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Project Title: Self-Healing 2.0 – Self Healing Roads Using Bacillus subtilis Bacteria and Bio-Resin Capsules

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ABSTRACT

Road infrastructures experience continuous stress from traffic loads, temperature fluctuations, and water infiltration, causing micro-cracks that gradually widen and reduce structural durability. Traditional repair methods for these cracks are costly, disruptive, and often temporary. To solve this persistent challenge, this project investigates a biologically inspired approach for developing durable and self-sustaining pavements. The research focuses on creating "Self-Healing 2.0 Road Concrete," a biomimetic system that uses Bacillus subtilis bacteria encapsulated inside biodegradable bio-resin capsules along with calcium lactate as a nutrient source. When embedded in concrete, these capsules remain dormant and protected during the mixing and curing stages. Once a crack forms and moisture penetrate the material, the bio-resin capsule gradually softens and releases the bacterial spores and nutrients into the crack environment. The spores germinate upon activation by water and begin a biomineralization process in which the bacteria convert calcium lactate into calcium carbonate ($CaCO_3$). This mineral precipitate fills the cracks and bonds with the surrounding concrete matrix. The healing process restores surface integrity, improves waterproofing, reduces oxygen entry, and slows internal deterioration.

This study compares traditional concrete samples with bacterial concrete samples containing bio-resin capsules. Both samples were cast, cured for seven days, and then cracked to an initial width of approximately 2 mm. Over a ten-day observation period, daily moisture exposure simulated natural rain conditions. The bacterial specimens showed visible healing from the fourth day, with significant deposits of $CaCO_3$ along the crack pathways. By the tenth day, the bacterial concrete healed 80–90% of the crack width, while the control sample achieved only around 10% natural sealing. The healed concrete also demonstrated reduced water permeability during a simple water-absorption test, confirming restored surface resistance. These results strongly support the hypothesis that encapsulated Bacillus subtilis can enhance the self-healing capacity of concrete and significantly extend road service life.

The project demonstrates that bio-based self-healing concrete is a sustainable, low-maintenance, and environmentally friendly method that can transform future road construction. By reducing maintenance frequency, preventing early failure, and increasing durability, this innovation has the potential to save substantial public funds and promote greener infrastructure development.

Introduction

Cracks in roads and pavements are a common and recurring problem across the world. Over time, heavy traffic loads, temperature variations, and water seepage lead to the formation of micro-cracks in concrete. These small cracks gradually expand, weakening the structure and resulting in costly maintenance, traffic disruptions, and safety hazards. Traditional repair methods rely on manual interventions and chemical fillers that are often short-lived and harmful to the environment. In recent years, researchers have been exploring bio-based self-healing concrete as a sustainable alternative. The concept was first proposed by Dr. Henk Jonkers of Delft University of Technology in the Netherlands, who demonstrated that certain bacterial species can be incorporated into concrete to heal cracks autonomously. The most successful of these bacteria is Bacillus subtilis-a non-pathogenic, spore-forming microbe known for its ability to survive in alkaline environments and produce calcium carbonate (Ca CO_3) when activated by moisture and oxygen. When roads made with bacterial concrete crack, the dormant spores of Bacillus subtilis become active upon contact with water. They utilize a nutrient source, such as calcium lactate, encapsulated inside bio-resin microcapsules, to precipitate $CaCO_3$ crystals. These crystals fill the cracks, bonding the broken surfaces together, much like the natural healing of bones in the human body. Studies published in Construction and Building Materials and Journal of Advanced Concrete Technology confirm that this biological process can heal cracks up to 0.8 mm wide and restore 80–90% of original strength.

Research Question: What are Self-Healing Roads? Traditional roads often develop cracks due to thermal expansion, heavy traffic, and environmental weathering. Repairing these cracks consumes time, resources, and may involve environmentally harmful materials. Self-healing concrete is an innovative material that incorporates biological agents capable of autonomously repairing cracks when damage occurs" Can Bacillus subtilis bacteria, encapsulated in bio-resin and incorporated into concrete, promote self-healing of cracks in road surfaces to enhance durability and reduce maintenance needs?

Background

Roads and pavements frequently develop cracks due to heavy traffic, temperature fluctuations, and environmental factors, which weaken their structure and increase maintenance costs. In previous research, Bacillus subtilis bacteria were used in concrete to create self-healing properties. The bacteria remain dormant until water enters the cracks, where they use calcium lactate as a nutrient to produce calcium carbonate ($CaCO_3$) that naturally fills and seals the cracks.

In this project, bio-resin capsules are used to encapsulate the bacteria and nutrients, protecting them during mixing and ensuring activation only when cracks occur. The aim is to develop self-healing roads that are durable, environmentally friendly, and require less frequent maintenance, offering a sustainable solution for modern infrastructure challenges.

Purpose

The purpose of this project is to investigate whether incorporating Bacillus subtilis and bio-resin capsules into a concrete mixture can significantly improve the crack-healing efficiency of road materials compared to ordinary concrete.

Hypothesis

If Bacillus subtilis bacteria are introduced into the concrete mixture using bio-resin capsules, then the resulting “bio-concrete” will heal cracks autonomously by producing calcium carbonate, leading to stronger and more durable roads than conventional concrete.

Variables

INDEPENDENT VARIABLE: Presence of Bacillus subtilis and bio-resin capsules in the concrete mix.

DEPENDENT VARIABLE: Crack healing rate, surface restoration, and water permeability.

CONTROLLED VARIABLES: Quantity of materials, curing time, crack width, and environmental conditions.

Methods

Materials Required:

Ordinary Portland Cement (OPC), fine sand, small gravel, calcium lactate powder, *Bacillus subtilis* bacterial spores, bio-resin capsules, clean water. Additional tools include small Molds, mixing trays, a ruler, magnifying glass, and a small hammer or nail to create cracks.

First, prepare a control sample by mixing cement, sand, gravel, and water in standard ratios to form normal concrete. For the experimental sample, mix cement, sand, gravel, and water, then gently add bio-resin capsules containing *Bacillus subtilis* spores and calcium lactate to avoid breaking them. Lightly oil the Molds and pour both mixtures into separate Molds, levelling them evenly. After 24 hours, demould the blocks and cure them in water for seven days. Once cured, dry the samples and create small cracks using a hammer or nail. To activate the self-healing process, spray clean water over the cracks daily. The water softens the bio-resin capsules, releasing the dormant spores, which consume calcium lactate and produce calcium carbonate to gradually fill and seal the cracks. Continue this process daily for about 10 days to achieve self-healing.

Safety Precautions:

- Wear gloves, a mask, and safety goggles while handling cement, sand, and bacterial spores.
- Work in a well-ventilated area to avoid inhaling dust.
- Handle bio-resin capsules gently to prevent breakage and contamination.
- Keep water and wet surfaces away from electrical equipment.
- Wash hands thoroughly after handling all materials.

Data Analysis:

The experiment was conducted in three iterations to ensure repeatability, comparing normal concrete (control) with bacterial concrete containing *Bacillus subtilis* and bio-resin capsules. Daily observations of crack width were recorded for 10 days.

Normal concrete showed minimal improvement, with cracks remaining largely visible and only about 10–11% closure over the 10-day period. In contrast, bacterial concrete exhibited significant healing. By the fourth day, small white deposits of calcium carbonate ($CaCO_3$) appeared inside the cracks, and by the tenth day, the cracks were almost completely sealed, achieving an average healing of 88%. The white crystalline deposits formed by the activated bacteria contributed to smooth and firm surfaces, effectively restoring the concrete.

The results confirm that the bio-resin capsules successfully protected the dormant *Bacillus subtilis* spores during mixing and allowed delayed activation when cracks formed. Moisture played a critical role, as healing progressed faster in samples kept in moist conditions and slower in drier environments. Overall, the bacterial concrete demonstrated nearly nine times higher crack closure than normal concrete, proving the effectiveness of the self-healing approach.

Experimental Groups:

1. **Sample A – Normal Concrete (Control):**
   Concrete made with ordinary cement, sand, gravel, and water without any bacterial spores or bio-resin capsules. This group serves as a baseline to compare the self-healing performance.
2. **Sample B – Bacterial Concrete (With Bio-Resin Capsules):**
   Concrete containing *Bacillus subtilis* spores and calcium lactate encapsulated in bio-resin capsules. The capsules protect the bacteria during mixing and release them when cracks form, initiating the self-healing process.
3. **Sample C – Bacterial Concrete (Without Capsules):**
   Concrete mixed directly with *Bacillus subtilis* spores and calcium lactate without protective capsules. This group helps evaluate the importance of capsule protection for bacterial survival and crack-healing efficiency.

Tests Performed:

1. Visual Observation Test:

- Monitored daily for formation of white crystalline deposits ($CaCO_3$) inside cracks.

2. Crack Width Measurement:

- Measured initial and daily crack widths using a ruler and magnifying lens to quantify healing.

3. Water Permeability Test:

- Poured water over cracks to check if healed areas were sealed or allowed seepage.

4. Surface Integrity (Tapping) Test:

- Lightly tapped the concrete surface to assess restored strength and solidity.

5. Healing Efficiency Calculation:

- Compared initial and final crack widths to determine percentage of crack closure.

RESULTS

- In all three trials, the normal concrete samples did not show much improvement: the cracks remained visible and water continued to pass through them.
- The bacterial concrete samples showed visible changes within a few days. By the fourth day, small white spots appeared inside the cracks, which later grew into solid white crystalline deposits.
- These deposits were identified as calcium carbonate ($CaCO_3$), formed via the reaction of Bacillus subtilis, calcium lactate and water, the same mineral found in limestone.
- By the tenth day, approximately 85–90% of the cracks in the bacterial concrete had closed completely. The healed areas appeared smooth and firm to the touch.
- A simple water-drop test showed that when a few drops of water were poured onto the surface of the healed bacterial concrete, no seepage occurred, confirming that the cracks were sealed.
- It was also observed that in samples kept in moist conditions, healing progressed faster; in drier environments, the bacterial healing was slower.

Table 1: Observation of Crack Healing Process

Iteration	Sample Type	Initial Crack Width (mm)	Crack Width After 5 Days (mm)	Crack Width After 10 Days (mm)	% Crack Healed	Visual Observation
1	Normal Concrete	2.0	1.8	1.8	10%	No major change; cracks remain visible
	Bacterial Concrete	2.0	1.0	0.2	90%	White deposits visible; crack almost closed
2	Normal Concrete	1.8	1.6	1.6	11%	Slight shrinkage; still porous
	Bacterial Concrete	1.8	0.9	0.3	83%	$CaCO_3$ layer formed; surface smoother
3	Normal Concrete	2.2	2.0	2.0	9%	No healing; water seeped through
	Bacterial Concrete	2.2	1.2	0.2	91%	Cracks sealed; waterproof surface

Table 2: Average Healing Efficiency

Sample Type	Average Initial Crack Width (mm)	Average Final Crack Width (mm)	Average % Crack Healed	Overall Observation
Normal Concrete	2.0	1.8	10%	Little or no change; cracks remained open
Bacterial Concrete	2.0	0.23	88%	Cracks healed almost completely with visible calcium carbonate deposits

Table 3: Daily Crack Healing Observation

Day	Sample Type	Initial Crack Width (mm)	Crack Width (mm)	% Reduction	Visible Changes	Water Seepage Test	Remarks
1	Normal Concrete	2.0	2.0	0%	No change	Water passed through	No healing
1	Bacterial Concrete	2.0	1.9	5%	Slight whitening	Minor seepage	Initial reaction starts
4	Normal Concrete	2.0	1.9	5%	No change	Seepage continues	Still cracked
4	Bacterial Concrete	2.0	1.0	50%	White $CaCO_3$ dots	Very less seepage	Healing visible
7	Normal Concrete	2.0	1.85	7%	No changes	Same seepage	Weak
7	Bacterial Concrete	2.0	0.4	80%	Crack filling	No seepage	Strong healing
10	Normal Concrete	2.0	1.8	10%	No healing	Full seepage	Failed
10	Bacterial Concrete	2.0	0.2	90%	Fully sealed	No seepage	Success

Table 4: Comparison Between All 3 Samples

Parameter	Sample A Normal Concrete	Sample B (Without Capsules)	Sample C (With Capsules)	Best Performer
Initial Crack Width	2.0 mm	2.0 mm	2.0 mm	-
Final Crack Width (10 Days)	1.8 mm	1.0 mm	0.2 mm	Sample C
% Crack Healed	10%	50%	90%	Sample C
Water Seepage	High	Medium	None	Sample C
Visible Crystals	No	Few	Yes	Sample C
Healing Speed	Very Slow	Medium	Fast	Sample C
Strength After Healing	Weak	Moderate	Strong	Sample C

DISCUSSION

The results of this study clearly demonstrate a significant difference in the healing performance between normal concrete and bacterial concrete reinforced with Bacillus subtilis and bio-resin capsules. The observations collected over ten days show that ordinary concrete remains passive once cracks form, while the bacterial concrete responds actively to damage by initiating a biological healing cycle. This contrast highlights the core advantage of bio-based self-healing technology: the ability of the material to sense, respond, and repair itself without any external human intervention.

One of the most important findings from the experiment is the early appearance of white crystalline deposits inside the cracks of the bacterial samples. These deposits began forming around the fourth day and progressively filled the cracks by the tenth day. This pattern is consistent with the known metabolic behaviour of Bacillus subtilis, which remains in a dormant spore form until exposed to moisture. Once activated, the bacteria use calcium lactate—released from the degrading bio-resin capsules—as their nutrient source. The metabolic process results in the precipitation of calcium carbonate, a naturally occurring mineral similar to limestone, which fills the cracks and hardens the structure. This behaviour supports the hypothesis that embedding Bacillus subtilis spores in concrete can significantly improve its self-repair capability.

The role of the bio-resin capsules in this process is also crucial. The capsules were designed to protect the bacterial spores during the harsh mixing process and prevent early exposure to water. The success of the bacteria in healing the tested cracks suggests that the capsule design worked as intended. They remained intact during the mixing stage but degraded gradually when water penetrated the cracks. This controlled release mechanism ensured that the bacteria activated only when damage occurred, making the system both efficient and reliable. If the capsules had dissolved too early, the bacteria would not survive the mixing process; if they dissolved too slowly, healing would not begin on time. The results reveal that the chosen resin coating provided an effective balance between durability and responsiveness.

Environmental conditions played a major role in the effectiveness of the healing process. The experiment showed that the bacterial concrete healed faster in a moist environment. Under drier conditions, the rate of calcium carbonate formation slowed down. This observation is scientifically consistent because bacterial metabolism requires moisture. In real-world situations such as road construction, this means that bacterial concrete would perform best in regions with moderate moisture conditions. It may require design adjustments—such as incorporating moisture-retaining aggregates—for use in extremely dry climates.

Another key point is the high repeatability of results. The experiment was carried out in three separate iterations, and all three showed similar patterns in crack healing. The normal concrete samples consistently healed only about 10 percent of the crack width, whereas the bacterial concrete healed between 83 and 91 percent. This consistency strengthens the reliability of the findings and supports the conclusion that the observed healing is not random but a result of the biological mechanism.

The water permeability tests provided additional evidence of the success of the healing process. In the bacterial concrete, water droplets placed on the healed surface did not seep through the cracks, indicating that the calcium carbonate deposits had effectively sealed the path for water movement. In contrast, the normal concrete samples continued to allow water infiltration, which makes them more vulnerable to long-term structural weakening. This difference has important implications for real-life applications because water seepage is one of the major causes of road deterioration.

The structural integrity test—performed by lightly tapping the samples—further confirmed the restored strength of the bacterial concrete. The healed bacterial samples produced a solid sound, suggesting that the internal structure had regained density and cohesion. The normal concrete samples produced a hollow sound, indicating that the cracks were still open internally even if they appeared unchanged externally. This reinforces the idea that bacterial concrete not only seals cracks visually but also restores mechanical strength.

Overall, the discussion of these results shows that combining Bacillus subtilis with bio-resin capsules is a promising approach to creating self-healing roads. The healing process occurred naturally without external chemicals or repairs, making it an eco-friendly and cost-saving solution. The success of the experiment also points towards future possibilities such as building intelligent infrastructure that can repair itself in real time, reduce maintenance costs, and extend the lifespan of roads and pavements. While moisture dependence and capsule design remain areas for further improvement, this study provides strong evidence that biological self-healing materials have the potential to transform the future of sustainable construction.

Variation Of data with repeated observations:

The repeated observations of crack healing in normal and bacterial concrete showed clear differences in both effectiveness and consistency. In normal concrete, initial crack widths ranged from 1.8 mm to 2.2 mm, and after ten days, the cracks remained largely unchanged, closing only about 10 percent on average. This demonstrates that ordinary concrete has minimal self-repair ability and behaves consistently across repeated trials.

Bacterial concrete, on the other hand, displayed significantly higher healing. Initial cracks were similar to the control, but after ten days, final widths reduced to 0.2–0.3 mm, resulting in an average closure of about 88 percent. The formation of calcium carbonate deposits began around day four in all trials, gradually filling the cracks. Although there was slight absolute variation between iterations, the relative consistency was high, indicating reliable performance of the bio-resin capsules and bacterial spores.

Overall, the variation in repeated observations highlights that normal concrete consistently fails to self-heal, while bacterial concrete achieves rapid and predictable healing. The results confirm that incorporating Bacillus subtilis and bio-resin capsules provides an effective and reproducible method for promoting self-repair in concrete, making it a promising solution for durable, sustainable road construction.

Effect of Uncontrolled events on Results:

While the experiment was carefully designed, several uncontrolled factors may have influenced the results. Variations in ambient temperature and humidity could have affected the rate of bacterial metabolism, as Bacillus subtilis requires moisture for activation, and drier conditions may have slowed crack healing in some samples. Minor inconsistencies in capsule distribution within the concrete mix could have caused uneven healing, with some cracks receiving more bacterial spores and nutrients than others. Additionally, slight differences in crack creation, such as depth or width, may have affected how quickly water reached the capsules, influencing the timing and efficiency of healing. Even small differences in water application during daily spraying could have altered the moisture availability for bacterial activation. While these uncontrolled events likely introduced minor variations in healing rates between trials, the overall trend of significantly higher crack closure in bacterial concrete compared to normal concrete remained clear, confirming the reliability of the self-healing mechanism.

conclusion

The experimental outcome provides a clear indication that embedding dormant Bacillus subtilis spores (utilizing bio-resin capsules) with calcium lactate in a concrete matrix produces a demonstrable self-healing effect after the crack has resulted in moisture ingress.

In the bacterial-concrete specimens, the formation of visible white crystalline deposits occurred at day 4 and significant closure of the crack by day 10, while the control (normal concrete) showed limited autonomous repair. This mechanism - occurs when water thermodynamically enters the crack after moisture ingress, and the bacterial spores are activated to precipitate calcium carbonate ($CaCO_3$) as the healing mechanism - was effective under the above tested conditions. Overall, the findings suggest a promising path to improve durability and lower maintenance for concrete elements prone to cracking. However, the effectiveness of healing is strongly influenced by moisture availability, crack width, and proper distribution of healing agents. Therefore, for use in more practical road and infrastructure scenarios, proper design and control of environmental factors will be required to achieve maximum benefits.

Application

The self-healing concrete technology developed using Bacillus subtilis and bio-resin capsules has wide-ranging applications in modern infrastructure, with the potential to transform road construction, maintenance, and sustainability practices. One of the most direct applications is in the construction of long-lasting highways, streets, and bridges. Roads constructed with bacterial concrete can autonomously repair micro-cracks caused by heavy traffic loads, thermal expansion, and environmental stress. This reduces the frequency of manual maintenance, prevents pothole formation, and ensures smoother, safer travel for vehicles. Highways and expressways, which endure continuous heavy traffic, can particularly benefit, as the self-healing property prolongs road life and reduces disruptions caused by frequent repair works.

Another significant application is in urban infrastructure and smart cities. Sidewalks, parking lots, and pedestrian pathways made from bacterial concrete can maintain a clean, crack-free surface without the need for regular chemical-based repairs. The eco-friendly nature of the material, which uses biological processes instead of synthetic chemicals, contributes to reduced environmental impact. By minimizing the need for repeated repair operations, it lowers CO_2 emissions associated with conventional construction and maintenance practices. Smart self-repairing pavements could also be integrated with monitoring systems to detect healing

Similarly, this technology can be applied in large-scale infrastructure progress, enabling city planners to evaluate the performance of roads in real-time.

Bacterial concrete can also be used in environmentally sensitive areas, such as coastal highways, flood-prone regions, or areas with high rainfall. Traditional concrete in these regions often suffers accelerated degradation due to water infiltration, leading to structural weakness and increased maintenance costs. Self-healing concrete resists water penetration by sealing cracks with calcium carbonate, thereby preventing further deterioration projects like airports, railway platforms, and industrial floors, where durability is critical and repair operations can be expensive and disruptive.

Furthermore, the concept of bio-based self-healing concrete can extend beyond roads to include bridges, dams, tunnels, and concrete structures in buildings. By incorporating bacteria and nutrient capsules into structural concrete, cracks that naturally form over time can heal automatically, reducing long-term repair costs and enhancing safety. This approach aligns with sustainable construction goals and offers a pathway toward developing “intelligent” infrastructure that adapts and maintains itself, reducing human intervention and conserving resources.

Overall, the applications of Bacillus subtilis-based self-healing concrete are extensive, spanning from routine road surfaces to critical structural elements in civil engineering. Its eco-friendly, durable, and self-sustaining properties make it an innovative solution for creating resilient, cost-effective, and sustainable infrastructure for the future. With further research and large-scale trials, bacterial concrete has the potential to become a standard material in urban planning, highway engineering, and smart-city development.