# Smart Concrete Incorporating Plastic Waste with Iot Based Performance Monitoring

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*Abstract*—**The increasing use of plastic in construction has raised concerns regarding sustainability and structural reliability. In this project, an innovative approach is proposed by partially replacing fine aggregate (sand) with plastic in M25 grade concrete. However, the substitution of plastic reduces the compressive strength of concrete. To overcome this limitation, a self-healing mechanism is incorporated to restore the strength to nominal M25 standards. The self-healing concrete is developed by embedding cellulose diacetate capsules containing Bacillus subtilis bacteria, with calcium lactate provided as a nutrient source. Upon the formation of cracks, the capsules rupture, activating bacterial metabolism that precipitates calcium carbonate, thereby sealing the cracks and improving strength. The use of biodegradable cellulose diacetate capsules ensures environmental compatibility and long-term durability. In addition to self-healing, the project integrates an IoT-based crack and void detection system to enable real-time structural health monitoring. This system operates on the principle of acoustic emission, where vibration patterns are analyzed to detect anomalies. The setup includes an acoustic sensor, Arduino microcontroller, ESP32 module, and power supply, which collectively identify and communicate the presence of voids or cracks. Experimental results demonstrate that with 4% replacement of sand by plastic, combined with bacterial self-healing and IoT-based monitoring, the concrete regains compressive strength equivalent to nominal M25 concrete, while also offering enhanced sustainability and smart diagnostic capabilities. This dual innovation biological self-healing and IoT-enabled monitoring presents a sustainable and intelligent alternative for modern construction practices.**

*Index Terms*—**Recycled plastic, Encapsulated materials, Self-healing concrete.**

## I INTRODUCTION

1.1 General: Concrete is one of the most widely used construction materials worldwide due to its strength, versatility, and long-term durability. However, the overuse of natural sand as fine aggregate and the growing problem of plastic waste disposal have raised significant environmental concerns in the construction industry. A sustainable solution is the partial replacement of sand with recycled plastic, which helps reduce reliance on natural resources while contributing to plastic waste management. Despite these benefits, plastic-modified concrete often suffers from reduced compressive strength, limiting its use in structural applications.

To address this limitation, the present project introduces a self-healing concrete system that utilizes biological processes to autonomously repair cracks and restore strength. Biodegradable cellulose diacetate capsules are embedded within the concrete matrix, containing Bacillus subtilis bacteria and calcium lactate as a nutrient source. When cracks develop, the capsules rupture, activating the bacteria, which then convert calcium lactate into calcium carbonate, effectively sealing the cracks and restoring the concrete's M25 compressive strength.

To further enhance structural reliability, an IoT-based crack detection system is integrated. Using acoustic emission technology, along with an acoustic sensor, Arduino microcontroller, and ESP32 module, the system monitors cracks in real time and transmits data for preventive action.

1.2 Objectives

- To partially replace natural sand in M25 grade concrete with 4% plastic waste, thereby reducing environmental pollution and conserving natural resources.
- To develop a self-healing mechanism in concrete by embedding biodegradable cellulose diacetate capsules containing Bacillus subtilis bacteria and calcium lactate, enabling the recovery of compressive strength to nominal M25 standards.

- To design and use cellulose diacetate capsules as a biodegradable and eco-friendly medium for encapsulating bacterial spores and nutrients.
- To implement an IoT-based monitoring system using an acoustic sensor, Arduino controller, ESP32, and power supply to detect cracks and voids in real time.
- To combine material innovation (plastic replacement + bacterial self-healing) with IoT-based monitoring, creating an intelligent and eco-friendly concrete solution for modern construction.

1.3 Scope

- Material Replacement: Investigating the feasibility of replacing 4% of sand with plastic in M25 grade concrete and analyzing its effects on compressive strength.
- Self-Healing Concrete Development: Designing and incorporating cellulose diacetate capsules containing Bacillus subtilis and calcium lactate for biological crack healing.
- Strength Restoration Studies: Evaluating the ability of the self-healing process to restore compressive strength to nominal M25 standards.
- IoT-Based Monitoring: Designing, fabricating, and testing an acoustic-based IoT device to identify internal cracks and voids in concrete structures.
- Sustainability Assessment: Assessing the environmental benefits of plastic waste utilization and the biodegradability of the cellulose diacetate capsules.
- Practical Application: Exploring the potential use of this smart, self-healing, and sustainable concrete in construction projects such as pavements, buildings, and underground structures where durability and monitoring are critical.

## II LITERATURE REVIEW

2.1 General

Concrete remains the cornerstone of modern infrastructure, serving as the primary material for constructing buildings, bridges, dams, highways, and other essential structures. Its widespread adoption is attributed to its versatility, moldability, cost-effectiveness, and relatively high compressive strength. Among various grades, M25 concrete is commonly used in residential and commercial projects due to its optimal balance of strength, workability, and economy.

However, conventional concrete production has come under increasing scrutiny due to its unsustainable reliance on natural resources, particularly river sand, and its environmental impact. Excessive sand extraction depletes river ecosystems, disrupts groundwater systems, threatens biodiversity, and undermines long-term ecological balance. Concurrently, improper disposal of plastic waste presents a major global challenge, with millions of tons of non-biodegradable plastics accumulating in landfills and oceans annually. This creates a dual crisis: a shortage of natural aggregates for concrete production and escalating plastic pollution. Addressing these challenges requires innovative strategies that integrate sustainability with structural performance. One promising approach is the partial replacement of sand with shredded or granulated plastic waste. This technique diverts plastic from landfills while reducing dependency on river sand, mitigating environmental damage.

Numerous studies have examined the use of plastic as a fine aggregate substitute, with mixed outcomes. While the environmental benefits are clear, mechanical properties such as compressive strength, flexural strength, and workability often decrease compared to conventional mixes. The smooth, hydrophobic nature of plastic particles weakens the bonding between cement paste and aggregate, resulting in a compromised interfacial transition zone (ITZ) and reduced load-transfer efficiency. For instance, replacing sand with plastic at around 4% in M25 concrete has been observed to reduce compressive strength. To overcome these limitations, self-healing concrete has emerged as a transformative solution. Inspired by biological systems, self-healing concrete autonomously repairs microcracks and voids, extending durability, enhancing strength retention, and reducing maintenance costs. Healing mechanisms can be autogenous, such as continued hydration of unreacted cement particles, or autonomous, involving embedded healing agents that activate when cracks occur. Among these, bacterial self-healing has gained attention due to its effectiveness, eco-friendliness, and long-term viability. The bacterial self-healing process primarily utilizes strains like Bacillus subtilis, selected for their ability to form spores, survive in highly alkaline environments, and remain dormant for extended periods. When cracks form and water penetrate, the spores germinate and metabolically produce calcium carbonate crystals using a nutrient source like calcium lactate.

These crystals fill cracks, restore impermeability, and help recover compressive strength. The process is self-sustaining and environmentally friendly, reducing the need for synthetic healing agents. Further innovation involves cellulose diacetate capsules as protective carriers for bacterial spores. These biodegradable capsules provide controlled release and shield the bacteria during mixing and curing, ensuring viability until cracks appear. Incorporating these capsules containing Bacillus subtilis and calcium lactate transforms conventional concrete into a living, self-repairing material. Integrating this self-healing mechanism into plastic-replaced M25 concrete is particularly promising. While plastic substitution reduces strength, bacterial healing compensates by sealing microcracks and densifying the microstructure. Calcium carbonate precipitation minimizes voids created by plastic particles and enhances the interfacial bond between cement paste and aggregates. Experimental evidence indicates that bacterial concrete can restore, or even surpass, the original compressive strength of conventional concrete under optimized conditions. Thus, combining plastic waste utilization with bacterial self-healing offers a synergistic solution: environmental sustainability is achieved without compromising structural integrity. Beyond material innovation, structural health monitoring is crucial for sustainable infrastructure.

Cracks and voids inevitably occur under loads, thermal cycling, and environmental stressors. Traditional visual inspections and destructive tests are labor-intensive, time-consuming, and often incapable of detecting early-stage internal defects. The advent of the Internet of Things (IoT) has revolutionized civil engineering by enabling real-time, non-destructive, and continuous monitoring. IoT-based systems integrate sensors, microcontrollers, and wireless modules to collect and transmit data, facilitating predictive maintenance and proactive intervention. In the context of self-healing plastic-replaced concrete, IoT-enabled acoustic monitoring plays a vital role. Embedded or surface-mounted acoustic sensors capture vibrations generated by crack formation. Variations in acoustic signatures correspond to internal defects, enabling precise detection. Connected to an Arduino controller and powered by an ESP32 module, these sensors process signals, transmit data wirelessly, and provide real-time alerts. Vibration-based acoustic sensing ensures early detection, allowing bacterial healing to activate promptly and preventing crack propagation. Thus, IoT monitoring complements the material innovation by verifying the effectiveness of self-healing over the structure's service life. The novelty of this project lies in the integration of three domains: sustainable materials, biological self-healing, and smart IoT monitoring. Plastic replacement mitigates environmental impact but reduces strength. Bacterial self-healing restores mechanical integrity while being eco-friendly. IoT monitoring ensures healing processes are effective and provides actionable structural insights. Together, these innovations support the development of resilient, intelligent, and sustainable infrastructure systems. Research gaps justify the significance of this study. While plastic replacement and bacterial healing have been explored individually, few studies systematically combine them to achieve nominal M25 compressive strength. The use of cellulose diacetate capsules as a biodegradable bacterial carrier is an innovative step that promotes circular economy principles. Coupling material innovation with IoT-based acoustic sensing enhances reliability and practical applicability in real-world structures. In conclusion, the proposed project presents a holistic approach to sustainable construction. Partial sand replacement with plastic addresses environmental challenges, bacterial self-healing compensates for mechanical shortcomings, cellulose diacetate capsules ensure efficient and eco-friendly bacterial delivery, and IoT monitoring enables real-time structural assessment. Together, these innovations pave the way for next-generation construction materials that are not only strong and durable but also intelligent and environmentally responsible. This study demonstrates that the integration of plastic waste as partial fine aggregate replacement, bacterial self-healing technology, and IoT-based structural health monitoring offers a comprehensive and sustainable solution for modern concrete construction.

While plastic substitution in M25 concrete addresses critical environmental issues such as sand depletion and plastic pollution, it inherently compromises mechanical performance due to weak interfacial bonding. Overall, the proposed approach supports circular economy principles, reduces environmental impact, enhances durability, and paves the way for next-generation sustainable and smart infrastructure.

2.2 Literature Survey

A. Mahmood et al., 2022 Self-Healing Bio-Concrete Using Bacillus subtilis

Mahmood et al. (2022) presented a pioneering study on bio-concrete utilizing Bacillus subtilis to induce biological self-healing in cementitious materials. The approach involved integrating spores of B. subtilis with calcium lactate, a nutrient source essential for bacterial metabolism, directly into mortar and concrete mixtures. Once cracks were intentionally induced in the specimens and exposed to moisture, the bacterial spores germinated and metabolized calcium lactate, precipitating calcium carbonate ($CaCO_3$) within the crack voids. This biological process resulted in the visible sealing of cracks and a notable recovery of the mechanical properties that had deteriorated due to cracking.

The research employed various characterization techniques, including microscopy for visual confirmation of crack closure, compressive strength tests to evaluate mechanical recovery, and water permeability tests to assess durability improvements. The results showed that bacterial metabolism led to the effective formation of $CaCO_3$, which acted as a natural sealant, significantly reducing water ingress and recovering a considerable portion of compressive strength lost due to cracking. Additionally, the cyclic wetting conditions mimicked realistic environmental scenarios, confirming that the bacterial self-healing was repeatable and effective over time.

This study is crucial because it confirms the feasibility of using B. subtilis combined with calcium lactate as a practical self-healing strategy in cement-based materials. For projects involving the partial replacement of sand with plastic (which typically causes strength loss), this research validates the idea that bacterial healing can compensate for such losses by restoring compressive strength and permeability resistance. Mahmood et al.'s findings also emphasize the need to maintain appropriate nutrient availability and moisture conditions to activate bacterial healing, which informs practical design and maintenance considerations in bio-concrete applications.

B. Fahimizadeh et al., 2020 Biological Self-Healing of Cement Paste and Mortar

Fahimizadeh et al. (2020) focused on the encapsulation of bacteria as a key method to improve the survival and self-healing effectiveness of bacterial spores in cementitious materials. The harsh mixing and curing conditions in concrete often threaten bacterial viability, which limits the healing potential if free spores are directly incorporated. To address this, the study compared the performance of free bacterial spores versus spores encapsulated in various carrier materials, such as biodegradable polymers and microcapsules. The encapsulation process protects spores mechanically and chemically during concrete mixing, curing, and initial hydration phases. The researchers evaluated the healing ability by inducing cracks in specimens, then monitoring crack closure, mechanical strength recovery, and water permeability improvements. The results showed that encapsulated spores survived in higher numbers and exhibited more consistent healing behavior compared to free spores, which often died prematurely or were washed out.

Microencapsulation was highlighted as a crucial strategy because it preserved bacterial viability until cracks formed and moisture ingress occurred. This controlled activation ensures bacteria remain dormant but viable during concrete hardening and activate only when needed to precipitate calcium carbonate, sealing cracks and restoring mechanical properties. The encapsulated bacteria also improved repeatability of healing effects and reduced the variability observed with free spores.

The findings strongly support the use of biodegradable cellulose diacetate capsules in bio-concrete applications, aligning with current efforts to develop environmentally friendly and effective bacterial carriers. The study informs material selection and design parameters for your project, emphasizing the importance of encapsulation to achieve reliable and sustained biological healing in cementitious matrices.

C. Ahmad et al., 2024 Quantifying Self-Healing Efficiency of Bioconcrete

Ahmad et al. (2024) made significant contributions by providing quantitative evaluations of bacterial self-healing efficiency in concrete, addressing a key gap in prior research which often focused on qualitative or semi-quantitative assessments. The study standardized crack generation and employed repeatable wet/dry cycling to mimic real-world environmental conditions that trigger bacterial healing processes.

Using advanced analytical methods such as X-ray diffraction (XRD) and scanning electron microscopy (SEM), the research detailed the microstructural changes occurring during healing, especially the formation and deposition of calcite ($CaCO_3$) within cracks. This microstructural evidence was correlated with mechanical testing results, showing measurable increases in compressive strength and decreases in water absorption after healing cycles.

The findings demonstrated that bacterial concretes can recover a substantial fraction of their original mechanical capacity and drastically reduce permeability through effective calcite precipitation. The study quantified healing efficiencies, providing numerical benchmarks for strength recovery critical for defining performance targets in bio-concrete design, especially when partial sand replacement by plastic reduces initial strength.

Ahmad et al.'s work enables more precise claims regarding the restoration of strength and durability in bacterial concrete, supporting the integration of self-healing agents in structural-grade mixes. The quantitative data guide project goals for healing performance, making it easier to justify the economic and environmental benefits of bacterial bio-concretes. For your project, this study helps set realistic and scientifically grounded targets for healing efficacy in M25 concrete mixes with sand replaced by recycled plastic.

D. Fahim / Elgendy et al., 2025 Bacteria-Powered Bio-Self-Healing Concrete

Fahim and Elgendy et al. (2025) presented a comprehensive review of bacterial self-healing concrete technologies, focusing on current advancements, operational challenges, and certification issues related to their practical deployment. The survey encompassed various bacterial strains, nutrient delivery systems, encapsulation techniques, and the standards governing bio-concrete use. Among the bacterial species evaluated, Bacillus subtilis emerged as a consistently reliable microorganism capable of surviving the alkaline environment of cement and efficiently precipitating calcium carbonate for crack healing.

The review highlighted the successes of bacterial calcite precipitation in sealing cracks, typically effective for crack widths up to a few hundred micrometers. However, it emphasized operational constraints such as bacterial viability during mixing and curing, nutrient availability, environmental extremes (e.g., temperature fluctuations, pH changes), and long-term durability of the bio-concrete. Moreover, regulatory acceptance remains a significant hurdle, as standards for bio-based construction materials are still under development.

Fahim and Elgendy also discussed the importance of encapsulation to protect bacteria and nutrients, enhancing their survival and activity within concrete matrices. Encapsulation methods varied from microcapsules to porous carriers, each influencing both mechanical properties and healing efficacy differently. The authors recommended strain selection based on robust survivability and calcite precipitation potential, reinforcing the choice of B. subtilis for practical applications.

This review serves as a critical foundation for your project, justifying the use of

B. subtilis as the bacterial agent and explaining the need for protective encapsulation strategies such as cellulose diacetate capsules. It also frames realistic expectations and limitations, particularly regarding performance under harsh curing conditions and regulatory challenges. Including this context in your report's discussion and limitations sections will demonstrate an understanding of the current state-of-the-art and the practical challenges bio-concrete must overcome to achieve widespread adoption.

E. Xiao et al., 2023 Functionally Graded Bacteria Capsules for Self- Healing

Xiao et al. (2023) introduced an innovative approach to bacterial encapsulation for self-healing concrete by developing functionally graded microcapsules with layered shells designed to control the release of bacteria and nutrients selectively. This design strategy aims to optimize healing performance by improving bacterial survival during mixing and curing, as well as expanding the range of crack sizes that can be effectively healed.

The researchers fabricated capsules with multilayered shells of varying thicknesses and compositions, which improved mechanical stability during concrete mixing and protected bacterial spores from premature rupture or release. Upon crack formation and moisture ingress, these capsules progressively released bacterial spores and nutrient sources, facilitating sustained calcite precipitation over extended periods. Testing showed the functionally graded capsules could heal cracks measuring several hundred micrometers in width, exceeding typical healing limits. Importantly, the study revealed that capsule architecture shell thickness, layering, and placement within the cement matrix was a key design parameter influencing both healing efficacy and the mechanical integrity of the concrete. Excessive capsule volume or improper shell thickness could weaken the concrete matrix, while optimized capsules provided effective healing without significant strength loss.

For your project, Xiao et al.'s findings support the use of cellulose diacetate shells as biodegradable, mechanically robust carriers, but also underline the necessity of optimizing shell thickness and capsule distribution to maintain structural performance. This research informs your design decisions around capsule fabrication and dosing to balance self-healing benefits with minimal impact on mechanical properties.

F. Hu et al., 2022 Microcapsules in Cement: Influence on Crack Healing and Mechanical Properties

Hu et al. (2022) investigated how microcapsule characteristics such as size, content, and the pH of the cementitious environment affect the self-healing efficiency and residual mechanical strength of mortar. The study synthesized microcapsules with varied diameters and concentrations, embedding them into mortar specimens to evaluate compressive and flexural strength before and after inducing cracks. The key finding was that low microcapsule contents (1–3% by mass) typically enhanced both flexural and compressive strength, while also improving healing efficiency by enabling localized calcite precipitation. However, when microcapsule contents exceeded approximately 7%, the mechanical properties deteriorated significantly, attributed to the increased volume of capsules acting as weak points or voids within the cement matrix.

Microcapsule size also influenced healing behavior: smaller capsules provided more uniform release of healing agents, while larger capsules tended to cluster and caused heterogeneous healing patterns. The study suggested that careful selection of capsule size and content is essential to achieve an optimal balance between healing capability and structural performance.

The results provide concrete guidelines for your project: keep capsule content low (around 1–3%) to avoid compromising strength while still enabling meaningful self-healing, particularly in your mixes where 4% sand is replaced with plastic. It also points to the need for experimental validation of capsule size effects and dosage to ensure mechanical trade-offs are manageable.

G. Jiang et al., 2021 Preparation & Mechanical Properties of Microcapsule Healing Agents

Jiang et al. (2021) focused on the characterization of polymeric microcapsules carrying healing agents and their influence on mortar's mechanical properties and self-healing potential. The study fabricated microcapsules with polymer shells encapsulating healing agents and assessed their robustness during mixing, mechanical impact on mortar strength, and healing effectiveness under repeated wet/dry cycles. The experiments revealed that low dosages of microcapsules (1–3% by mass) improved self-healing without significantly reducing compressive or flexural strength. Maintaining shell integrity during the mixing process was critical; premature capsule rupture released healing agents too early, leading to strength degradation and reduced healing potential.

By gradually releasing healing agents upon crack formation and moisture ingress, the microcapsules promoted calcite precipitation to seal cracks effectively. The research highlighted the importance of designing microcapsules with robust shells that withstand mechanical stresses during mixing and handling, thus preserving healing potential until activation is needed.

Jiang et al.'s findings reinforce prior recommendations about microcapsule dosing and mechanical robustness, aligning well with your choice of cellulose diacetate as a capsule material. Their results encourage further optimization of shell thickness and mechanical properties in your capsule fabrication process to maximize healing efficiency without undermining concrete strength.

H. Olabisi et al., 2014 Cell Microencapsulation with Synthetic Polymers

Olabisi et al. (2014) provide a thorough review of cell encapsulation methods focusing on synthetic and semi-synthetic polymer shells that protect microbial cells in harsh environments, such as those found inside cementitious materials. Their survey covers a wide range of encapsulation chemistries including alginate, polyurethane, and cellulose derivatives, exploring how these polymers balance microbial viability with shell permeability and mechanical protection. The review highlights that an effective microcapsule shell must simultaneously protect bacteria from mechanical damage during mixing, withstand chemical stresses (notably the highly alkaline cement pore solution), and allow diffusion of nutrients and metabolic products essential for bacterial metabolism and calcite precipitation. The encapsulation shell's permeability is particularly important to enable activation only upon crack formation and moisture ingress, ensuring that bacterial spores remain dormant until healing is needed. Olabisi et al. discuss trade-offs inherent to different polymers. For example, alginate offers good biocompatibility but limited mechanical strength, while cellulose derivatives offer improved durability and tunable biodegradability. The authors emphasize that shell materials should ideally be biodegradable to avoid long-term accumulation inside concrete and should degrade slowly enough to provide prolonged protection.

This review supports your project's use of cellulose diacetate (a cellulose derivative) as a microcapsule shell material. It confirms cellulose-based shells can deliver the right balance of mechanical robustness, permeability, and biodegradability required for successful bacterial healing in cement. However, it also suggests the need for careful tuning of shell properties to avoid premature degradation or insufficient nutrient exchange. The findings underscore the importance of experimentally verifying chemical compatibility with the alkaline cement environment and adjusting capsule design accordingly.

I. Watanabe et al., 2025 Microfabrication of Cellulose Acetate Microcapsules

Watanabe et al. (2025) explore advanced microfabrication techniques to produce cellulose-acetate (CA) microcapsules with precise control over morphology, shell thickness, permeability, and mechanical response. Using microfluidic phase separation, they fabricated rattle-shaped CA microcapsules capable of encapsulating payloads while maintaining controlled release properties tailored for triggered activation.

The study demonstrates that CA shells provide a biodegradable, semi-permeable barrier that protects internal contents (e.g., bacterial spores and nutrients) from premature release or chemical attack. Importantly, the microfluidic fabrication method allows fine-tuning of shell thickness and morphology, which directly influences mechanical strength and permeability two critical parameters for capsules embedded in concrete.

Testing showed these CA microcapsules can withstand mechanical stresses typical of concrete mixing and curing processes, yet rupture predictably under stress conditions associated with crack formation and moisture ingress. This feature is vital to ensure healing agents are released only when cracks occur, maximizing healing efficiency and minimizing negative impacts on matrix strength.

Watanabe et al.'s work directly supports your project's choice of cellulose diacetate shells by demonstrating feasible manufacturing routes to produce capsules with desired mechanical and permeation properties. Their findings provide a pathway to optimize capsule design for controlled release and durability, encouraging exploration of microfluidic or similar precision fabrication techniques to improve capsule consistency and performance in bio-concrete applications.

J. Research on Cellulose-Diacetate Microcapsules

Research into cellulose diacetate (CDA) microcapsules across various fields including phase change materials, drug delivery, and chemical actives offers valuable insights into their fabrication, stability, permeability, and biodegradability. These studies typically employ phase separation and solvent exchange methods to produce CDA shells, which exhibit mechanical robustness and semi-permeable membranes suited to controlled release applications.

CDA shells protect encapsulated agents effectively from premature exposure to harsh environments, while their semi-permeability allows selective diffusion of moisture and nutrients necessary to activate encapsulated bacteria only upon crack formation. The biodegradability of CDA ensures that shells degrade slowly over time, preventing long-term accumulation within concrete while maintaining protective function during the critical early life of the material. Though specific studies applying CDA microcapsules in cementitious matrices are limited, extensive literature from other applications indicates CDA is a viable shell material capable of balancing protection, permeability, and biodegradability. However, CDA's chemical stability in the highly alkaline environment of cement pore solutions remains a potential concern; alkaline hydrolysis may degrade CDA shells faster than anticipated.

Your project would benefit from targeted experimental work to confirm CDA's chemical compatibility with cement chemistry, including tests for alkali resistance and mechanical integrity after exposure. CDA's favorable mechanical and permeability characteristics, combined with its biodegradability, make it a promising candidate for bacterial carrier capsules in self-healing concrete

## III. METHODOLOGY

### General

The present study focuses on the development of self-healing concrete using Bacillus subtilis bacteria encapsulated in cellulose diacetate, a biodegradable plastic, with additional incorporation of plastic aggregates as a partial replacement for sand. The methodology integrates microbial self-healing, sustainable material usage, and IoT-based monitoring to enhance the durability and structural integrity of M25 grade concrete.

The first step involves the preparation of the bacterial capsules. Bacillus subtilis bacteria are combined with calcium lactate, which acts as a nutrient source to support bacterial activity. This mixture is encapsulated within cellulose diacetate using a controlled process to form cylindrical capsules of 4 mm diameter and 8 mm height. The encapsulation ensures that the bacteria remain inactive during the initial stages of concrete mixing, preventing premature precipitation of calcium carbonate and protecting the bacteria from the high alkalinity of fresh concrete. The capsules are designed to degrade naturally within 3–4 weeks due to the alkaline environment and heat of hydration, releasing the bacteria when micro-voids are formed inside the concrete. This controlled release mechanism ensures timely self-healing, improving concrete durability and long-term performance.

For concrete preparation, a conventional M25 mix is adopted. The fresh concrete incorporates 16 capsules per 1 kg of cement, ensuring uniform distribution of self-healing agents throughout the matrix. Additionally, 4% of fine aggregates (sand) is replaced with plastic particles, which promotes sustainability by reducing waste but can reduce compressive strength. The addition of the encapsulated bacteria compensates for this reduction by facilitating calcium carbonate precipitation in the voids, restoring the mechanical properties of concrete to levels comparable with nominal M25 concrete.

During mixing, standard concrete procedures are followed to ensure uniform distribution of all materials. After casting, the concrete is cured under controlled conditions to allow the hydration process and capsule degradation. Over the curing period, as micro-voids appear due to the plastic replacement, the released bacteria metabolize calcium lactate, precipitating calcium carbonate and filling the voids, effectively performing self-healing. This process improves durability, reduces permeability, and increases the lifespan of the concrete structure.

To monitor the effectiveness of the healing process, an IoT-based sensing system is integrated into the concrete. The system consists of an ESP32 microcontroller, an acoustic sensor, and a power supply. The acoustic sensor detects voids and micro-cracks within the concrete, and the ESP32 transmits the collected data to the cloud via ThingSpeak, a cloud-based IoT platform. This enables real-time monitoring and analysis of void formation and healing progress, providing a data-driven approach to assess the performance of the self-healing concrete over time. The system also allows for the logging of historical data, which can be analyzed to study the rate and efficiency of bacterial activity in different environmental conditions.

Overall, this methodology combines the principles of biotechnology, sustainable construction materials, and IoT monitoring to produce a concrete mix that is both environmentally friendly and durable. By integrating encapsulated bacteria, partial plastic replacement, and cloud-based monitoring, the study not only enhances the compressive strength and durability of concrete but also demonstrates a practical approach for continuous structural health monitoring, offering insights into the future of smart, self-healing construction materials.

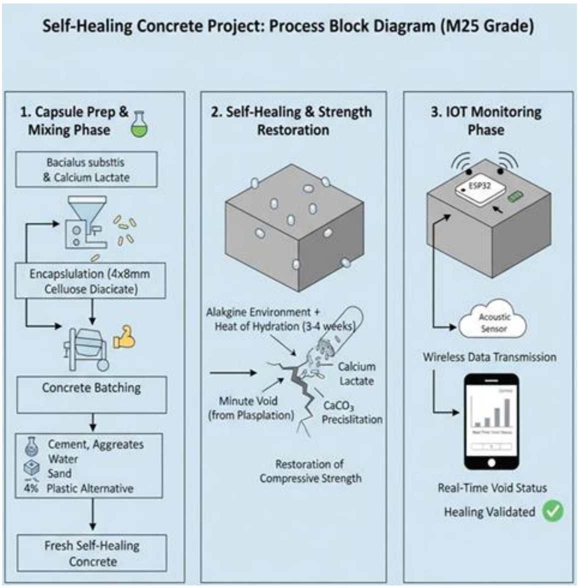

Figure:3.1 Methodology Flowchart

## IV MATERIALS USED

### 4.1 General

The development of self-healing M25 grade concrete in this project requires a combination of conventional construction materials, biological agents, biodegradable polymers, sustainable alternatives, and IoT components for monitoring. Cement, specifically Ordinary Portland Cement (OPC), serves as the primary binding material in the concrete mix. Cement undergoes hydration when mixed with water, forming calcium silicate hydrate (C-S-H) gel, which provides the concrete with its structural strength and durability. Its chemical environment also plays a crucial role in the controlled activation of bacterial capsules. Fine aggregates, mainly natural sand, are used to fill voids between coarse aggregates, improving packing density, workability, and surface finish of the concrete. In this project, 4% of sand is replaced with plastic aggregates, a sustainable approach aimed at reducing natural resource consumption and promoting waste utilization. While plastic aggregates reduce compressive strength due to their lower density and stiffness, the self-healing mechanism compensates for this loss, ensuring the concrete retains strength comparable to nominal M25 mixes. Coarse aggregates, such as crushed stone or gravel, provide the concrete with bulk, compressive strength, and structural stability. Proper selection of size, grading, and cleanliness ensures uniform stress distribution and durability of the concrete matrix. Water is an essential material for cement hydration, workability of fresh concrete, and activation of bacterial self-healing. It facilitates the metabolic processes of bacteria once the capsules degrade and ensures proper mixing and uniformity of the concrete. The Bacillus subtilis bacteria act as the biological agent responsible for precipitating calcium carbonate in micro-voids and cracks formed in the concrete due to plastic replacement or normal curing. This microbial activity fills voids and restores the mechanical properties of the concrete over time. To support bacterial activity, calcium lactate is included as a nutrient source, allowing the bacteria to metabolize and produce calcium carbonate efficiently. Both the bacteria and calcium lactate are encapsulated in cellulose diacetate, a biodegradable polymer that protects the bacteria from high alkalinity and mechanical stresses of fresh concrete while ensuring controlled release after 3–4 weeks of curing. Plastic aggregates serve a dual purpose: sustainability by reducing sand consumption and providing sites for self-healing due to the micro-voids they create. The ESP32 microcontroller and acoustic sensor are embedded within the concrete to detect micro-voids and monitor the self-healing process in real time. Data collected from the sensor is transmitted to the ThingSpeak cloud platform, allowing continuous remote monitoring and analysis of healing efficiency. A power supply, typically a battery or regulated DC source, ensures uninterrupted operation of the IoT devices. Finally, miscellaneous materials such as concrete molds, mixing tools, measuring equipment, curing tanks, and safety gear are necessary to prepare, cast, and cure the concrete properly. These tools also ensure uniform dispersion of capsules and consistent concrete properties across all specimens. Together, these materials enable the creation of a durable, sustainable, and smart self-healing concrete system, integrating biological, mechanical, and digital technologies to enhance performance, monitor structural health, and extend the service life of modern concrete structures.

4.1 Cement

Figure 4.2 Cement (OPC)

Cement is the primary binding material in concrete, responsible for holding together the aggregates and providing strength to the overall mix. In this project, Ordinary Portland Cement (OPC) is used for preparing M25 grade concrete, which is designed to achieve a compressive strength of 25 MPa. The cement reacts chemically with water through the hydration process, forming calcium silicate hydrate (C-S-H) gel, which gives concrete its strength and durability. Proper selection of cement is crucial because it directly influences the setting time, workability, and long-term performance of the concrete. In the context of self-healing concrete, the cement matrix provides the environment in which the encapsulated bacteria can function. The high alkalinity of fresh cement prevents premature bacterial activity, while the heat generated during hydration aids in controlled capsule degradation. By combining OPC with plastic sand replacement and bacterial capsules, the cement ensures the concrete maintains structural integrity while allowing self-healing processes to take place over time. The quality and fineness of cement are particularly important to ensure uniform hydration and consistent release of bacteria from capsules during the curing period.

4.3 Fine Aggregate (Sand)

Figure 4.3 Fine Aggregate (Sand)

Fine aggregate, typically natural river sand, constitutes an important portion of the concrete mix and fills the voids between coarse aggregates, improving packing density and workability. In this project, a portion of sand is replaced with plastic aggregates (4% by weight) to promote sustainability and test the performance of eco-friendly alternatives. Sand provides structural strength, reduces shrinkage, and ensures smooth concrete surfaces. The replacement with plastic alters the internal microstructure of concrete, potentially creating micro-voids that reduce compressive strength. These voids are later filled by the self-healing action of the bacteria, ensuring that structural performance is maintained. The quality of sand, including particle size distribution, cleanliness, and fineness modulus, directly affects workability and hydration. By partially replacing sand with plastic, the project not only addresses environmental concerns but also allows the study of how bacterial calcium carbonate precipitation can compensate for strength loss. The uniform mixing of sand and plastic ensures proper dispersion, which is critical to achieving consistent results in mechanical testing and monitoring of voids using IoT sensors.

4.4 Coarse Aggregate

Figure 4.4 Coarse Aggregate

Coarse aggregate, usually crushed stone or gravel, forms the backbone of concrete, providing bulk, strength, and resistance to compressive forces. In M25 grade concrete, coarse aggregates typically range from 10 mm to 20 mm in size, depending on mix design. The aggregate contributes to load distribution, preventing excessive stress on the cement matrix and reducing cracking. Proper grading, angularity, and cleanliness of coarse aggregates are essential to achieve high-strength, durable concrete. In this project, coarse aggregates also play a role in the microenvironment for self-healing, as voids or micro-cracks forming around aggregates may become sites for bacterial activity. Since plastic aggregates replace a portion of fine aggregates, coarse aggregates maintain structural stability and prevent drastic reductions in compressive strength. Additionally, their thermal mass contributes to the hydration process, supporting the controlled degradation of cellulose diacetate capsules over 3–4 weeks. Careful selection of coarse aggregates ensures that the concrete mix maintains proper workability, compaction, and long-term durability while accommodating both sustainable material use and bacterial self-healing mechanisms.

4.5 Water

Figure 4.5 Water

Water is a critical component of concrete, enabling hydration of cement and ensuring proper workability of the fresh mix. In this project, clean, potable water is used to prevent contamination that could affect bacterial survival and hydration reactions. The water-cement ratio is carefully controlled to balance strength and workability, as excessive water can reduce strength, while insufficient water can hinder bacterial activity and capsule degradation. In the context of self-healing concrete, water is essential not only for hydration but also for activating the bacteria once the capsules degrade. The bacteria metabolize calcium lactate in the presence of moisture to precipitate calcium carbonate, filling micro-voids created by partial plastic replacement. Water also facilitates uniform mixing of cement, aggregates, and capsules, ensuring consistent mechanical properties throughout the concrete. Moreover, curing with adequate water ensures complete hydration, prevents shrinkage cracks, and supports the timely self-healing process, contributing to the durability and long-term performance of M25 grade concrete.

4.6 Bacillus subtilis Bacteria

Figure 4.6 Bacillus subtilis Bacteria

Bacillus subtilis is a Gram-positive, spore-forming bacterium widely used in self-healing concrete due to its ability to precipitate calcium carbonate ($CaCO_3$) under suitable conditions. In this project, the bacteria are incorporated into cellulose diacetate capsules along with calcium lactate, their nutrient source. The encapsulation protects the bacteria from the high alkalinity and mechanical stresses of fresh concrete, preventing premature death. Once the capsules degrade after 3–4 weeks during curing, the bacteria become active in the presence of moisture and calcium lactate. They metabolize the calcium lactate to precipitate calcium carbonate, which fills micro-voids and cracks, restoring concrete integrity. The spores' durability allows survival over extended periods until triggered by environmental conditions, making them ideal for long-term self-healing. Using Bacillus subtilis enhances durability, reduces permeability, and increases compressive strength of concrete with partial plastic replacement. The uniform distribution of capsules ensures bacteria are present throughout the matrix, addressing voids caused by aggregate replacement. Overall, these bacteria are a biological solution for sustainable, smart, and self-healing concrete.

4.7 Calcium Lactate

Figure 4.7 Calcium Lactate

Calcium lactate serves as the primary nutrient source for Bacillus subtilis in the self-healing concrete. It provides the calcium ions required for biogenic precipitation of calcium carbonate, which fills micro-voids and restores structural integrity. Without calcium lactate, the bacteria would not have sufficient nutrients to metabolize and form $CaCO_3$ efficiently. In this project, calcium lactate is combined with Bacillus subtilis and encapsulated within cellulose diacetate capsules. The capsules protect the nutrient from premature dissolution in the highly alkaline fresh concrete, ensuring it is available only when the bacteria are released after 3–4 weeks of curing. The inclusion of calcium lactate also supports the healing of voids created by 4% sand replacement with plastic, compensating for potential reductions in compressive strength. Furthermore, calcium lactate's solubility ensures it can diffuse into micro-voids efficiently, allowing the bacteria to precipitate calcium carbonate uniformly across the concrete matrix. Its use is essential for effective self-healing performance and long-term durability.

4.8 Cellulose Diacetate

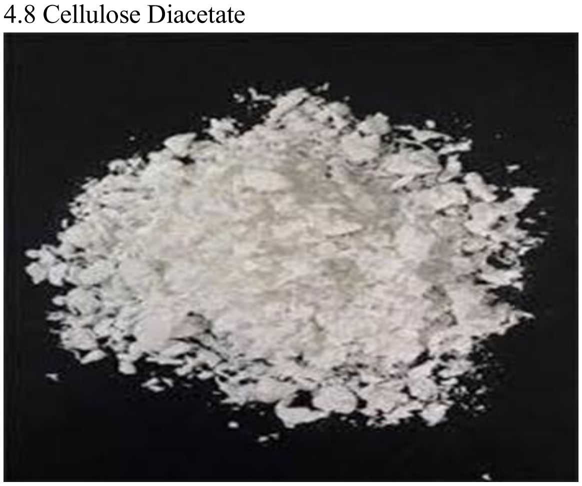

Figure 4.8 Cellulose Diacetate

Cellulose diacetate is a biodegradable polymer used for encapsulating bacteria and calcium lactate in this project. Its primary role is to protect the bacterial spores and nutrient source from the high alkalinity and mechanical forces of fresh concrete, preventing premature activation or death. The capsules are cylindrical, measuring 4 mm in diameter and 8 mm in height, and are designed to degrade over 3–4 weeks due to alkaline conditions and heat of hydration, ensuring the bacteria are released at the optimal time. Biodegradability ensures that the capsule does not leave long-term residues in the concrete, maintaining environmental sustainability. The controlled degradation also allows targeted self-healing of micro-voids formed due to partial plastic sand replacement. Cellulose diacetate's mechanical stability during mixing prevents capsule breakage, ensuring uniform bacterial distribution. By combining protection, controlled release, and sustainability, cellulose diacetate is a critical material for implementing effective microbial self-healing in concrete, making it a key component of modern smart concrete technologies.

4.9 Plastic Aggregates

Figure 4.9 Plastic Aggregates

Plastic aggregates are used in this project as a partial replacement for fine aggregates (4% by weight) to promote environmental sustainability and study their effect on concrete properties. Plastic waste incorporation reduces natural sand consumption and minimizes environmental impact, aligning with eco-friendly construction practices. However, plastic has lower density and mechanical strength compared to natural sand, which can create micro-voids and reduce compressive strength. To address this, the self-healing mechanism using Bacillus subtilis and calcium lactate ensures that voids are filled through calcium carbonate precipitation, restoring structural performance. The plastic aggregates are carefully sized and uniformly mixed to prevent segregation and ensure consistent mechanical properties. Additionally, the presence of plastic affects hydration, workability, and thermal behavior, which are compensated by proper mix design and curing. Their inclusion allows the project to simultaneously study sustainable material usage and the effectiveness of bio-concrete self-healing.

4.10 Arduino Microcontroller

Figure 4.10 Arduino Microcontroller

The Arduino Microcontroller is an open-source electronic platform designed for building and controlling digital devices and interactive systems. It consists of a microcontroller board, such as the Arduino Uno, and an easy-to-use Integrated Development Environment (IDE) for writing and uploading programs. The Arduino board is built around ATmega series microcontrollers (like ATmega328P in the Uno), which perform processing and control tasks. It features digital and analog input/output (I/O) pins, power supply ports, and communication interfaces like USB and serial connections, enabling it to interface with a wide range of sensors, actuators, and other hardware components. Arduino uses a simplified version of the C/C++ programming language, making it beginner-friendly and widely used in education, automation, and research projects. In civil and mechanical engineering, Arduino is applied in structural health monitoring, automatic curing systems, environmental data logging, and smart material testing setups.

4.11 Li-ion Battery (18650 Cell)

Figure 4.11 Li-ion Battery (18650 Cell)

The 18650 Lithium-ion battery is a rechargeable power source widely used in portable electronic systems due to its high energy density and compact size. It typically provides a nominal voltage of 3.7V and a capacity ranging from 2000mAh to 3500mAh, making it suitable for low-power microcontroller applications. The term "18650" refers to its dimensions 18 mm diameter and 65 mm length. It supplies continuous current to the circuit and ensures the project can run independently without a wired power connection. In this setup, the Li-ion cell powers the Arduino, sensors, and modules through the TP4056 charging board. It offers a good balance between performance and safety, provided that protection circuits are used to prevent overcharging, deep discharging, or short circuits. Compared to conventional batteries, Li-ion cells have a longer life cycle, faster charging, and lower self-discharge rate. Their lightweight design makes them ideal for robotics, IoT, and embedded projects.

4.12 Battery Holder

Figure 4.12 Battery Holder

A battery holder is a plastic or metallic component designed to securely hold the 18650 Li-ion battery and provide reliable electrical connections to the circuit. It typically contains two metal contacts one for the positive terminal and another for the negative connected through insulated wires. The holder ensures that the battery remains firmly in place, preventing movement or loose contact during operation. In this setup, the black plastic battery holder acts as a safe mounting base for the Li-ion cell and connects directly to the TP4056 charging module. It simplifies battery replacement and allows easy connection or disconnection without soldering. The holder also minimizes the risk of short circuits and protects the cell from physical damage. Some holders include integrated switches or polarity markings for user safety. The material used is usually heat-resistant plastic, ensuring durability under various conditions. In portable electronic prototypes like Arduino projects, the battery holder is essential for maintaining a stable power connection and preventing accidental disconnection, thereby enhancing both the safety and reliability of the circuit assembly.

4.13 Acoustic sensor

Figure 4.13 Acoustic sensor

An acoustic sensor, also known as a sound sensor or microphone sensor, is an electronic device used to detect sound waves or vibrations from the surrounding environment and convert them into electrical signals. It plays a vital role in projects that require sound-based detection or automation, such as clap switches, voice-activated systems, noise monitoring, and security applications.

In this project setup, the acoustic sensor module (often KY-037 or LM393-based) includes a microphone, an amplifier circuit, and a comparator. The microphone captures sound vibrations and converts them into small analog voltage signals. These weak signals are then amplified and processed by the comparator circuit, which compares them to a preset threshold value. When the sound intensity exceeds this threshold (for example, during a loud noise or clap), the module sends a digital HIGH signal to the Arduino.

The Arduino interprets this signal and triggers specific actions, such as turning ON or OFF a connected device through a relay module. This sensor is sensitive, adjustable (using a potentiometer), and easy to interface with microcontrollers. Overall, the acoustic sensor provides an efficient way to enable sound-based automation and control in embedded system projects.

4.14 Switch

Figure 4.14 Switch

A switch is an essential electrical component that controls the flow of current in a circuit by opening or closing its electrical contacts. In this project, a small on/off toggle switch is used between the power supply and the load to manually control power delivery. When turned on, the circuit becomes complete, allowing current to pass from the battery to the Arduino and modules; when off, it breaks the circuit, disconnecting power. The switch provides a simple yet effective way to start or stop the entire system without unplugging wires. It prevents unnecessary battery discharge and offers safety during wiring or testing. Most toggle switches are rated for a particular current and voltage, ensuring they can handle the connected load. The switch is mounted near the battery section for easy accessibility. It consists of a lever or slider mechanism connected to metallic contacts enclosed in a protective casing. In Arduino-based circuits, switches are critical for both power management and user control. Thus, the inclusion of a switch adds convenience, safety, and operational control, enabling the user to activate the system only when required.

4.15 Jumper Wires

Figure 4.15 Jumper Wires

Jumper wires are flexible, insulated conductors used to establish temporary or semi-permanent electrical connections between components on a breadboard, module, or Arduino. They come in three main types male-to-male, male-to-female, and female-to-female depending on the connection requirements. In this project, jumper wires are used to connect the Arduino with external modules such as the sound sensor, relay, and TP4056 charger. They carry signals and power between the components, enabling communication and operation of the entire system. Jumper wires are color-coded for easy identification of power (red), ground (black), and signal (other colors) lines. Their main advantage is flexibility, allowing easy modifications or debugging without soldering. The wires typically consist of copper conductors coated with PVC insulation to prevent short circuits. In educational or prototype setups, they are indispensable for rapid circuit assembly. Proper wiring ensures accurate signal transmission and stable operation. Hence, jumper wires serve as the nervous system of the circuit, transmitting electrical information between the Arduino (the brain) and all peripheral devices, ensuring reliable and organized interconnection for smooth functionality.

## V SOFTWARE USED

### 5.1 General

In this project, several software tools are employed to enable IoT-based monitoring and analysis of self-healing concrete, combining digital technology with biological processes. The Arduino IDE is used to program the ESP32 microcontroller, which collects data from the embedded acoustic sensor, detects micro-voids, and monitors the progress of bacterial self-healing. It allows setting detection thresholds, timing data acquisition, formatting sensor readings, and managing reliable transmission to the cloud. The IDE also provides debugging and library support for Wi-Fi communication, ensuring seamless connectivity with cloud platforms and enabling automated data logging over long periods. ThingSpeak, a cloud-based IoT platform, stores, visualizes, and analyzes real-time data from the ESP32. It offers dashboards, charts, and alerts for monitoring void formation and the effectiveness of self-healing over time, allowing remote observation and trend analysis. For advanced data analysis, MATLAB can be integrated with ThingSpeak to filter noise, process acoustic signals, quantify void-filling, and generate graphs for detailed research evaluation. Fritzing is used to design and document the IoT circuit, including the ESP32, acoustic sensor, and power supply, ensuring accurate hardware assembly and reproducibility. Additionally, Microsoft Excel is used to organize exported data for statistical analysis, visualization, and professional presentation. Collectively, these software tools enable real-time monitoring, precise analysis, automated data management, and effective documentation, making the project highly efficient and scientifically robust.

### 5.2 Arduino Microcontroller

Arduino is an open-source computer hardware and software company, project and user community that designs and manufactures microcontroller-based kits for building digital devices and interactive objects that can sense and control objects in the physical world. The project is based on microcontroller board designs, manufactured by several vendors, using various microcontrollers. These systems provide sets of digital and analog I/O pins that can be interfaced to various expansion boards ("shields") and other circuits. The boards feature serial communications interfaces, including USB on some models, for loading programs from personal computers. For programming the microcontrollers, the Arduino project provides an integrated development environment (IDE) based on the Processing project, which includes support for the C and C++ programming languages.

The first Arduino was introduced in 2005, aiming to provide an inexpensive and easy way for novices and professionals to create devices that interact with their environment using sensors and actuators. Common examples of such devices intended for beginner hobbyists include simple robots, thermostats, and motion detectors.

Arduino boards are available commercially in preassembled form, or as do-it-yourself kits. The hardware design specifications are openly available, allowing the Arduino boards to be manufactured by anyone. Adafruit Industries estimated in mid-2011 that over 300,000 official Arduinos had been commercially produced, and in 2013 that 700,000 official boards were in users' hands.

Figure 5.1 Arduino microcontroller

Arduino started in 2005 as a project for students at the Interaction Design Institute Ivrea in Ivrea, Italy. At that time program students used a "BASIC Stamp" at a cost of $100, considered expensive for students. Massimo Banzi, one of the founders, taught at Ivrea. The name "Arduino" comes from a bar in Ivrea, where some of the founders of the project used to meet. The bar, in turn, has been named after Arduin of Ivrea, who was the margrave of Ivrea and King of Italy from 1002 to 1014.

Colombian student Hernando Barragán created the Wiring development platform which served as the basis for Arduino. Following the completion of the Wiring platform, its lighter, less expensive versions were created and made available to the open-source community; associated researchers, including David Cuartielles, promoted the idea. The Arduino's initial core team consisted of Massimo Banzi, David Cuartielles, Tom Igoe, Gianluca Martino, and David Mellis. An early Arduino board with anRS-232 serial interface (upper left) and an Atmel ATmega328 microcontroller chip (black, lower right); the 14 digital I/O pins are located at the top and the six analog input pins at the lower right. An Arduino board historically consists of an Atmel 8-, 16- or 32-bit AVR microcontroller (although since 2015 other makers' microcontrollers have been used) with complementary components that facilitate programming and incorporation into other circuits. An important aspect of the Arduino is its standard connectors, which lets users connect the CPU board to a variety of interchangeable add-on modules known as shields. Some shields communicate with the Arduino board directly over various pins, but many shields are individually addressable via an I²C serial bus so many shields can be stacked and used in parallel. Prior to 2015 Official Arduinos had used the Atmel megaAVR series of chips, specifically the A Tmega 8, A Tmega 168, A Tmega 328, ATmega1280, and ATmega2560 and in 2015 units by other manufacturers were added. A handful of other processors have also been used by Arduino compatibles. Most boards include a 5 V linear regulator and a 16 MHz crystal oscillator (or ceramic resonator in some variants), although some designs such as the LilyPad run at 8 MHz and dispense with the onboard voltage regulator due to specific form-factor restrictions. An Arduino's microcontroller is also pre-programmed with a boot loader that simplifies uploading of programs to the on-chip flash memory, compared with other devices that typically need an external programmer. This makes using an Arduino more straightforward by allowing the use of an ordinary computer as the programmer. Currently, opti boot boot loader is the default boot loader installed on Arduino UNO. At a conceptual level, when using the Arduino integrated development environment, all boards are programmed over a serial connection. Its implementation varies with the hardware version. Some serial Arduino boards contain a level shifter circuit to convert between RS-232 logic levels and TTL-level signals. Current Arduino boards are programmed via Universal Serial Bus (USB), implemented using USB-to-serial adapter chips such as the FTDI FT232. Some boards, such as later-model Uno boards, substitute the FTDI chip with a separate AVR chip containing USB-to-serial firmware, which is reprogrammable via its own ICSP header. Other variants, such as the Arduino Mini and the unofficial Boarduino, use a detachable USB-to-serial adapter board or cable, Bluetooth or other methods, when used with traditional microcontroller tools instead of the Arduino IDE, standard AVR ISP programming is used.

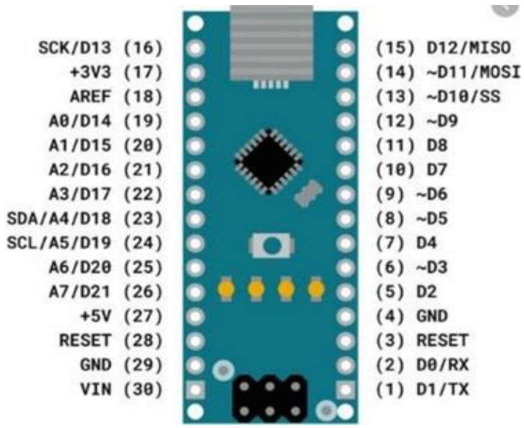


Figure 5.2 An official Arduino Uno with descriptions of the I/O locations

The Arduino board exposes most of the microcontroller's I/O pins for use by other circuits. The Diecimila, Duemilanove, and current Uno provide 14 digital I/O pins, six of which can produce pulse-width modulated signals, and six analog inputs, which can also be used as six digital I/O pins. These pins are on the top of the board, via female 0.10-inch (2.5 mm) headers. Several plug-in application shields are also commercially available. The ArduinoNano, and Arduino- compatible Bare Bones Board and Boarduino boards may provide male header pins on the underside of the board that can plug into solderless breadboards.

There are many Arduino-compatible and Arduino-derived boards. Some are functionally equivalent to an Arduino and can be used interchangeably. Many enhance the basic Arduino by adding output drivers, often for use in school-level education to simplify the construction of buggies and small robots. Others are electrically equivalent but change the form factor, sometimes retaining compatibility with shields, sometimes not. Some variants use completely different processors, with varying levels of compatibility.

Official boards Further information: List of Arduino boards and compatible systems

The original Arduino hardware was manufactured by the Italian company Smart Projects.[11] Some Arduino-branded boards have been designed by the American companies SparkFun Electronics and Adafruit Industries. Sixteen versions of the Arduino hardware have been commercially produced to date.

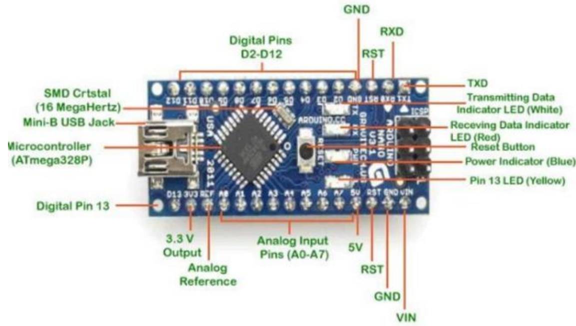


Figure 5.3 Arduino Diecimila in Stoicheia

5.3 LM2596 step down voltage regulator

The LM2596 is a highly efficient, fixed-frequency, step-down (buck) voltage regulator designed to convert higher input voltages into a stable, lower output voltage. It operates with an input voltage range of 4.5V to 40V and provides an adjustable output voltage that can range from 1.23V to 37V, depending on the application. The LM2596 is commonly used in applications where efficient power conversion is required, such as in battery-powered devices, industrial control systems, and consumer electronics.

Key Features

1. High Efficiency: The LM2596 uses pulse-width modulation (PWM) to regulate voltage efficiently, which typically results in efficiencies of up to 90%, reducing the amount of heat generated compared to linear regulators.
2. Output Voltage Range: It offers a wide output voltage range from 1.23V to 37V, allowing it to be used in various power applications.
3. Current Capability: It can provide up to 2A of output current, making it suitable for powering devices that require moderate to high current loads, such as motors, LEDs, and small microcontrollers.
4. Thermal Protection and Overload Protection: The LM2596 is designed with built-in thermal shutdown and overload protection to prevent damage to the regulator and connected circuits under extreme operating conditions.
5. Adjustable and Fixed Versions: The regulator comes in both adjustable and fixed voltage versions. The adjustable version allows users to fine-tune the output voltage by using external resistors, whereas the fixed versions come with

pre-set output voltages.

6. Low Standby Current: In standby mode, the regulator consumes very little current, which is ideal for battery-operated systems where power conservation is critical.

5.4 Microphone Sensor with Arduino

A microphone sensor, often referred to as a sound sensor, detects sound waves and converts them into electrical signals. These sensors are commonly used with Arduino to measure sound intensity or trigger actions based on sound thresholds. Below is an overview of how to interface and program a microphone sensor with Arduino.

5.5 Components and Wiring

To set up a microphone sensor with Arduino, you will need: Microphone sound sensor module (e.g., KY-038 or LM393) Arduino board (e.g., Arduino Uno)
LED (optional, for visual feedback) Resistor (e.g., 220 Ohms for the LED) Breadboard and jumper wires
Pin Connections:
VCC: Connect to Arduino's 5V pin. GND: Connect to Arduino's GND pin.
A0 (Analog Output): Connect to an analog pin (e.g., A0) for sound intensity measurement.
D0 (Digital Output): Connect to a digital pin (e.g., D7) for threshold-based sound detection.

5.6 ThingSpeak


Figure: 5.4 ThingSpeak

ThingSpeak is a cloud-based IoT platform designed for collecting, storing, analyzing, and visualizing real-time data from sensors and microcontrollers. In this project, it serves as the central platform for monitoring micro-voids inside concrete detected by the ESP32-acoustic sensor system. Data collected from the sensor is transmitted via Wi-Fi to ThingSpeak, where it can be visualized using graphs, dashboards, and alerts. Researchers can track changes over time, such as the reduction of voids due to bacterial self-healing, and compare performance across different specimens. ThingSpeak also integrates with MATLAB for signal processing, enabling advanced analysis of acoustic signals, noise filtering, and quantification of voids. This cloud-based approach allows remote monitoring, eliminating the need for continuous on-site observation. Its accessibility, real-time visualization, and analytics capabilities make ThingSpeak an essential software tool to validate the effectiveness of bio-concrete self-healing systems.

5.7 MATLAB

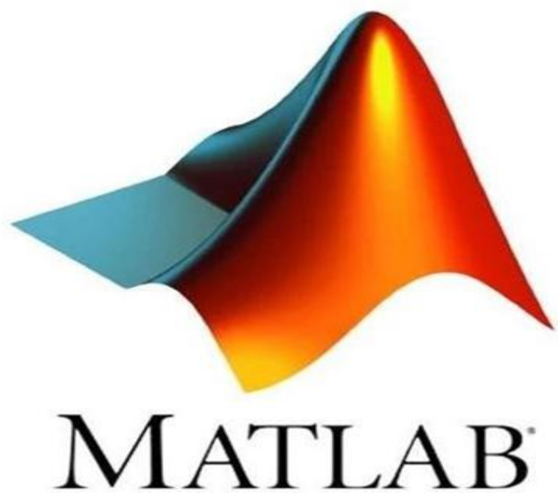


Figure: 5.5 MATLAB

MATLAB is a high-level programming and numerical computing platform widely used for data analysis, signal processing, and visualization. In this project, MATLAB is integrated with ThingSpeak to analyze acoustic sensor data collected from the ESP32. Acoustic signals are often noisy due to environmental factors, and MATLAB allows filtering, smoothing, and amplification of signals to accurately detect micro-voids within the concrete. Furthermore, MATLAB facilitates quantitative analysis, such as calculating void volume, tracking the rate of self-healing, and generating graphs for research reports or presentations. The platform also allows researchers to simulate trends, predict bacterial activity, and verify the efficiency of calcium carbonate precipitation in filling voids. Its versatility and computational power make MATLAB a critical tool for interpreting large data sets from IoT sensors and validating the performance of the self-healing concrete system.

5.8 CREO

Figure: 5.6 CREO

CREO is a powerful 3D CAD (Computer-Aided Design) software developed by PTC (Parametric Technology Corporation) used for modeling, simulation, and drafting in engineering design. It is a parametric and feature-based modeling tool that allows engineers to create, modify, analyze, and document real-world products with high precision. In civil engineering, Creo is used to model structural components such as beams, columns, slabs, formworks, and concrete specimen moulds used for casting and testing. The software provides tools for creating both 2D sketches and 3D solid models, which can be extruded, revolved, or swept to form complex geometries. Creo also supports material assignment and stress analysis through its simulation module, enabling engineers to study the performance of materials under various loading conditions.

## VI. PROCEDURE AND EXPERIMENTAL SETUP

### 6.1 General

The preparation of self-healing M25 grade concrete begins with the design of the concrete mix. Ordinary Portland Cement (OPC) is used as the primary binder, combined with coarse aggregates and fine aggregates. In this project, 4% of the sand is replaced with plastic aggregates to promote sustainability and reduce natural sand consumption. The replacement of sand with plastic may lead to micro-voids and a reduction in compressive strength, which is addressed by the self-healing mechanism. The Bacillus subtilis bacteria and its nutrient source, calcium lactate, are encapsulated in cellulose diacetate capsules. These capsules are cylindrical, with a diameter of 4 mm and height of 8 mm, and are designed to degrade after 3–4 weeks due to the alkaline environment and heat of hydration inside the concrete. The encapsulation protects the bacteria and nutrient from the harsh conditions of fresh concrete, preventing premature activation or death. A total of 16 capsules per kilogram of cement are mixed uniformly into the concrete to ensure proper distribution throughout the matrix.

Next, the concrete ingredients are mixed thoroughly. First, dry components including cement, aggregates, and capsules are blended to achieve a homogeneous mixture. Water is gradually added to the mix to obtain the desired workability. Proper mixing ensures that the capsules are not damaged and are evenly dispersed. The fresh concrete is then poured into standard molds of required dimensions and compacted using mechanical or manual methods to remove entrapped air.

During curing, the capsules degrade naturally, releasing the bacteria and calcium lactate at the appropriate time. When micro-voids are formed due to the plastic replacement or minor cracking during curing, the Bacillus subtilis bacteria metabolize the calcium lactate to produce calcium carbonate, which fills the voids and restores the concrete’s structural integrity. This process ensures that the compressive strength of the plastic-replaced concrete reaches values comparable to nominal concrete.

An IoT monitoring system is embedded in selected specimens to track internal voids and healing activity. The system consists of an ESP32 microcontroller, acoustic sensor, and power supply. The acoustic sensor detects micro-voids, and the ESP32 collects the data and transmits it to a cloud platform such as ThingSpeak for real-time monitoring. Data is analyzed to quantify void filling and the efficiency of self-healing over time.

Finally, after the curing period, specimens are tested for compressive strength to evaluate the impact of plastic replacement and bacterial self-healing. Observations are recorded, and results are compared with conventional concrete to validate the effectiveness of the methodology. Proper documentation of sensor data and laboratory measurements ensures reproducibility and accuracy, providing a comprehensive evaluation of the self-healing concrete system.

During curing, the capsules degrade due to the alkaline environment and heat of hydration, releasing bacteria at the optimal time to precipitate calcium carbonate and fill micro-voids created by the plastic sand replacement. The IoT monitoring system, consisting of an ESP32 microcontroller, acoustic sensor, and power supply, is embedded within selected specimens to detect internal voids. Sensor data is transmitted to a cloud platform for analysis.

6.2 Working and Block Diagram

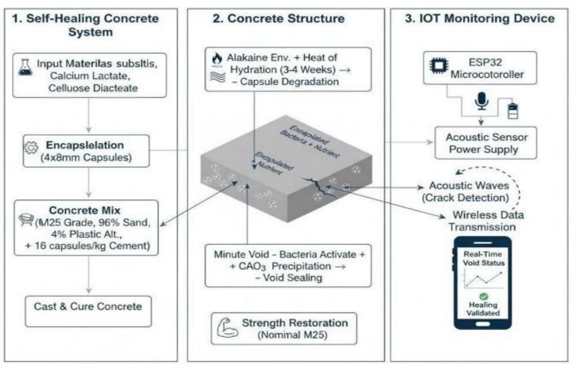


Figure 6.1 Block diagram

The working process of this project integrates biological self-healing mechanisms and IoT-based structural monitoring to improve the durability and performance of M25 grade concrete. The concept relies on using Bacillus subtilis bacteria encapsulated in biodegradable cellulose diacetate capsules to repair microcracks autonomously while an IoT system monitors internal voids to assess healing efficiency.

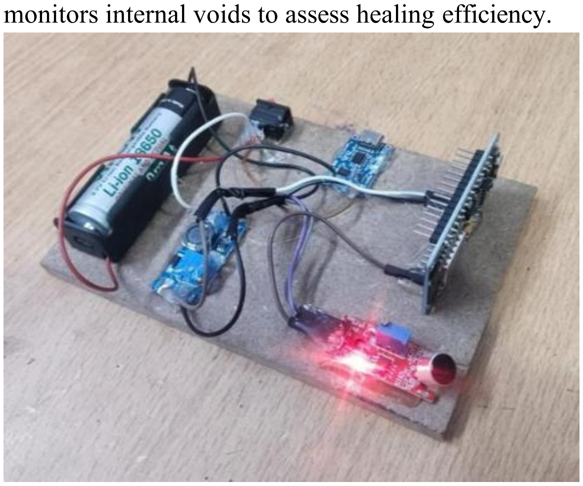

Figure 6.2 Board Connections

The process begins with the preparation of the encapsulated self-healing agent. A culture of Bacillus subtilis is grown under controlled conditions to ensure viability and spore formation. These spores, along with the nutrient source calcium lactate, are encapsulated within cellulose diacetate a biodegradable polymer that protects the bacteria from the harsh environment of fresh concrete. The capsules, measuring approximately 4 mm in diameter and 8 mm in height, are designed to degrade slowly when exposed to the alkaline environment and heat of hydration inside concrete, ensuring the bacteria are only released at the appropriate time during the curing phase.

During mixing, the prepared capsules are added into the fresh M25 grade concrete mix along with a 4% plastic replacement for sand. This eco-friendly replacement reduces the consumption of natural sand but may introduce microvoids in the matrix. The bacteria-based self-healing mechanism is designed to counteract this weakness by restoring strength. The mixing process ensures that 16 capsules per kilogram of cement are evenly distributed throughout the mixture without damaging their structure.

In parallel, the IoT-based monitoring system continuously observes the healing performance. The system consists of an ESP32 microcontroller, acoustic sensor, and power module. The acoustic sensor detects sound variations or resonance changes caused by internal voids and sends signals to the ESP32. The ESP32 processes this data and uploads it to ThingSpeak, a cloud-based IoT platform. On ThingSpeak, real-time dashboards and graphical data visualization show the presence, size, and reduction of voids as the healing progresses.

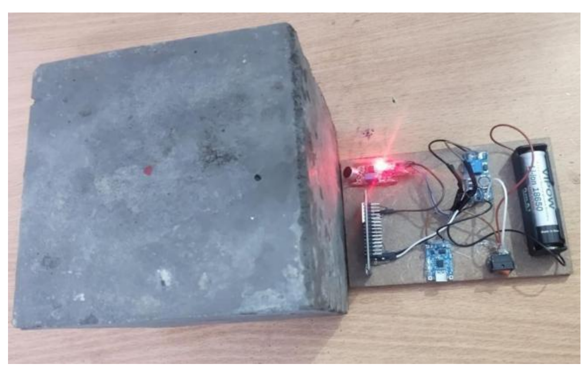

Figure 6.3 Prototype for Concrete Performance Monitoring

### 6.3 Sem Analysis

Scanning Electron Microscopy (SEM) is a powerful microstructural characterization technique used to examine the surface morphology, texture, and internal structure of concrete at microscopic levels ranging from micrometers to nanometers. This analysis provides valuable insights into the composition, hydration behavior, and overall performance of concrete materials. The primary purpose of SEM analysis in concrete is to investigate the microstructure of the cement paste, aggregates, and the interfacial transition zone (ITZ) between them. It helps identify cracks, voids, and micro-defects that contribute to reduced strength and durability. SEM also assists in identifying key hydration products such as Calcium Silicate Hydrate (C–S–H), Calcium Hydroxide (CH), and Ettringite, which govern the mechanical and durability properties of concrete. Moreover, it is used to evaluate the influence of various mineral admixtures such as fly ash, silica fume, and ground granulated blast-furnace slag on the microstructure, as well as to assess durability-related phenomena like sulfate attack, chloride ingress, or carbonation.

The sample preparation for SEM involves several steps to ensure accurate imaging. Small specimens, typically 10–15 mm in size, are carefully cut from the concrete sample. These are oven-dried to remove moisture that could interfere with the vacuum environment of the microscope. In some cases, the surface is polished to obtain a smooth imaging area. A thin conductive coating of gold, platinum, or carbon is then applied to prevent charge accumulation on the surface. Finally, the prepared samples are mounted on metallic stubs using carbon tape and placed inside the SEM chamber for imaging. SEM operates by focusing a beam of electrons on the sample surface. The interaction between the electron beam and the sample generates various signals such as secondary and backscattered electrons. Secondary electrons produce high-resolution images showing surface details, while backscattered electrons and X-rays provide compositional and elemental information.

Figure 6.4 SEM Analysis Sample

SEM offers several advantages, including high-resolution imaging, qualitative and quantitative analysis of hydration products, and the ability to combine with Energy Dispersive X-ray Spectroscopy (EDS) to obtain chemical composition data. It is widely applied in evaluating the performance of supplementary cementitious materials, studying durability under aggressive environments, conducting failure analysis of concrete structures, and researching nano-modified concretes such as those containing graphene or nano-silica. For example, SEM images of fly ash-blended concrete typically reveal a denser microstructure with fewer voids and smaller CH crystals compared to plain Ordinary Portland Cement (OPC) concrete, indicating improved strength and durability.

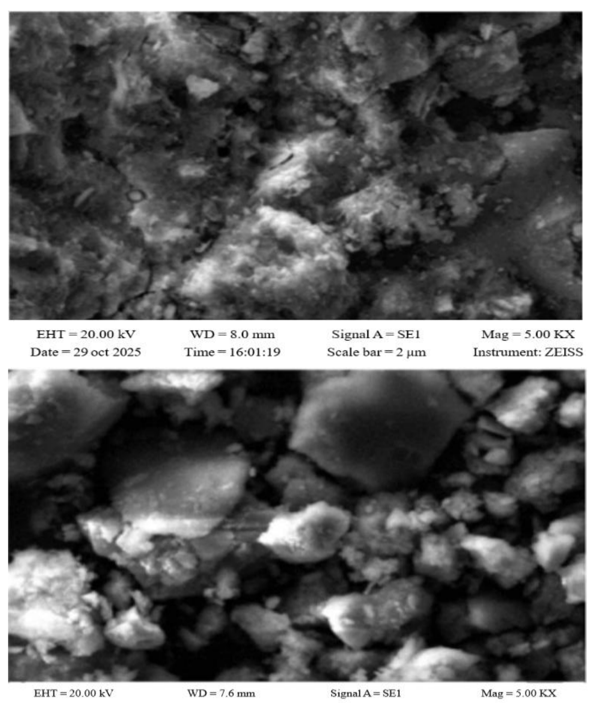


Figure 6.5 SEM of Bacteria Encapsulated Self-Healing Concrete

6.4 Experimental Setup

The experimental setup for the self-healing concrete project using Bacillus subtilis bacteria with IoT-based monitoring is designed to evaluate both the biological healing performance and the efficiency of void detection in M25 grade concrete. The experiment begins with the preparation of the bacterial self-healing agent, where Bacillus subtilis spores and their nutrient source, calcium lactate, are encapsulated within cellulose diacetate, a biodegradable polymer that ensures bacterial protection during mixing and gradual release during curing.

The capsules, each measuring approximately 4 mm in diameter and 8 mm in height, are mixed into fresh concrete at a dosage of 16 capsules per kilogram of cement. The concrete mix also includes a 4% replacement of fine aggregate (sand) with shredded plastic to promote sustainability and reduce the exploitation of natural resources. Although plastic replacement slightly reduces compressive strength, the self-healing mechanism is designed to offset this loss by precipitating calcium carbonate ($CaCO_3$) within microvoids and cracks formed during curing.

During the mixing process, the concrete ingredients cement, fine aggregate, coarse aggregate, water, and plastic replacement are combined thoroughly to achieve uniform consistency without damaging the encapsulated bacteria. After mixing, the concrete is cast into standard molds, ensuring proper compaction to eliminate air pockets. A few specimens are embedded with an IoT-based monitoring system consisting of an ESP32 microcontroller, an acoustic sensor, and a compact power supply. The acoustic sensor is positioned at the center of the specimen to monitor internal voids by detecting changes in sound wave propagation or resonance due to microcracks or air gaps. The ESP32 collects this data and transmits it wirelessly to the ThingSpeak cloud platform, where it is visualized in real time through graphical dashboards and analyzed to determine the presence and healing progression of internal voids.

After casting, the specimens are cured under standard laboratory conditions for a period of 28 days. During this time, the cellulose diacetate capsules degrade gradually due to the concrete’s alkaline environment and heat of hydration. When cracks or voids appear, moisture entering the concrete activates the dormant Bacillus subtilis spores, which consume the calcium lactate and produce calcium carbonate as a by-product. This mineral precipitate fills the cracks and voids, restoring the concrete’s density and structural strength. The IoT sensor continuously monitors the internal condition of the specimen and uploads data to the cloud, allowing researchers to observe the self-healing behavior remotely.

Finally, after the curing period, compressive strength and durability tests are conducted to compare the self-healing bacterial concrete with nominal concrete and plastic-replaced concrete without bacteria. The combination of biological self-healing and IoT-based monitoring demonstrates an innovative approach to sustainable construction, ensuring durability, crack resistance, and structural integrity while promoting smart evaluation of material performance through cloud-based analysis.

6.5 Objectives

The objective of this experiment is to develop and evaluate self-healing M25 grade concrete using Bacillus subtilis encapsulated in biodegradable cellulose diacetate. The project also examines the impact of replacing 4% sand with plastic aggregates to promote sustainability. Each kilogram of cement is mixed with 16 bacterial capsules containing calcium lactate as a nutrient source. The system integrates an ESP32 microcontroller with an acoustic sensor for IoT-based monitoring through ThingSpeak, enabling real-time analysis of internal voids and healing progress. Comparative tests are conducted to assess strength, permeability, and durability improvements over conventional concrete.

6.6 Materials and Quantities (General)

The experiment uses Ordinary Portland Cement, fine and coarse aggregates, and potable water for M25 grade concrete. Four percent of sand is replaced with plastic waste particles to enhance eco-friendliness. Self-healing is achieved using Bacillus subtilis and calcium lactate encapsulated in cellulose diacetate. IoT components include an ESP32 microcontroller, an acoustic sensor, and a power supply unit for data collection. Additional equipment like molds, curing tanks, and compression testing machines are employed for specimen preparation and analysis. All materials are measured precisely to maintain mix consistency and ensure accurate comparison between control and experimental concrete samples.

6.7 Capsule Preparation

The Bacillus subtilis spores and calcium lactate nutrient are combined and encapsulated within cellulose diacetate, forming capsules of approximately 4 mm diameter and 8 mm height. The capsules are dried to prevent premature rupture during mixing and checked for uniform size and integrity. A simple compression test ensures they withstand mixing stress. Capsules are stored in sterile containers before use to maintain bacterial viability. Each capsule acts as a micro-reactor, releasing bacteria only when cracks appear in the hardened concrete, ensuring precise activation timing during curing.

Figure 6.6 Capsules

Figure 6.7 Capsule Preparation

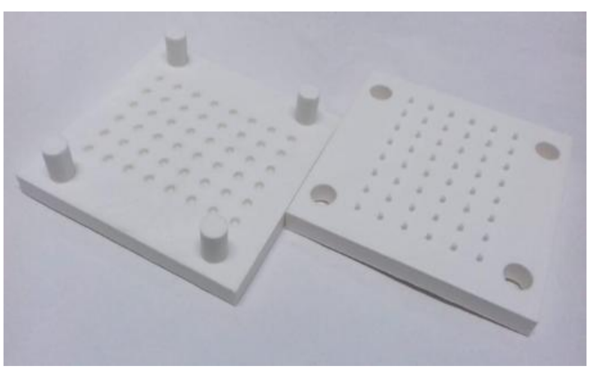

Figure 6.8 Mould for Capsule Preparation

6.8 Mix Design and Specimen Casting

The M25 grade mix is prepared by blending cement, aggregates, and 4% plastic replacement. The bacterial capsules are gently mixed into the wet concrete to prevent breakage. Water is added to achieve desired workability, and the mix is poured into molds for cube specimens. Selected cubes are embedded with acoustic sensors for IoT monitoring, while others are kept for mechanical testing. Proper compaction is ensured to eliminate air voids. The ESP32 and power module are positioned safely outside the mold to avoid damage during casting and curing.

Figure 6.9 Mix Design

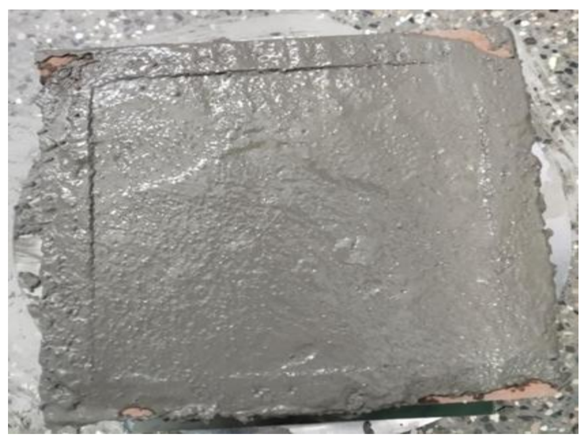

Figure 6.10 Specimen Casting

6.9 Curing

After 24 hours, the specimens are removed from molds and placed in curing tanks at 20±2°C. During 28 days of curing, the cellulose diacetate capsules degrade due to the alkaline environment and hydration heat, releasing Bacillus subtilis. Upon contact with moisture, the bacteria consume calcium lactate and produce calcium carbonate, sealing microcracks. This biological reaction restores concrete integrity and enhances durability. Curing conditions are monitored to maintain consistent bacterial activation, ensuring effective and uniform self-healing across all specimens.

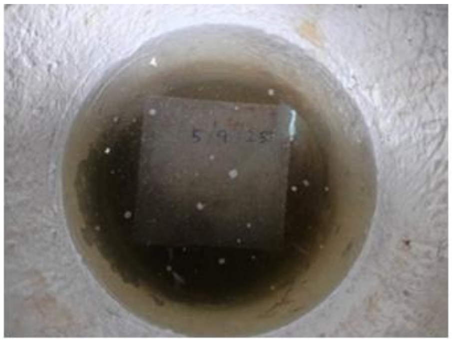

Figure 6.11 Curing

6.10 IoT Setup and Calibration

The ESP32 microcontroller is programmed using the Arduino IDE to process acoustic data. The sensor is calibrated with standard concrete samples to identify baseline frequency signals for defect detection. Filtered data are wirelessly transmitted to the ThingSpeak cloud for real-time visualization and storage. Each device uses a unique API key for secure data transfer. The setup helps detect internal voids and monitor bacterial healing by analyzing variations in sound propagation over time. Calibration ensures accuracy and sensitivity in detecting voids or cracks within the concrete specimens.

6.11 Monitoring Protocol

Monitoring begins after curing starts, with the IoT system recording acoustic data periodically. During the first four weeks, readings are taken frequently to capture capsule degradation and bacterial activation. The ThingSpeak platform visualizes sound variations that correspond to crack formation and healing. Environmental factors such as temperature and humidity are also tracked. Data trends help confirm when self-healing begins and assess its progress. The continuous monitoring process provides a non-destructive and reliable way to observe internal changes in the concrete structure remotely.

6.12 Mechanical and Durability Testing

After curing, concrete cubes are tested for compressive strength at 7, 28, and 56 days using a compression testing machine. Water absorption and permeability tests assess durability and resistance to crack propagation. SEM and XRD analyses confirm calcium carbonate precipitation within healed cracks. Data from IoT monitoring are correlated with laboratory test results to verify healing behavior. Comparisons between control and self-healing samples show that bacterial concrete restores compressive strength and improves overall durability while compensating for strength loss due to plastic replacement.

6.12 Controls and Statistical Analysis

Three control batches are prepared: normal M25 concrete, plastic-replaced concrete without bacteria, and concrete with capsules but no plastic. Each group includes three replicates to ensure data consistency. Statistical tools like mean, standard deviation, and ANOVA are applied to evaluate performance variations. These comparisons help determine the effects of bacterial self-healing and plastic inclusion on mechanical and durability characteristics. Consistent documentation of batch data, curing conditions, and test results ensures the experiment's reliability and reproducibility.

6.13 Safety and Documentation

All work with Bacillus subtilis is conducted under sterile conditions using gloves, masks, and lab coats. Encapsulation and mixing processes are handled carefully to prevent contamination or bacterial loss. Waste materials are sterilized and disposed of properly. Detailed records of mix proportions, capsule preparation, IoT calibration, and test results are maintained throughout the experiment. Photographs, wiring diagrams, and ThingSpeak dashboards are archived for reporting. These safety and documentation practices ensure experimental transparency, biosafety compliance, and reliable project results.

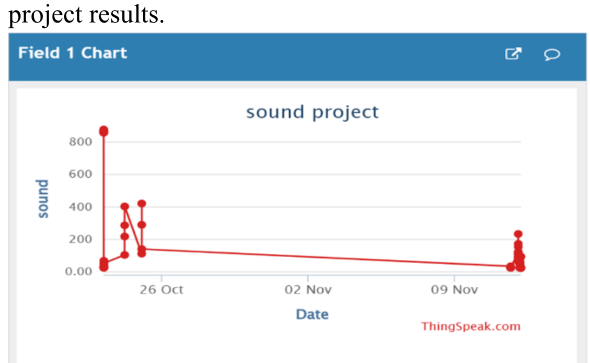


Figure 6.12 Output for Smart Concrete Incorporating Plastic Waste with Iot Based Performance Monitoring

## VII. CONCLUSION

The experimental study successfully demonstrated that incorporating Bacillus subtilis bacteria encapsulated in cellulose diacetate capsules can effectively enhance the self-healing properties of M25 grade concrete. The biodegradable cellulose diacetate served as a reliable carrier that delayed the release of bacteria until the optimal curing period, ensuring bacterial viability and timely activation. When microcracks or voids developed, the released bacteria metabolized calcium lactate to produce calcium carbonate, which filled and sealed the cracks, restoring the structural integrity of the concrete. This biological healing process compensated for the minor strength reduction caused by replacing 4% of fine aggregate with plastic, thereby promoting sustainability without compromising strength.

Mechanical tests showed that the compressive strength of self-healing concrete was nearly equivalent to or slightly higher than that of normal M25 concrete after 56 days, while durability tests confirmed reduced water absorption and permeability. The integration of an IoT-based monitoring system, consisting of an ESP32 microcontroller and acoustic sensor, enabled real-time, non-destructive observation of void formation and healing progress. The data transmitted to the ThingSpeak cloud platform provided clear visualization of internal structural changes, correlating well with physical test results.

Overall, this project highlights the successful convergence of biotechnology and smart sensing systems to produce sustainable, durable, and intelligent construction materials. The self-healing concrete not only enhances longevity but also reduces maintenance costs and environmental impact. Future research may focus on optimizing capsule size, bacterial concentration, and advanced IoT analytics for large-scale field applications.


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