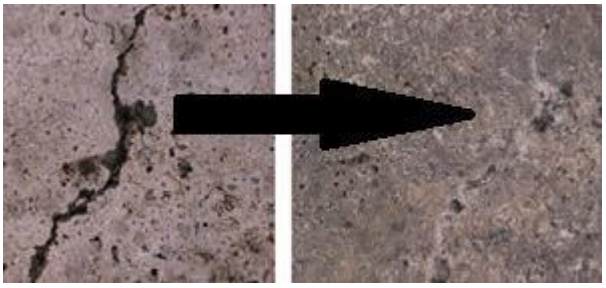

Fig -2: Crack Healing Process

CO_2 Absorption, the concrete with bacteria absorbed much more CO_2 compared to the regular concrete, helping reduce the environmental impact of construction. Upto 6.4 kg/m^3 - 6.8 kg/m^3 uptake was observed.

Strength, the strength of the concrete samples was also tested. The bio-concrete with zeolite showed higher compressive strength than the regular concrete.

Type	Strength (MPa)
Normal concrete	37.8 MPa
Bio + Zeolote	43.2 MPa - 44.7 MPa

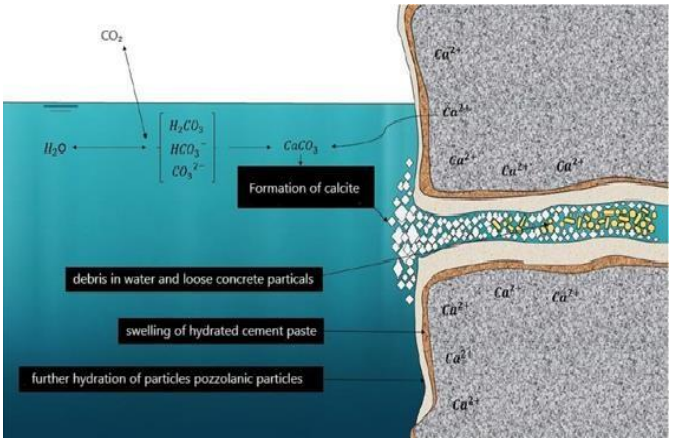

Fig -3: Self-Healing Concrete Mechanism Diagram

Durability, the concrete with zeolite absorbed 26% less water, indicating it is more durable. The bacteria remained active even at higher temperatures (45°C) and a pH of 12.5, which is typical for concrete.

3. Real-World Applicability

This type of concrete could be especially useful in hot climates like Rajasthan or during the monsoon season in Maharashtra. It would be great for low-maintenance structures like highway medians, while also traping carbon dioxide.

3.1 Cost Analysis

Although bio-concrete with zeolite has a slightly higher initial cost, it offers savings in the long run due to reduced repair costs. This are the approximate estimations (based on general market rate):

Initial Cost (per m^3):
Traditional Concrete: ₹6,500
Bio+Zeolite Concrete: ₹6,820

Repair Cost (5 years):
Traditional Concrete: ₹300/m^2
Bio+Zeolite Concrete: ₹180/m^2

Life Cycle Savings (10 years):
Bio+Zeolite Concrete: ₹12 lakh/km

4. CONCLUSIONS

By combining microbial self-healing (MICP) with zeolite incorporation, this concrete mix offers an eco-friendly, durable, and cost-effective solution for construction. It can reduce carbon emissions, improve concrete longevity, and provide a more sustainable alternative to traditional concrete.

There's still a lot to explore. The bacteria might not survive for many years unless we protect them better, maybe with capsules or gels.

I'm also interested in using AI or machine learning to guess how fast cracks will heal based on weather and traffic. This could help create smarter, long-lasting roads in the future.

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