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Self-Healing Concrete

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Abstract: Crack formation is very common phenomenon in concrete structure which allows the water and different type of chemical into the concrete through the cracks and decreases their durability, strength and which also affect the reinforcement when it comes in contact with water, CO2 and other chemicals. Cracks in concrete structures can significantly decrease their lifespan by exposing reinforcement to outside environment, leading to concrete degradation. To address this issue, self-healing techniques have been developed, including Biomineralization-based-self healing, where bacteria are employed to initiate Microbially Induced Calcium Precipitate (MICP), promoting the healing of cracks. Moreover, there exists a direct correlation between bacterial cell concentration and alterations in the mechanical properties of concrete. The incorporation of bacteria in concrete leads to increment in strength properties, with strength enhancement of up to 42.8 %. The selection of the bacteria was according to their survival in the alkaline environment such as Bacillus subtilis and B. lichenformis which are mainly used for the experiments by different researchers for their study. Cement and concrete matrices reinforced with randomly oriented short fibers are finding increasing applications in both precast and in situ concrete construction. In this process, fibers are incorporated to regulate crack width, ensuring an optimal environment for bacterial activity. By limiting crack expansion, the effectiveness of bacteria in the self-healing mechanism is enhanced, leading to improved durability and performance of the material.

Keywords: Self-healing, Biomineralization, Microbially Induced Calcium Precipitate (MICP), Bacterial cell concentration, Bacillus subtilis, B. lichenformis

I. INTRODUCTION

In the current era of continuous urbanization, concrete stands out as an exceptionally versatile and valuable product. Typical concrete structures can succeed a time period of 50 years or even longer, they are susceptible to issues such as settlement, thermal cracking, corrosion cracking, premature drying and other conditions. These cracks may form a continuous network, which results in increased permeability of concrete. The severity of cracks can differ from one structure to another. In case of reinforced concrete structures, the size of permissible cracks is mostly maintained through reinforcement. In general, the acceptable crack width is 0.3 mm. Though these cracks do not impact the structural integrity, they reduce the concrete's durability, allowing moisture and chemical to corrode steel reinforcement, leading to failure of structures.[1] As a result of undesirable occurrences such as shrinkage, external loads, and thermal deformation, the development of cracks in cementitious materials is a key aspect in reducing the functional integrity of the structure and, therefore, its lifespan and durability. Particularly when toxic gases and liquids (e.g., sulfide, chloride) may enter the matrix through these fissures, the cracks pose a threat to the structural integrity of the concrete. Consequently, fractures may expand, and reinforcement may begin to touch the environment. When reinforcement begins to corrode, this condition might lead to the entire collapse of a building. To increase the lifetime of concrete buildings, it is evident that crack treatment must be accompanied by thorough inspection and maintenance. A structure's collapse might result from larger fissures caused by inappropriate structural design, inferior materials, stress, and inadequate structure maintenance. However, fixing cracks remains tough when their specific positions are impossible to pinpoint.[2]

In addition, it is predicted that the cost of repairs will account for half of the annual building budget. Every year, a considerable global budget is set aside for the restoration of current concrete structures. In contrast, while the production expenses of concrete vary between \$60 and \$80/m3, the costs related to maintenance and repairs escalate to a substantial \$147/m3. Traditional crack repair methods using synthetic repair agents like resin and epoxy are limited, facing issues of short-term effectiveness, environmental issue, high cost, time-consuming process, and require professional supervision. Also, such agents are able to repair an external fracture but not internal damage or micro-cracks. In some construction projects, 20 % of the repair deteriorates within duration of 5 years, and 55 % deteriorates within 10 years; thus, this is not considered a sustainable solution. Besides, construction industry contributes to carbon footprint, through aggregate extraction and cement production. Construction waste, constituting 59 % of the world's total waste, with 40 % ending up in landfills. However, strict environmental protection laws have reduced landfill usage to 65 %, prompting researchers to address disposal issue and conserve natural resources.

Traditional concrete remediation is time-consuming, and environmentally damaging. Sustainable alternatives like bacterial concrete, continuously retrofitting and improving concrete durability, are gaining attention. Applying calcite precipitation through bacteria to concrete before the cracks appear could be both resource and budget saving. Bacteria-based self-healing reduces maintenance costs, extends service life of concrete structures. Furthermore, the production of self-healing system can lower resource requirements for concrete fabrication and reduce demolition waste by increasing the life span of existing structures. Increasing the life time of the structure indirectly contributes to lower carbon emissions by decreasing the demand for construction materials.

Addressing traditional crack maintenance limitations calls for exploring more cost-effective and environ-mentally friendly repair techniques. This has led to a transition from conventional methods to advanced concrete self-healing, promising to mitigate these challenges effectively. The self-healing process, being biological in nature, can be influenced by various biotic and abiotic factors. Key biological factors include the number, age, and physiological state of bacterial cells, dependent on environmental conditions like temperature and pH, which affect bacterial growth. Except for the spore-forming bacteria, most bacteria require proper pH and temperature for survival. In environmental conditions with higher pH (>12), bacteria can only survive in a spore form without reproducing. However, has primarily focused on conventional bacterial culturing, overlooking factors that could influence bacterial growth, viability and the rate of microbial calcium carbonate precipitation. Therefore, further understanding is needed to fully comprehend how pH and temperature factors impact bacterial survival and effectiveness. In addition to environmental factors, protecting micro-organisms in concrete to address their short survival time involves various implementation approaches. Improving the self-healing bacteria's efficiency presents a notable challenge, with two plausible approaches: direct inclusion or encapsulation. Encapsulation, especially due to the alkaline nature and temperature of concrete, has proven more effective. However, high pH levels above 12 can diminish bacterial effectiveness and concrete hydration process might lead to a decline in bacterial cell count.[1]

The concept behind FRC is that the deformation of the matrix under stress will transfer the load to the fibers. Low-modulus fibers such as nylon and polypropylene may not lead to significant improvement in composite strength, but they do help absorb huge amounts of energy and resist impact and shock loading. How much high-modulus steel and other fibers can strengthen composites depends on the strength characteristics of the fibers themselves, the bond in the matrix-fiber interface, the ductility of fibers, the volume of fiber reinforcement and its spacing, the dispersion of orientation of fibers, and their shapes and aspect ratios. High-strength fibers, a large volume of fibers, longer fibers, and small-diameter fibers each improve the strength of the composites.[3]

Strains of the bacteria genus Bacillus will be found to succeed in high alkaline environment. The bacteria survive in the high alkaline environment that formed spores comparable to the plant seeds. The spores are of very thick wall and they activated when concrete start cracking and water transude into the structure. The pH of the highly alkaline concrete lowers to the values in the range 10 to 11.5 where the bacterial spores become activated.[4]

II. TECHNICAL ASPECTS

Self-healing of concrete is a phenomenon where in the material replenishes itself to heal internal cracks using a variety of techniques.

A. Autogenous healing

In conventional concrete almost 20–30 % of cement particles remain unhydrated. If cracks are produced in concrete, unhydrated particles react with external water. This reaction initiates the process of hydration and fills cracks with hydration materials. This inherited process of self-healing is called as autogenous healing. Some of the major factors that affect autogenous healing include.

1) Concrete composition and age
2) Presence of water
3) Size and shape of crack

Furthermore, the healing process of concrete is greatly influenced by its age. The presence of unhydrated bonding particles necessary for the formation of new calcium-silicate-hydrate (CSH) gel is greater in freshly made concrete. Autogenous healing of concrete takes place in different ways.

a) By precipitation of Ca (OH)2 or CaCO3, which blocks the crack
b) By hydration of unhydrated cement grains
c) Blockage of cracks due to the impurities present in water
d) New calcium-silicate-hydrate (CSH) gel formation
e) Carbonation with NaCO3
f) Additional cementitious materials like fly ash, blast furnace slag.
g) Anhydrites and Na2SO4

B. Autonoumus Healing

Autonomous concrete repair represents an artificial method of repairing concrete, attainable through chemical and biological processes. Chemical healing is done by concrete mixing with the chemical reagent (liquid) such as fibers,crystalline admixtures and polymers. Meanwhile, biological healing involves the integration of microorganisms within the concrete matrix as a self-healing mechanism.

1) Chemical Process

Crystalline admixtures. Crystalline admixtures including silica based crystalline admixtures, calcium-based crystalline admixtures and alumina-based crystalline admixtures are commercial admixtures that can react with moisture content present in newly mixed concrete and the by-products generated during cement hydration. This interaction leads to the formation of insoluble crystals that facilitate the healing of cracks. These crystals, utilized in employed in commercial applications, consist of chemical constituents found in sand and cement, such as silica, calcium, and alumina. Exhibiting water-reactive and hydrophilic properties, these crystalline admixtures contribute to an augmented density of CSH, creating a barrier layer at the surface that renders the material impervious to water penetration.

Synthetic fibers. There are two distinct categories of fibers: natural and man-made. Natural fibers are obtained from a variety of sources such as plants, animals, wool, and wood. In contrast, synthetic fibers like polyester, polypropylene, polyethylene, asbestos fiber, ethylene vinyl alcohol, polyvinyl alcohol, etc. are produced in industries. These fibers decrease the permeability of concrete and prevent water from penetrating through the pores. There has been extensive research on the application of fibers as healing agents in concrete, including polyvinyl alcohol, ethylene-vinyl alcohol, polyacetal, and polypropylene. The findings indicate that fiber composites with high polarity exhibit a greater propensity for the precipitation of $CaCO_3$ in crack widths up to 0.3 mm, leading to a reduction in water permeability. Effects of integrating various fibres into the concrete mix to enhance healing efficacy and revealed an impressive ability for self-repair, effectively addressing cracks as wide as 500 μm. Introduction of cellulose fibre decreased the water permeability coefficient by 42 % whereas the healing ratio increased at higher rate for initial days and a 7.84 % increase in flexural strength was found compared to conventional concrete.

2) Bacteria Based self healing

Bacteria-based healing is an efficient technique for crack healing. Depending on the bacterial strain, the increased pH levels present in concrete can render the bacteria dormant for up to 200 years. Injecting bacteria into cracks within concrete results in the production of a layer of calcium carbonate, and subsequently healing of the cracks. Ureolytic bacteria are considered more effective in healing cracks than non-ureolytic bacteria as they do not survive at high pH. Ureolytic bacteria such as S. pasteurii, B. subtilis, B. sphaericus,B. megaterium can heal cracks up to 0.85–0.97 mm, while non-ureolytic bacteria such as B. halodurans, B. licheniformis, B. thuringiensis heal crack up to 0.45 mm and recover only 65 % of strength. Bacteria can heal cracks of larger width more efficiently than autogenous healing[1]. Bacteria make long-lasting healing possible, and this process is known as microbiologically induced calcium carbonate precipitation (MICP). MICP acts as a binder, filling cracks and binding the concrete constituents. Bio-mineralization is the basic mechanism of incorporating bacteria in concrete using different processes to produce $CaCO_3$. Generally, biomineralization can be divided into two significant processes: heterotrophic and autotrophic. Heterotrophic processes precipitate more $CaCO_3$ than autotrophic ones.[4]

The bacterial activity within concrete can be influenced by a number of factors, which can impact their development, growth, replication and spore creation (sporulation). Factors such as pH variations, oxygen levels, mineral concentration temperature changes play a role in sporulation. However, the density of populations and nutrient scarcity have significant influence. When conditions become unfavorable for growth, they enter a mode where genetic material is preserved until favorable conditions return. This reduction in metabolic activities allows bacterial spores to withstand conditions like heat/cycles, chemicals exposure, dry/wet cycles and radiation. Consequently, bacteria can survive for longer periods, under extreme circumstances.Under favorable conditions cement-based materials can heal themselves, known as autogenous healing. This process occurs when there is water and the cracks are small up to 100 μm, in width. However, for cracks this natural healing may not be effective. On the other hand, microbial self-healing has demonstrated its effectiveness in repairing cracks of larger widths, reaching up to 1 mm. To fully understand how bacteria based self-healing works in concrete, it is importantto examine the mechanism. The mechanism in which bacteria actively produce calcium carbonate, an element that significantly contributes to the healing process, is detailed in the following section-3.[1]

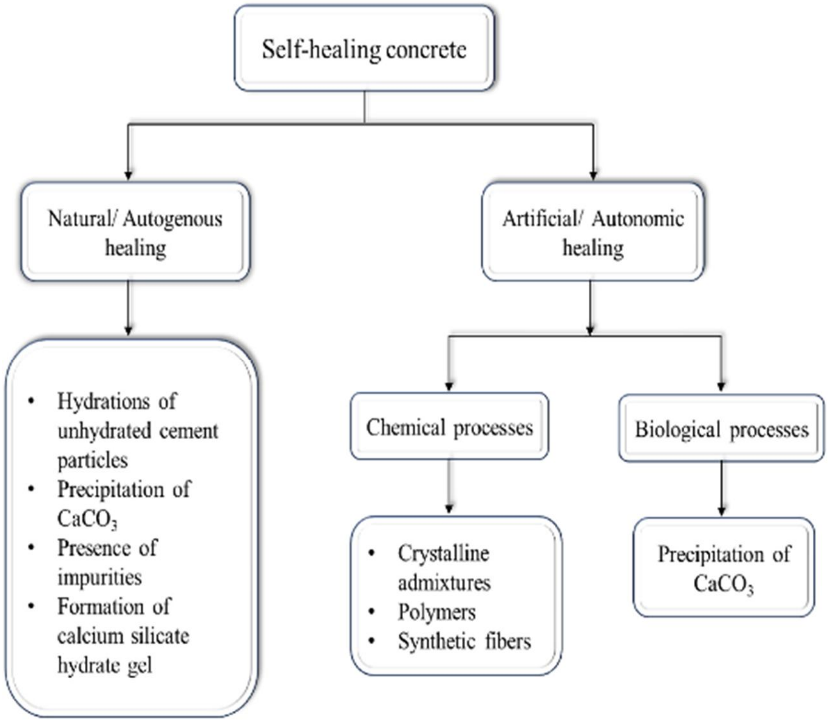


Fig No. 1: Classification of Self Healing Techniques

III. MECHANISM OF SELF HEALING CONCRETE

Bacteria-based self-healing concrete works by filling cracks with Microbial Induced Carbonate Precipitate (MICP). When the cracks are formed, bacteria become activated from dormant stage and begin the self-healing process due to water ingression. As soon as the crack is formed in concrete, the bacteria are activated and produce calcium carbonate to seal the crack. Once the crack has been repaired, the bacteria return to dormant condition until the next crack is produced and environmental conditions are favorable. For most self-healing processes, the mechanism studied for calcium carbonate precipitation is the urea decomposition by bacteria. Bacterial species produce urease as a component of metabolism which catalyzes urea to ammonium and carbamic acid (Eq. (1)), increasing carbonate concentrations and pH. In equation (2) and (1) mol of bicarbonate and 2 mol of ammonia are formed when carbamic acid reacts with water. These two products [H2CO3 and NH3] are further equilibrated in water to form bicarbonate (Eq. (3)). Ammonia produces ammonium and hydroxide ions, whereas carbonic acid produces bicarbonate ions (Eq. (4)). Further ammonia is converted to ammonium ion and OH (Eq. (5)). Hydroxide ion increases pH, resulting in a change in bicarbonate equilibrium and the formation of carbonate ions in (Eq.(6)).

$CO\,(NH_2)_2 + H_2O \xrightarrow{urease} NH_2COOH + NH_3$ (1)

$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$ (2)

$H_2CO_3 \leftrightarrow HCO^{3-} + H^+$ (3)

$HCO^3 \leftrightarrow (CO_3)^{2-} + H^+$ (4)

$2NH_3 + 2H_2O \rightarrow 2NH^{4+} + 2OH^-$ (5)

$CO\,(NH2)_2 + 2H_2O \rightarrow (CO_3)^2 + 2NH^{4+}$ (6)

An increase in H^+ and OH^- ion increases in pH, resulting in the reaction shifting to the right because of the law of mass action. Carbonate ions, [CO_3^{2-}], then react with calcium cations, [Ca^{2+}], which are present in the concrete mix, and are driven to the negatively charged bacterium walls, as represented in equation (7). In equation (8), the bacterial wall draws Ca^{2+} ions and reacts with CO32− ions to create calcium carbonate ($CaCO_3$) precipitation which fill the gaps in concrete. The more lime particles are produced, the higher the ability for self healing. Calcium carbonate precipitation occurs as a result of successive stratification.

$Ca^{2+} + Cell \rightarrow cell - Ca^{2+}$ (7)

$Cell - Ca^{2+} + CO_3^{2-} \rightarrow cell – CaCO^3$ (8)

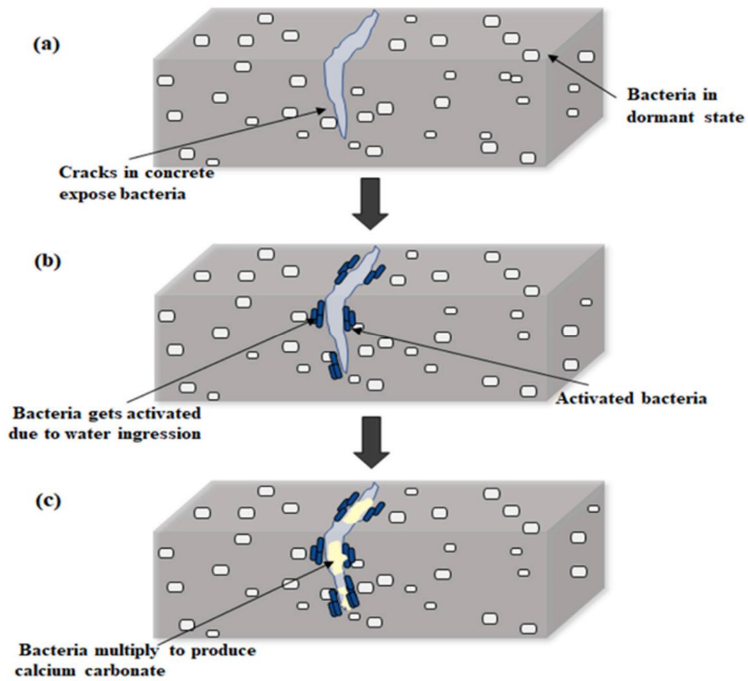


Fig No. 2: Precipitation of calcium carbonate by bacteria

IV. SPECIMEN'S SPECIFICATION

The specimen is a bacterial-induced reinforced concrete beam. Four beams have been casted.

A. Common Features

1) Size

- Cross-sectional size: 100 mm x 100 mm
- Length: 500 mm

Fig No. 3: Size of the Specimen

2) Reinforcement

The specimen is a reinforced concrete beam that uses fiber-reinforced nylon for reinforcement. The nylon reinforcement has a density of 0.9 per kg.

3) Calcium Source

To enhance the bioactivity in the concrete, 5% of the total cement mass was replaced with calcium lactate. This addition serves as a calcium source for the bacteria used in self-healing concrete applications, which aims to improve the durability of the beams by promoting calcium carbonate precipitation when cracks develop.

B. Distinct Feature

1) Specimen 1

The first specimen contains Bacillus subtilis bacteria at a concentration of 10^5 CFU/mL (colony-forming units per milliliter).

2) Specimen 2

The first specimen contains Bacillus licheniformis bacteria at a concentration of 10^5 CFU/mL (colony-forming units per milliliter).

Note: The above 2 bacteria were introduced without encapsulation, allowing them to interact directly with the surrounding concrete matrix. The absence of encapsulation means the bacteria are not protected, which could influence their survival and bioactivity under the given conditions.

Specimen 3 and 4 are based on the same bacterial concentration and type as Specimens 1 and 2, respectively. The key difference between them lies in the encapsulation of the bacteria, which may influence their survival and effectiveness in the concrete matrix. For encapsulation Sodium Alginate is mixed with bacterial solution at concentration of 2%.

V. METHODOLOGY

Experimental Procedure for Self-Healing Concrete

A. Preparation of Materials

1) Prepare a mould of size 100 × 100 × 500 mm.
2) Measure and prepare the required quantities of cement, aggregates, water, nylon fibers, bacterial solution, and calcium lactate as per the mix design.
3) 10 to 15 minutes before mixing, introduce the required bacteria into normal water to prepare the bacterial solution.

B. Mixing and Casting (Layer-wise addition of materials)

1) Step 1: Fill 1/3rd of the mould with concrete.
2) Add 1/3rd of the total required nylon fibers and 1/3rd of calcium lactate.
3) Add 1/3rd of the total required bacterial solution (substituting an equal amount of water).
4) Step 2: Fill the next 1/3rd of the mould, repeating the process:
5) Add another 1/3rd of the nylon fibers, calcium lactate, and bacterial solution.
6) Step 3: Fill the final 1/3rd of the mould with concrete.
7) Incorporate the remaining nylon fibers, calcium lactate, and bacterial solution.

C. Adjustments in Mix Design

1) The volume of bacterial solution added should replace an equal amount of water in the concrete mix.
2) The cement content should be reduced to balance the addition of nylon fibers.
3) The cement content should be reduced to balance the addition of Calcium lactate.

D. Setting and Crack Generation

1) Allow the concrete to set for 24 hours in the mould.
2) After setting, perform flexural loading (three-point or four-point loading method) to induce controlled cracks.

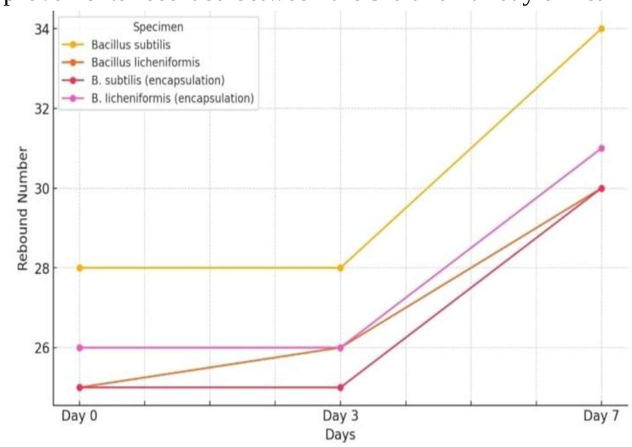
E. Testing and Analysis

1) Perform initial mechanical tests after crack generation.
2) Continue testing the same specimen after 7, 14, and 28 days to evaluate strength recovery.
3) Visually inspect the cracks to assess self-healing effectiveness over time.

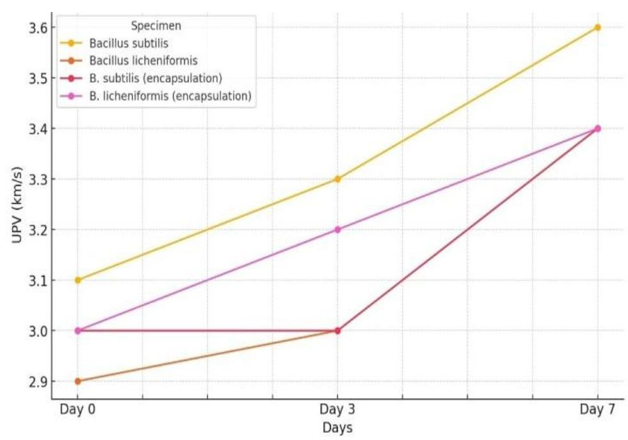
VI. RESULTS

The observed results reflect the biological response time of bacteria and their interaction with the concrete matrix. Initially, after crack induction, the bacterial spores remain in a dormant state, leading to minimal recovery or change in mechanical properties within the first few days. This lag phase is due to the time required for the bacteria to become metabolically active after exposure to moisture and oxygen within the cracks. As the days progress, the bacteria begin to metabolize the calcium lactate and initiate the biomineralization process through Microbial Induced Calcium Carbonate Precipitation (MICP). This leads to gradual deposition of calcium carbonate, effectively sealing the cracks and improving the structural integrity. Nylon fibers played a supportive role by controlling the crack width, providing the bacteria sufficient time and space to act efficiently.

The encapsulated bacteria showed more consistent performance over time, indicating that the sodium alginate layer provided additional protection against harsh alkaline conditions during hydration, thus improving bacterial viability and healing efficiency. The rebound number and UPV test results confirm this trend, showing a progressive increase in surface hardness and internal density, respectively, with higher improvements recorded between the 3rd and 7th day of healing.



Graph No. 1: Rebound values over Time



Graph No. 2: Ultra Sonic Pulse Velocity (UPV) over Time

The experimental evaluation showed a consistent increase in compressive strength across all bacterial combinations between Day 0 and Day 7. The highest percentage increase, was observed in the Bacillus subtilis specimen with a gain of approximately 9.78%, followed closely by the encapsulated Bacillus licheniformis specimen with an 8.43% increase.

VII. BENEFITS

Self healing concrete offers numerous advantages over traditional concrete, including enhanced durability through autonomous crack repair, which extends the lifespan of structures and reduces maintenance needs. By sealing cracks, it protects steel reinforcements from corrosion, thereby preserving structural integrity. The reduced necessity for repairs and reconstructions contributes to a lower carbon footprint, aligning with sustainable construction practices. Additionally, the incorporation of bacteria that precipitate calcium carbonate crystals not only repairs cracks but also improves the flexural strength of the concrete. The use of nutrients like calcium lactate, calcium nitrate, and urea further enhances this process, leading to more resilient and long-lasting infrastructure. The elasticity of self-healing cement composites can be increased making them more resistant to fractures and better able to withstand mechanical stresses from natural disasters and extreme weather conditions. By autonomously repairing cracks, self-healing concrete can significantly extend the lifespan of structures, reducing the frequency of repairs and reconstructions. The ability to self-seal and heal cracks enhances the overall durability of concrete structures, making them more resistant to environmental factors and reducing the likelihood of structural failures.

VIII. CONCLUSION

The development and evaluation of self-healing concrete using bacterial strains such as Bacillus subtilis and Bacillus licheniformis demonstrate a promising shift in the construction industry toward smarter and more sustainable materials. Through the process of Microbial Induced Calcium Carbonate Precipitation (MICP), cracks in the concrete matrix can be autonomously sealed, thereby improving the material's durability, strength, and service life. The use of calcium lactate as a nutrient and sodium alginate for encapsulation proved effective in enhancing bacterial viability and healing performance, especially under the high pH conditions of concrete. The experimental results confirmed that crack healing efficiency increased significantly between the 3rd and 7th day after bacterial activation. The integration of nylon fibers further supported this healing mechanism by controlling crack width and giving bacteria sufficient time to act. Overall, this study reinforces the potential of bacterial self-healing concrete as a sustainable and cost-effective solution for reducing long-term maintenance and increasing the lifespan of concrete structures. Continued research and optimization can further pave the way for its practical implementation in infrastructure projects worldwide.

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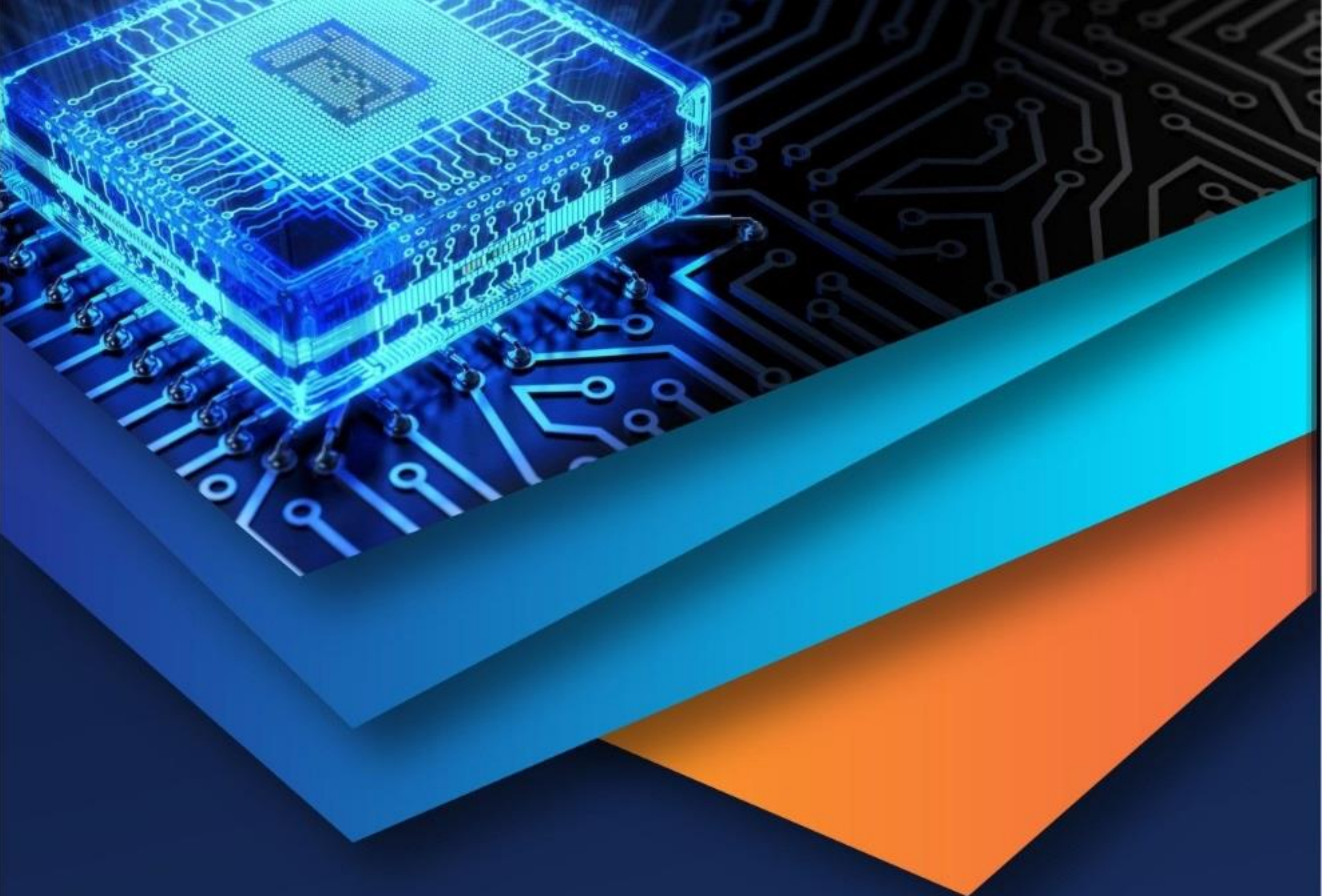

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