Implementation of Self-Healing Concrete Technology in Road Pavements

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Abstract : Road pavement cracks detection has been a hot research topic for quite a long time due to the practical importance of crack detection for road maintenance and traffic safety. Many methods have been proposed to solve this problem. This paper reviews the three major types of methods used in road cracks detection: image processing, machine learning and 3D imaging based methods. Image processing algorithms mainly include threshold segmentation, edge detection and region growing methods, which are used to process images and identify crack features. Crack detection based traditional machine learning methods such as neural network and support vector machine still relies on hand-crafted features using image processing techniques. Deep learning methods have fundamentally changed the way of crack detection and greatly improved the detection performance. In this work, we review and compare the deep learning neural networks proposed in crack detection in three ways, classification based, object detection based and segmentation based. We also cover the performance evaluation metrics and the performance of these methods on commonly-used benchmark datasets. With the maturity of 3D technology, crack detection using 3D data is a new line of research and application

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I. INTRODUCTION

Self-healing concrete represents a revolutionary breakthrough in the field of civil engineering, offering a transformative solution to the perennial challenges faced in infrastructure maintenance and longevity. This cutting-edge technology has sparked a paradigm shift, moving away from traditional repair methods that are often costly, environmentally disruptive, and labor-intensive. The evolution of self-healing concrete stands as a testament to the remarkable progress made in material science and construction engineering, ushering in a new era of resilient and sustainable infrastructure development

A crucial aspect driving the advancement of self-healing concrete technologies is the comprehensive exploration of microbial profiles, with particular emphasis on the role of bacteria such as Bacillus subtilis. Bacillus subtilis has emerged as a focal point of research due to its robust survival mechanisms and adaptability to a wide range of environmental stressors. Extensive studies have illuminated Bacillus subtilis' remarkable ability to withstand extreme temperatures, including those encountered during rigorous heat sterilization processes, showcasing its resilience and suitability for integration into self-healing concrete systems

Further delving into the resilience mechanisms of Bacillus subtilis, researchers have meticulously examined its exceptional heat resistance and its capacity to thrive in harsh environmental conditions. These investigations have yielded valuable insights into the bacterium's long-term viability within concrete structures, ensuring sustained self-healing efficacy over extended periods. Understanding Bacillus subtilis' survival dynamics under high temperatures and varying environmental stresses is paramount for optimizing concrete's self-healing capabilities and expanding its applications across diverse infrastructure projects

The encapsulation of bacteria within specialized matrices has emerged as a critical facet of preserving their viability and functionality within concrete structures. Extensive research, particularly in asphalt concrete studies, has explored innovative encapsulation techniques, effectively shielding bacteria to repair concrete fissures and enhance overall durability. Moreover, the development of advanced healing agents has further bolstered concrete's self-healing properties, promising long-term resilience and sustainability. Integrating these research findings into practical applications, notably in road pavement construction, holds immense potential for revolutionizing infrastructure resilience and maintenance practices.

II. Literature Survey

Microbe Profile: Bacillus subtilis: model organism for cellular development, and industrial workhorse. Jeffery Errington* et al. The paper explores Bacillus subtilis, focusing on its taxonomy, survival mechanisms, industrial applications, and ecological adaptations. It discusses the organism's genetic and cellular biology, its ability to withstand diverse environmental stressors, its relevance in biotechnology, and its interactions with plants. The review also touches on future research directions in understanding B. subtilis' survival strategies and ecological roles.

Effect of Bacillus subtilis on mechanical and self-healing properties in mortar with different crack widths and curing conditions: Martin Eduardo Espitia-Nery, et al. (2019). Espitia-Nery et al. conducted a thorough review of the mechanisms of bacterial encapsulation in self-healing concrete. The study addresses the prevalent issue of concrete fissures resulting from factors like structural deterioration and inadequate building processes. Traditional repair methods are often costly and complex, leading to the development of self-healing techniques. The focus is on bacteria, specifically Bacillus subtilis, known for precipitating calcium carbonate to seal fissures. The authors critically evaluate various bacterial encapsulation methods and their impact on fissure repair and concrete resistance.

MICROCAPSULE FOR SELF-HEALING CONCRETE AND PREPARATION METHOD THEREOF, AND SELF-HEALING CONCRETE AND PREPARATION METHOD THEREOF: Biqin DONG (2018). In the paper authored by Biqin DONG in 2018, the focus is on a microcapsule designed for self-healing concrete. The microcapsule, developed by SHENZHEN UNIVERSITY, features a core-wall structure. Within the core, a combination of a healing agent, microcrystalline cellulose, and Tween 80 is employed. The wall, a high-molecular organic material, exhibits sensitivity to stress cracks. The preparation method outlined involves weighing precise amounts of cement, sand, water, and microcapsules, with recommended volumes for each cubic meter of concrete. Stirring the cement, sand, and microcapsules until uniformly dispersed, followed by the uniform pouring and stirring of water into the mixture, is proposed. This encapsulation method and its constituents aim to address stress cracks in concrete, showcasing a promising avenue for enhancing the material's self-healing properties and, consequently, its durability and longevity. The detailed methodology provided in the paper serves as a practical guide for the application of this technology in the construction industry, contributing to advancements in sustainable and resilient concrete materials.

Self-Healing Properties of Asphalt Concrete with Calcium Alginate Capsules Containing Different Healing Agents: Huoming Wang, et al. **(2022).** The study investigates the self-healing properties of asphalt concrete using calcium alginate capsules encapsulating different healing agents. Three types of capsules, containing sunflower oil, waste cooking oil, and a commercial rejuvenator, were fabricated using the orifice-coagulation bath method. The capsules were characterized for their interior structure, mechanical strength, thermal stability, and oil content. The healing levels of asphalt mixtures with these capsules were evaluated under various loading cycles and stress levels. The study also assessed the saturates, aromatics, resins, and asphaltenes (SARA) fractions, as well as the rheological properties of the extracted asphalt binder within test beams with different capsules after various loading conditions. Results showed that all three types of capsules met the mechanical and thermal requirements for mixing and compaction. Test beams containing vegetable oil capsules exhibited higher healing levels compared to those with waste cooking oil capsules and industrial rejuvenator capsules. Notably, the strength recovery ratio and fracture energy recovery ratio of test beams with vegetable oil capsules reached 82.8% and 96.6%, respectively, after 20,000 cycles of compressive loading at 1.4 MPa. Waste cooking oil capsules also demonstrated a high fracture energy recovery ratio of 90%, suggesting the potential use of waste cooking oil as a healing agent for calcium alginate capsules to enhance the self-healing property of asphalt mixtures. The findings offer valuable guidance for selecting healing agents for self-healing capsules in future applications.

PROCESS FOR THE PRODUCTION OF HYALURONIC ACID IN ESCHERICHIA COLI OR BACILLUS SUBTILIS:Vincenza Corsa, Alessandro Negro, Susanna Vaccaro, Luciano Messina (2016). The paper focuses on the method for the production of hyaluronic acid (HA) in Bacillus subtilis and Escherichia coli using plasmid vectors controlled by the strong promoter Pgrac. The study explores the genetic and microbial processes involved in cultivating HA in bacterial strains, offering a detailed analysis of the patented method by FIDIA FARMACEUTICI S.P.A. The review also incorporates key references, including publications on enhanced HA production in Bacillus subtilis and the cloning of the Hyaluronan Synthase (sz-has) gene.

III. METHODOLOGY

3.1 To study Bacillus subtilis and the conditions essential for its survival and proliferation.
Study on Bacillus subtilis: Survival and Nutrient Requirements:

Survival in Various Conditions:

- **Temperature:** Bacillus subtilis shows robust survival across a wide temperature range, from 15°C to 55°C, with optimal growth between 30°C to 37°C.
- **pH**: It can survive in pH levels ranging from acidic (pH 4) to slightly alkaline (pH 9), with optimal growth around pH 7 to 8.
- **Moisture:** Bacillus subtilis is adaptable to varying moisture levels, from dry conditions to moderate humidity, making it versatile in different environments.
- **Oxygen Availability:** Being a facultative anaerobe, it thrives in both aerobic and anaerobic conditions, utilizing oxygen when available and switching to fermentation in anaerobic settings.

TABLE 1: Survival in Various Conditions

Sporulation Temperature (°C)	Core Water Content	Resistance to Wet Heat	Resistance to UV Radiation and Dry Heat	Resistance to Formaldehyde	Resistance to Hydrogen Peroxide	Resistance to Betadine, Glutaraldehyde, Sterilox
22	Lower	Lower	Similar	Similar	Similar	Similar
30	Lower	Lower	Similar	Similar	Similar	Similar
37	Lower	Lower	Similar	Similar	Similar	Similar
48	Lower	Higher	Similar	Similar	Higher	Higher

1. **Core Water Content:** Spores prepared at higher temperatures (30°C, 37°C, 48°C) exhibit a lower core water content compared to those prepared at 22°C. This is likely due to increased dehydration during sporulation at higher temperatures.
2. **Resistance to Wet Heat:** Spores prepared at higher temperatures (30°C, 37°C, 48°C) show higher resistance to wet heat compared to those prepared at 22°C. This is because lower core water content makes spores more resistant to denaturation by wet heat.
3. **Resistance to UV Radiation and Dry Heat:** Spores at all temperatures show similar resistance to UV radiation and dry heat. Core water content plays no role in these resistances; instead, the major determinants are the a/b-type SASP.
4. **Resistance to Formaldehyde:** Spores at all temperatures exhibit similar resistance to formaldehyde. Formaldehyde mainly acts on spore DNA, and small changes in core water content do not significantly affect its lethal action.
5. **Resistance to Hydrogen Peroxide:** Spores at higher temperatures (37°C, 48°C) show higher resistance to hydrogen peroxide compared to those at lower temperatures (22°C, 30°C). This may be influenced by changes in coat protein composition and structure, as well as spore coat thickness, which are affected by sporulation temperature.
6. **Resistance to Betadine, Glutaraldehyde, Sterilox:** Spores at higher temperatures (37°C, 48°C) exhibit higher resistance to these chemicals compared to those at lower temperatures (22°C, 30°C). The spore coats play a major role in resistance to these agents, and changes in coat protein composition and structure due to sporulation temperature affect resistance levels.

3.2 Material requirement and estimate calculation of material:

- **Carbon Source:** Utilizes sugars, starches, and organic compounds as carbon sources for energy and growth.
- **Nitrogen Source:** Requires nitrogen for protein synthesis and cell growth, utilizing sources like ammonium salts, nitrates, and amino acids.
- **Phosphorus:** Essential for nucleic acid synthesis and energy transfer, obtained from phosphates in the environment or organic phosphorus compounds.
- **Minerals:** Requires various minerals like potassium, magnesium, calcium, and trace elements for enzyme function and cell structure.
- **Vitamins:** Some strains may require specific vitamins like biotin, thiamine, and riboflavin for metabolic processes.
- **Water:** Adequate water availability is crucial for Bacillus subtilis growth and metabolism.

Urea

Potassium Phosphate

Magnesium Carbonate

Potassium Carbonate **$CaHPO_4.2H_2O$**

List of materials typically required for conventional concrete of M30 grade:

1. Cement: Ordinary Portland Cement (OPC) or blended cement like Portland
2. Pozzolana Cement (PPC) or Portland Slag Cement (PSC).
3. Fine Aggregate: Sand conforming to grading zone II of IS 383.
4. Coarse Aggregate: Crushed stone or gravel with a nominal size of 20 mm.
5. Water: Clean and potable water free from impurities.
6. Admixtures: Optional additives such as plasticizers, superplasticizers, air-entraining agents, etc., to modify the properties of concrete.

Material, Quantity & Uses

Table 2: Material, Quantity & Uses

Sr No.	Ingredients	Concentration		Uses
		In Capsules	In Concrete	
1.	Calcium Lactate	15-20% of the total capsule volume	2-5% of the total concrete weight.	Acts as a calcium source for the bacteria. Calcium is essential for bacterial growth and enzyme activity.
2.	Urea	5-10% of the total capsule volume	0.5-2% of the total concrete weight.	Provides nitrogen, an essential nutrient for bacterial metabolism and protein synthesis.
3.	Phosphate	1-5% of the total capsule volume	0.1-0.5% of the total concrete weight.	Supplies phosphorus, another essential element for bacterial metabolism and nucleic acid synthesis.
4.	Sucrose	1-5% of the total capsule volume.	0.1-0.5% of the total concrete weight.	Serve as carbon sources for the bacteria. Bacteria utilize carbon for energy and growth
5.	Potassium:	1-5% of the total capsule volume.	0.1-0.5% of the total concrete weight.	Provides potassium ions, which play a role in various cellular processes, including enzyme activation.

6.	Magnesium:	1-5% of the total capsule volume.	0.1-0.5% of the total concrete weight.	Supplies magnesium ions, essential for many enzymatic reactions within the bacteria.

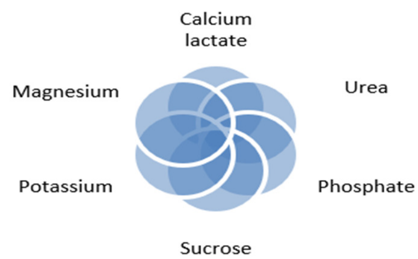


Fig. MATTERIAL USED

3.3 Percentage of nutrients in the table:

TABLE 3: CALCULATING PERCENTAGE IN VOLUME

NUTRIENTS	*PERCENTAGE %*	*VOLUME (mm3)*
Calcium Lactate	17 %	34.18 mm^3
Urea	8 %	16.04 mm^3
Potassium Phosphate	4 %	8.04 mm^3
Magnesium Carbonate	4 %	8.04 mm^3
Sucrose	4 %	8.04 mm^3
Potassium Carbonate	4%	8.04 mm^3
Total	37%	82.42 mm^3

TABLE 3: CALCULATING PERCENTAGE IN VOLUME

NUTRIENTS	**VOLUME OF NUTRIENTS 'A'(m^3)**	**DENSITY OF NUTRIENTS 'B' (kg/m^3)**	**C=AXB kg**	**C mg**
Calcium Lactate	3.418 $X10^{-8} m^3$	1490 kg/m^3	5092.82 X 10^{-8}	50.9
Urea	1.604 $X10^{-8} m^3$	1320 kg/m^3	2122.56 X 10^{-8}	21.2
Potassium Phosphate	8.04 $X10^{-9} m^3$	2338 kg/m^3	18797.52 X 10^{-9}	18.8
Magnesium Carbonate	8.04 $X10^{-9} m^3$	1960 kg/m^3	23798.4 X 10^{-9}	23.8
Sucrose	8.04 $X10^{-9} m^3$	1560 kg/m^3	12542.4 X 10^{-9}	12.5

Table 4: CALCULATE NUTRIENTS IN 'mg'

Potassium Carbonate	8.04 X $10^{-9} m^3$	2430 kg/m^3	1953.2 X 10^{-9}	19.5
Total	82.42 X $10^{-9} m^3$			146.7 mg

3.4 Designing the encapsulation of Bacillus subtilis by tablet punching processes.

1. **Preparation of Nutrient Mix:**
   Combine the required nutrients for Bacillus subtilis survival, such as calcium lactate, urea, phosphate, sucrose, potassium, and magnesium, in the desired proportions.
2. **Sieving of Nutrient Mix:**
   Sieve the mixed nutrients to ensure a uniform and fine texture, facilitating better integration with Bacillus subtilis powder. It has sieved from 60 no sieve.

3. **Formation of Tablet Mix:**
   We carefully measure out the appropriate proportions of Bacillus subtilis and the necessary nutrients, which have been sifted through a 60-number sieve. We then incorporate liquid Bacillus subtilis into the mixture according to the calculated amounts.
4. **Tablet Punching Preparation:**
   Set up the tablet punching machine with the appropriate specifications, considering the tablet dimensions required for your project (e.g., 8 mm in diameter and 4 mm in height).
5. **Loading the Machine:**
   Place the prepared tablet mix into the machine's compartment for compression and punching
6. **Compression and Punching:**
   Activate the machine to compress the mix and form tablets of the specified size (8 mm diameter, 4 mm height).

7. **Quality Check:**
   We check the strength of the tablet it was 20 N/mm^2. The strength check after the moisture is taken out.

Storage and Handling:
Store the punched tablets in a suitable container with proper labeling and handling instructions to maintain their integrity and effectiveness until use in the concrete mix.

3.5 Coating the tablets:

Cement Paste Coating:
- Prepare a mixture of cement paste according to the specified formula.
- Coat the tablet evenly with the cement paste using a suitable method (e.g., dipping or brushing).
- Allow the coated tablet to dry and cure for the recommended duration.

Red Ocher Powder Coating:
- Create a mixture of red ocher powder as per the required concentration.
- Apply the red ocher powder mixture uniformly onto the tablet surface, ensuring complete coverage.
- Let the coated tablet dry thoroughly under appropriate conditions.

Direct Mix with Concrete:
- Integrate the tablet directly into the concrete mix during batching.
- Ensure uniform distribution of the tablet within the concrete mixture.
- Proceed with the concrete pouring and curing process as per standard procedures.

3.6 Observing bacillus with nutrients under the microscope:

Steps for Observing bactria Under the Microscope:

1) Dissolve the tablet containing Bacillus subtilis bacteria and nutrients in mineral water.
2) Allow the solution to settle, letting the powder particles settle at the bottom.
3) Carefully collect a sample of the upper water layer, avoiding disturbance to the settled powder.
4) Place a drop of the collected water sample on a clean glass slide.
5) Cover the water droplet with a coverslip to prevent evaporation and contamination.
6) Place the prepared slide on the stage of the compound microscope.
7) Start with a low magnification objective (e.g., 10x) to locate and focus on the bacteria.
8) Gradually increase the magnification (e.g., 40x or 100x) for detailed observation and analysis.
9) Record observations regarding the presence, size, and behavior of Bacillus subtilis bacteria over time.

For our project, we conducted observations of Bacillus subtilis bacteria with nutrients under a microscope. We initiated the observation by dissolving the tablet containing the bacteria in mineral water. After allowing it to settle, we collected a sample from the upper water layer where the powder had settled. This sample was carefully extracted to ensure we captured a representative portion.

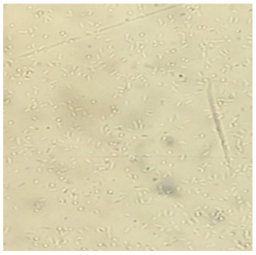


Fig. Bacillus subtilis Bactria covered with nutrients shell under 40x

Our observation process involved meticulous steps to ensure accuracy and reliability. After collecting the settled sample, we prepared microscope slides using standard procedures. We carefully placed a small amount of the settled material onto the slide, ensuring even distribution for consistent viewing.

Throughout the observation period, we documented our findings systematically, recording the emergence of bacterial colonies, changes in colony size, and any concurrent developments such as calcite formation. These observations contribute valuable insights into the behavior and growth patterns of Bacillus subtilis bacteria in nutrient-rich environments, essential for our project's objectives and understanding of self-healing concrete mechanisms.

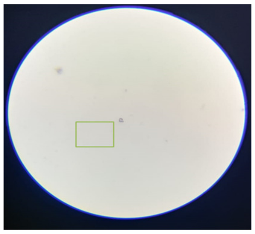


Fig. BACILLUS SUBTILIS seen in tablet solution

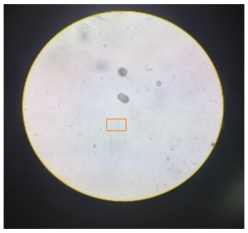


Fig. INCREASE IN THE QUANTITY OF BACTRIA

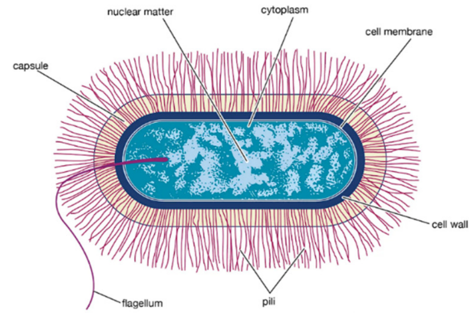
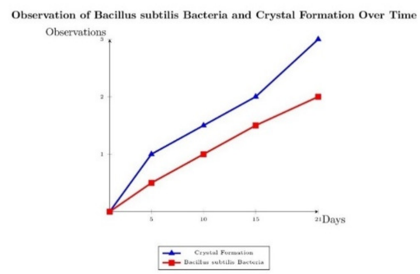


Fig. BACILLUS SUBTILIS BACTRIA PARTS



GRAPH 1 : Observation of Bacillus subtilis Bacteria and Crystal Formation Over Time

The graph depicts the progression of observations made during a 21-day study involving Bacillus subtilis bacteria and crystal formation. The x-axis represents the days of observation, ranging from day 1 to day 21. The y-axis shows the level of observations, with higher values indicating more significant observations. The blue line with triangular markers represents the formation of crystals, showing a notable increase from day 1 to day 21, peaking at day 21. The red line with square markers represents the presence of Bacillus subtilis bacteria, starting from day 1 with minimal presence, gradually increasing in observation by day 15, and peaking alongside crystal formation at day 21. This graph visually illustrates the correlation between the presence of Bacillus subtilis bacteria and the formation of crystals over the observation period, showcasing a clear progression of observations over time.

3.7 Ultrasonic testing machine:

As part of our team, we conducted ultrasonic pulse velocity (UPV) testing to assess the quality and integrity of concrete structures. Here's how we approached and executed the UPV testing process from our perspective:

- **Preparation and Setup:** We began by setting up the UPV equipment, including the pulse generator, transmitting transducer, and receiving unit. Ensuring precise calibration and alignment, we prepared the equipment for accurate measurements.
- **Positioning and Coupling:** Carefully positioning the transducers on the concrete surface, we applied coupling gel to ensure optimal transmission of ultrasonic waves. This step is crucial for obtaining reliable and consistent results.
- **Sending Ultrasonic Pulses:** Activating the pulse generator, we sent high-frequency pulses into the concrete specimen through the transmitting transducer. These pulses travel through the material, encountering boundaries, defects, or changes in density along the way.
- **Wave Reception and Analysis:** The receiving transducer detected the reflected waves from the concrete. We meticulously recorded the time taken for the waves to travel from the transmitter to the receiver, which is crucial for calculating the ultrasonic pulse velocity.
- **Calculation of Pulse Velocity:** Using the measured time and the known distance between transducers, we calculated the ultrasonic pulse velocity for the concrete specimen. This velocity serves as a key indicator of material quality, density, and uniformity.
- **Interpretation and Evaluation:** Comparing the calculated pulse velocity with established standards and reference values, we interpreted the results to assess the concrete's condition. Variations in pulse velocity indicated areas of interest such as defects, voids, or potential structural issues.
- **Documentation and Reporting:** Comprehensive documentation was maintained throughout the testing process, including equipment settings, measurements, and analysis outcomes. We generated a detailed report summarizing the UPV testing procedure, results, interpretations, and any recommendations for further action or inspection.
- **Collaborative Analysis:** Our team collaborated to analyze the UPV data collectively, leveraging each member's expertise to ensure thorough and accurate assessments of the concrete's quality and integrity.

	Cube I Time(μS)	Cube II Time(µS)	Cube III Time(µS)
Direct Method	36.5	37.1	36.8
Semi-direct Method	24.7	25.2	27.1
Indirect Method	70.11	73.2	71.2

TABLE 6: CONVENTIONAL CONCRETE (TIMING READING FOR UPV TEST)

Self Healing Concrete (Time Readings):

	Cube I Time(μS)	Cube II Time(μS)	Cube III Time(μS)
Direct Method	33.2	35.3	33.6
Semi-direct Method	23.6	25.0	23.8
Indirect Method	41.7	45.2	42.1

TABLE 7: SELF HEALING CONCRETE (TIMING READING FOR UPV TEST)

Conventional Concrete (Pulse Velocity Readings):

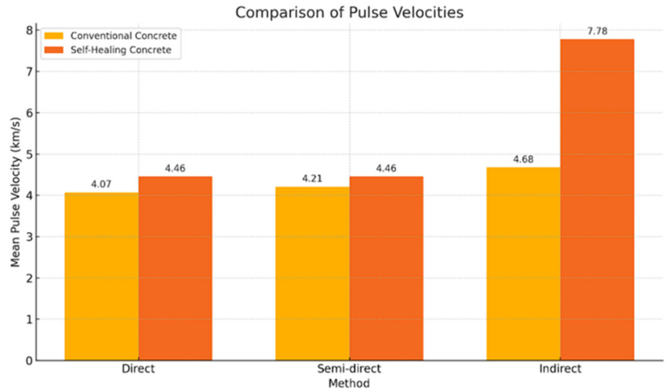
	Cube I Velocity(km/s)	Cube II Velocity(km/s)	Cube III Velocity(km/s)	Mean Pulse Velocity	Remark
Direct Method	4.10	4.04	4.07	v_D= 4.07	GOOD
Semi-direct Method	4.29	4.20	4.14	v_S=4.21	GOOD
Indirect Method	4.77	4.57	4.70	v_I=4.68	EXCELLENT

TABLE 8: CONVENTIONAL CONCRETE (PULSE VELOCITY TEST FOR UPV TEST)

Self-healing concrete (Pulse Velocity Readings):

	Cube I Velocity(km/s)	Cube II Velocity(km/s)	Cube III Velocity(km/s)	Mean Pulse Velocity	Remark
Direct Method	4.51	4.24	4.46	v_D=4.46	EXCELLENT
Semi-direct Method	4.51	4.24	4.45	v_S=4.46	EXCELLENT
Indirect Method	8.03	7.41	7.91	v_I=7.78	EXCELLENT

TABLE 9: SELF HEALING CONCRETE (PULSE VELOCITY TEST FOR UPV TEST)



GRAPH 2 :COMPARISOIN OF PULSE VELOCITY BETWEEN SELF HEALING CONCRETE AND CONVENTIONAL CONCRETE

3.8 Compression Test on Concrete Cubes:

The compressive strength of concrete is a fundamental parameter that reflects its ability to withstand axial loads. In our project, we conducted compression tests on concrete cubes to determine their compressive strength following standard procedures.

Step 1]Cube Preparation: Concrete cubes of dimensions 150mm x 150mm x 150mm were prepared and cured as per standard protocols.

Step 2]Testing Machine Setup: We calibrated and set up the compression testing machine in accordance with ASTM/IS standards to ensure accurate and reliable results.

Step 3]Testing Procedure: Each cube was carefully placed on the lower platen of the testing machine, ensuring proper alignment and contact.

Step 4]Load Application: Gradual load application was initiated on each cube using the compression testing machine. Load and deformation readings were recorded at regular intervals.

Step 5]Observation: During testing, we observed the behavior of the cubes, noting any visible cracking or deformation until failure occurred.

Step 6]Failure Analysis: The failure pattern, whether brittle or ductile, was analyzed to understand the concrete's response under compressive stress.

Step 7]Maximum Load at Failure: The maximum load at failure for each cube was recorded, and the average compressive strength was calculated using standard formulas.

Step 8]Comparative Analysis: Results from multiple cube tests were compared to assess the uniformity and quality of the concrete batch.

Based on the compression test results, we derived valuable insights into the compressive strength characteristics of the concrete used in our project. These findings contribute significantly to evaluating the structural integrity and performance of the concrete elements in real-world applications.

Conventional concrete (compression test):

Cube	Weight (kg)	Kg/cm^2	N/mm^2
I	8.12	324.27	31.8
II	8.3	316.11	31
III	8.18	329.36	32.3

TABLE 10: CONVENTIONAL CONCRETE (COMPRESSION TEST)

Self healing concrete (compression test):

Cube	Weight (in grams)	Kg/cm^2	N/mm^2
I	8.38	387.04	37.95
II	8.5	362.34	35.53
III	8.42	385.42	37.8

TABLE 11: SELF HEALING CONCRETE (COMPRESSION TEST)

GRAPH 3: COMPARISON OF WEIGHT AND COMPRESSIVE STRENGTH OF CONVENTIONAL & SELF HEALING CONCRETE

IV. RESULT

4.1 Result of Observing bacillus with nutrients under the microscope

We observed Bacillus subtilis bacteria with nutrients under a microscope over 21 days.

- Days 1-5:

Dissolved Bacillus subtilis tablet in mineral water.
Observed crystal formation (calcite) but no significant bacterial presence.

- Days 6-15:

Gradual emergence of Bacillus subtilis bacteria around day 15.

- Days 16-21:

Significant increase in bacterial colony size by day 21.
Continued crystal formation, correlating with increased bacterial presence.

4.2 Ultrasonic testing machine

Conventional Concrete:
Direct Method: 4.01 km/s to 4.10 km/s (Good quality)
Semi-direct Method: 4.14 km/s to 4.29 km/s (Good quality)
Indirect Method: 4.57 km/s to 4.77 km/s (Excellent quality)

Self-Healing Concrete:
Direct Method: 4.24 km/s to 4.51 km/s (Excellent quality)
Semi-direct Method: 4.24 km/s to 4.51 km/s (Excellent quality)
In all testing methods, self-healing concrete showed consistently higher pulse velocities, indicating its superior quality and integrity compared to conventional concrete.

4.3 Result of Compressive testing

Conventional Concrete:
Average Weight: 8.20 kg
Average Compressive Strength: 31.7 N/mm²

Self-Healing Concrete:
Average Weight: 8.43 kg
Average Compressive Strength: 37.09 N/mm²
Self-healing concrete exhibited higher average compressive strength compared to conventional concrete, suggesting enhanced durability and structural performance.

4.4Nutrient requirement calculation result

Tablet Dimensions and Nutrient Composition:
The tablet has dimensions of 8mm diameter and 4mm height, resulting in a volume of 201.061mm³.
Nutrients such as calcium lactate, urea, potassium phosphate, magnesium carbonate, sucrose, and potassium carbonate are present in percentages ranging from 4% to 17% in the tablet.
Nutrient Mass Calculation:
The total mass of nutrients in one tablet is determined to be 146.7 mg.
Concrete Mix Calculation (M30 Grade):
The M30 grade concrete mix includes 2.322 kg of cement, 1.935 kg of sand, and 3.749 kg of aggregates, totaling 5.182 kg.

Incorporation of Bacillus Subtilis Powder:
Bacillus subtilis powder is added at a rate of 0.1 grams per gram of concrete.
For the given concrete volume, 518.2 grams of Bacillus subtilis powder are required per cubic meter, equivalent to 324 tablets of 1.6 grams each.

V. CONCLUSION

- **Effective Crack Healing:** Our project has demonstrated that self-healing concrete, incorporating Bacillus subtilis bacteria, effectively repairs cracks. For instance, after five days of curing, minor cracks resulting from thermal reactions in our concrete cubes were visibly healed, with filled cracks containing white-colored calcite.
- **Enhanced Structural Integrity:** The self-healing concrete cubes showed higher compressive strength compared to conventional concrete. For example, our compression test results revealed that self-healing concrete had an average compressive strength of 37.09 N/mm², showcasing its ability to maintain structural integrity under loading conditions.
- **Cost-Efficiency:** By reducing the need for frequent repairs and maintenance, self-healing concrete offers cost-efficiency in the long run. Our project calculations showed that self-healing tablets with specific nutrient compositions, such as calcium lactate, urea, and potassium phosphate, can be incorporated into concrete mix designs, potentially saving on future maintenance costs.
- **Environmental Sustainability:** Self-healing concrete contributes to environmental sustainability by minimizing material waste and extending the lifespan of concrete structures. The use of Bacillus subtilis bacteria and nutrients in our project aligns with sustainable construction practices by promoting autonomous crack repair and reducing the environmental impact of concrete degradation.
- **Future Prospects:** Our project highlights the potential for further research and development in self-healing concrete technology. For instance, optimizing the nutrient compositions and bacterial activation mechanisms can enhance the technology's effectiveness and applicability in various construction scenarios, ensuring durable and long-lasting infrastructure.
- **Monitoring and Maintenance:** Continuous monitoring and maintenance protocols are crucial for ensuring the ongoing effectiveness of self-healing concrete in real-world applications. Regular assessments, such as ultrasonic testing to evaluate concrete quality and integrity, are essential for proactive maintenance and maximizing the benefits of self-healing mechanisms.

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