A Novel Approach to Crack Repair: Self-Healing Concrete Using Bacteria

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Abstract - *It is a new material self-healing concrete specially created to autonomously mend cracks and damage in the present (and future) which could extend the service life of reinforced, lasting longer in-service or requiring less maintenance. This review highlights the extensive investigation being conducted on self-healing concrete while emphasizing various mechanisms and presenting different types of material along with coverage strategies such as Encapsulation, Bacterial Subtilis & Pseudo Bacillus. Highlighted in this paper that bacteria, encapsulated healing agents and shape memory materials are the main routes for researchers in the field of self-healing. Also, the effectiveness of these methods under different environmental conditions and their effects on mechanical properties like Durability, Compressive Strength & Tensile strength etc. are studied. The review also highlights the bottlenecks in upscaling Bio-concrete technology to field applications and suggests directions for future research. The paper will present an overview of the field and summarize recent advances that can pave the way for self-healing concrete to revolutionize sustainable construction practices.*

Key Words: Self-healing Concrete, Encapsulation, Bacillus Subtilis, Pseudo Bacillus, Bacillus Sphaericus, Bio-concrete, Durability, Sustainability.

1. INTRODUCTION

Self-healing concrete is a game changer in the construction industry — it heals its cracks and damage all by itself! The new technology is expected to considerably prolong the life span of concrete structures while reducing their maintenance expenditures. One of the most promising self-healing solutions for years has been adding bacteria to concrete mixtures.

1.1 Significance of Self-healing Concrete

Cracking in concrete structures leads to a common problem of deterioration and the condition is most commonly experienced during construction. Self-healing concrete proposes a solution to this issue, uniting autonomous repair mechanisms into the building material which can reactivate and restore functionality in case of damage without external intervention. This technology can change the way we design and construct for a sustainable construction future while driving infrastructure durability.

1.2 Bacterial Mechanisms in Self-healing Concrete

In concrete, the unique capacity of bacteria as agents to self-heal is largely determined by its unsaturated pores circuitry. The metabolic activity of some bacterial species, like Bacillus subtilis and Pseudomonas aeruginosa allows them to produce calcium carbonate. In another process known as biomineralization, the bacteria produce calcium carbonate (limestone) within and beneath concrete structures which restores their structural integrity.

1.3 Types of Bacteria

1. **Sporosarcina pasteurii :** Spore-forming bacteria such as Sporosarcina pasteurii are widely used in self-healing concrete. With several advantages over other bacteria used in this application.

   High calcium carbonate production efficiency : S. pasteurii is very Efficient in producing calcium carbonate which is one of the key elements to fill cracks and restore the structural integrity of concrete.

   Durability: It is a robust bacterium that endures in the alkaline and nutrient-poor conditions of concrete.

   Environmental Friendliness : S. Bacillus licheniformis strain pasteurii is a non-pathogenic bacterium so it can be safely used in construction applications.

   Mechanism of S. pasteurii in self-healing concrete:
   Encapsulation: To protect the bacteria from being crushed during concrete mixing, they are encapsulated in microcapsules or other carriers.

   Crack formation: When a crack appears in the concrete, the capsule's burst open and release the bacteria. The calcium carbonate is produced by the bacteria metabolizing nutrients drawn from the concrete-a process known as microbiologically induced calcium carbonate precipitation (MICP).

2. **Bacillus sphaericus:** Bacillus sphaericus is a very effective little type of bacteria and has been used for a

long time for self-healing concrete. it is a spore-forming bacterium which is naturally resistant to extreme environments like that of concrete. As cracks appear in concrete, spores of Bacillus sphaericus germinate, and the bacteria begin to secret calcium carbonate. This calcium carbonate fills any cracks and heals the damage, restoring the structure strength of the concrete. **Bacillus sphaericus** has multiple advantages over the other bacteria used in self-healing concrete. Such As a more robust nature to PH that exists in cement. It is also better at making calcium carbonate so can Fill cracks faster. Bacillus sphaericus is a promising novel technology to significantly durable the concrete structural systems.

3. **(E-coli) Bacteria:** Self-healing concrete has been researched using Escherichia coli (E-coli) bacteria. E-coli in the presence of water can also trigger the crystallization of calcium carbonate which is capable of filling in cracks in concrete. On the other hand, E-coli is rarely considered for practical use of self-healing concrete due to its pathogenicity and the environmental conditions required for it to flourish.

1.4 Scope of the Review

This review discusses the development status of bacterial-based self-healing concretes through research. It focuses on the different manner, and components that have been used for self-healing and how it is prepared. Self-healing strategies are mainly classified as those that incorporate bacteria, encapsulated healing agents and shape memory materials in this work.

1.5 Objectives of the Review

The primary aims of this review include:

1. For preparing a state-of-the-art review on bacterially mediated self-repairing mechanisms of concrete.
2. The relative importance of bacterial strains and their encapsulation with respect to efficacy.
3. The self-healing effect via bacterial activity towards properties of concrete such as durability, compressive strength and tensile strength.
4. Some underlying issues in the commercialization of bio-concrete technology.
5. Some possible trends and needs related to research and development in terms of self-healing concrete.

This review is intended to add to the knowledge of the new technology and how it is useful in self-healing concrete construction in a sustainable manner by reviewing recent development in the field.

2. REVIEW OF LITERATURE

- **Ramakrishnan et al., (2024)** Bacillus subtilis and Bacillus megaterium are commonly used bacteria that facilitate carbonate precipitation, effectively sealing cracks. Self-healing concrete reduces maintenance costs and environmental impact associated with traditional repair methods

- **Vettrivelou et al., (2024)** The presence of bacteria can improve compressive strength, split tensile strength, and flexural strength of concrete mixes.

- **Luo et al., (2024)** Studies show that bacteria-based self-healing concrete can achieve a crack width repair ratio of up to 94.5% after 56 days. The use of bio mineralization modified recycled aggregates enhances bacterial protection, further improving self-healing efficiency.

- **Durga et al., (2024)** Research indicates that varying doses of bacterial solutions can significantly affect the durability and healing efficiency of concrete.

- **Rajadesingu et al., (2024)** Bacteria like Bacillus pasteurii and Bacillus megaterium facilitate the precipitation of calcium carbonate, effectively filling cracks as small as 0.05 mm.

- **Wong et al., (2024)** The efficacy of self-healing is influenced by pH, temperature, and moisture levels, which affect bacterial activity and healing efficiency. Ensuring the viability of bacteria over time remains a challenge for large-scale applications.

- **Dutta et al., (2024)** Utilizes Bacillus subtilis bacteria to precipitate calcite, effectively healing cracks. Achieves significant strength improvements: 13.2% in compressive strength and 21.4% in split tensile strength.

- **Lima et al., (2024)** The Ratio of cement to sand and the type of encapsulation method can significantly impact the self-healing efficiency and mechanical properties of the concrete. Water presence is crucial for optimal healing efficiency.

- **Hanna, (2024)** Self-Healing concrete has shown promise in various construction project, demonstrating its feasibility in real-world scenarios.

- **Zhang et al. (2024)** Future studies should focus on optimizing healing mechanisms and addressing cost implications for widespread adoption.

3. SELF-HEALING MECHANISM

A. **Autogenous Healing -Mechanism :** Natural healing of microcracks by the chemical reactions between the water and unhydrated cement particles present in the concrete mix.

Process: When a crack forms, water penetrates into the crack, reacting with the remaining unhydrated cement particles, leading to the formation of calcium carbonate that seals the crack.

B. **Healing with An Encapsulation-Centric Approach**

Mechanism : Healing agents (bacteria, polymer capsules or crystalline compounds) are encapsulated in the concrete matrix and upon cracking, these are released & activated to heal.

Types of Encapsulations :

1. Polymer-based Capsules : Healing agents (e.g., epoxy, polyurethane) are released when the capsules break due to cracking.

2. Microencapsulation : Micro capsules of healing agents such as bacteria or chemicals are embedded in the concrete mixture The shells break when created cracks, and the healing agents are released.

Common healing agents include: Bacteria (Bacillus species)Healing Polymer chemical agents (sodium silicate or calcium carbonate precursors).

Bacterial Self-Healing: Bacteria are encapsulated in the concrete and can lie dormant for long periods of time until cracks permit water to trigger them.

C. **Crystalline Self-Healing**

Mechanism : Addition of water-reactive chemicals such as crystalline admixtures (e.g., sodium silicate, potassium silicate) to the concrete mix. When cracks form, these chemicals react with water and other components to form crystalline structures that seal the cracks.

Advantages : Effective for sealing both micro and macro cracks.

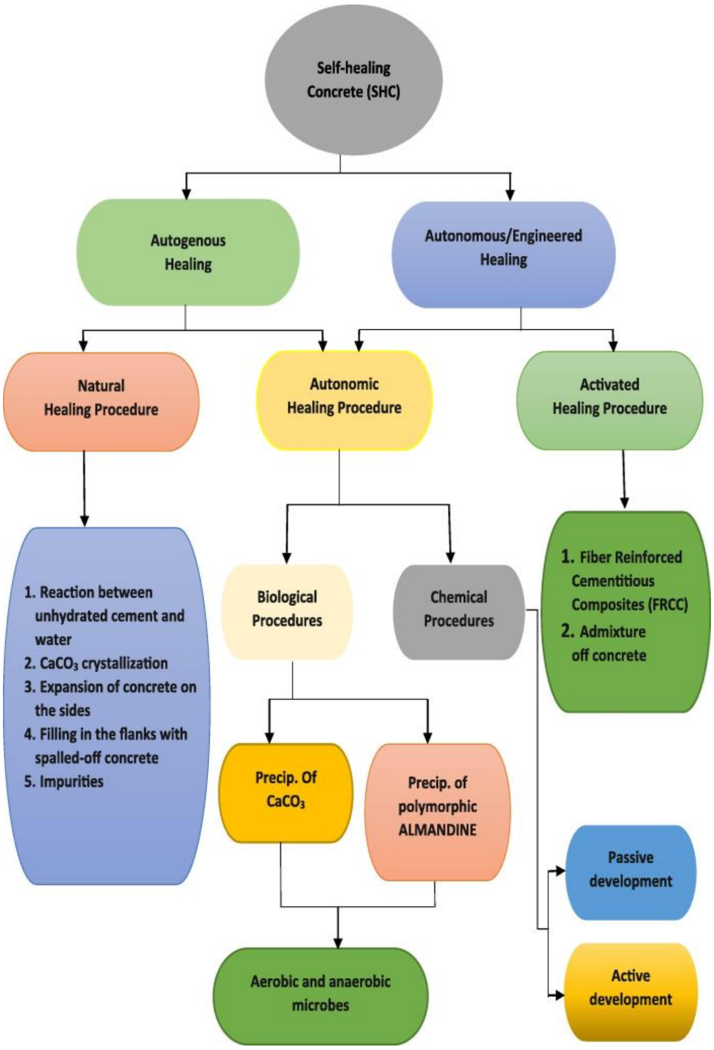
Limitations : Limited by the amount of chemicals in the mix and the size of the crack.

D. **Internal curing System**

Mechanism : A network of micro-channels or vascular networks is embedded within the concrete. These channels carry healing agents that can be activated when cracks form.

Approach : Similar to how blood vessels function in living organisms, these channels release healing agents directly to the site of the crack, providing an immediate response.

Challenges : Complexity in embedding a vascular system, uniformity of distribution, and ensuring sufficient quantity of healing agent.



4. SELF-HEALING CONCRETE MATERIALS USED

Cementitious Materials: Ordinary Portland cement, fly ash, silica fume and slag.

Agents used for healing: Bacterial cultures, such as Bacillus; calcium carbonate precursors; epoxy resins; sodium silicate.

Microcapsules : Polymers such as urea-formaldehyde or melamine-formaldehyde, and also silica-based encapsulation.

Fibre reinforcement: Fibre support to crack bridging self-healing concrete mechanical properties.

5. EXPERIMENTAL METHODS FOR EVALUATING SELF-HEALING CONCRETE

Experimental insight is of utmost importance to characterize these involved self-healing mechanisms. Some common techniques for evaluation include:

Crack Monitoring: Analysing Change in Crack Width (Digital Image Processing or Strain Gauges)

Mechanical Tests: Compression, flexural and tensile tests to assess strength recovery and endurance.

Water Tightness and Permeability Tests : To evaluate the self-healed concrete ability against water penetration.

Microscopic analysis: Techniques including scanning electron microscopy (SEM), X-ray diffraction (XRD) and etc to see the healing products at crack interface.

Long-term Healing Rate Tests : Inducing healing under accelerated environmental conditions (temperature, humidity, and types of cracks) to evaluate the rate of crack repair.

6. CHALLENGES & LIMITATIONS

Durability: The longevity of self-healing systems (exposed or embedded) needs to be evaluated more to determine if they can function effectively over time and after multiple rounds of repair.

Money: Some self-healing technologies (for example bacterial or encapsulation) may add to the upfront costs of concrete.

Efficacy: The healing ability to heal cracks based on the type and size of a crack as well as how activated it is.

Controlled Release of Healing Agent : The release of healing agent should be controlled so that it is released only when required, and not earlier– a challenge in conventional healing systems.

7. FUTURE DIRECTIONS

Multiphasic Systems: Incorporating multiple healing mechanisms in one single concrete mix to maximise the self-healing process.

Better Bio-Based Healers: These include new strains of bacteria and other microorganisms capable of enhanced healing efficiency and durability.

Encapsulation Methods with Enhanced Control: Controlling the release of healing agents and modifying mechanical properties.

Integration with smart technologies: The perfect match of self-healing and sensor-based monitoring systems, which can detect the formation of cracks over a period of time and activate healing whenever required.

8. CONCLUSIONS

Self-healing concrete is an innovative step towards more sustainable construction materials, providing a self-repair solution that increases the lifetime of concrete constructions and decreases maintenance costs. Based on bacterial mechanisms, encapsulation methods, and crystalline systems for concrete crack repair.

Concrete crack repairs and its mechanical properties were enhanced by carbonate precipitation using bacterial strains like Bacillus subtilis and Bacillus megaterium. Studies show that high crack repair ratios and improved durability can be achieved with self-healing concrete.

However, the long-term viability of healing microbes as well as their performance under different environmental conditions remains a challenge. Emerging trends in this area are multiphasic systems, enhanced bio-based healers and convergence with smart technologies.

Though beneficial, challenges surrounding cost, scalability and performance of self-healing systems over time and in diverse environments remain. future studies are required to maximize healing performance, engineer inexpensive formulations/processes, and insure compatibility with diverse structural necessities.

With further developments in material sciences and engineering, self-healing concrete can be one of the building blocks of sustainable infrastructure, encouraging resilience and curbing the environmental impact of modern construction practices.

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