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Self-Healing Concrete: A Review of New Era in Advance Construction Concrete and Future Prospects

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Abstract- Cracks in concrete buildings can make them last much less long because they let outside elements damage the support, which in turn damages the concrete. Cracks in concrete can find and fix themselves with microbial weathering technology. However, this technology hurts concrete during freeze-thaw cycles because of the water that is present, especially in cold places. A lot of research has been done on the progress made in making self-healing devices for concrete. This review paper looks at self-healing bacterial concrete systems, a new type of material that can make concrete buildings last longer and be more durable. The article talks about how bacteria help the body heal, including how bacteria make calcium carbonate to fill in cracks in the concrete substrate. The review also talks about how the technology could be used and the problems that might come up when it is scaled up in real-world building projects. The review points out the study's flaws, hopes for the future, and important areas for further research.

Key Words: Self-Healing Concrete (SHC); Self-Healing Bacterial Concrete (SHBC); CO2 emissions; calcium carbonate; Microbial mineralization; Freeze-thaw

1. INTRODUCTION

Cracks in SHC can be fixed and the concrete's mechanical features can be restored without any help from outside sources. This remarkable property is achieved through various methods, including autogenous and autonomous self-healing techniques (Amran et al., 2022) (Meraz et al., 2023). Autogenous self-healing occurs naturally in concrete due to the presence of un-hydrated cement particles and the dissolution of calcium. When cracks appear, these particles react with water, initiating a healing process that helps fill the cracks. However, this method is limited to repairing only minor cracks (Meraz et al., 2023).

To address larger cracks and improve the self-healing performance, autonomous methods have been developed. These techniques involve incorporating additional external healing agents or mechanisms into the concrete mix. Some examples include (Amran et al., 2022) (Meraz et al., 2023):

1. Vascular self-healing: Embedding a network of hollow tubes containing healing agents within the concrete.
2. Capsule-based self-healing: Encapsulating healing agents in the concrete mix that are released upon crack formation.
3. Bacterial self-healing: Using bacteria that consume calcium lactate and produce limestone to fill cracks.

SHC has several advantages over traditional concrete. It can limit reinforcement corrosion, reduce concrete deterioration, lower maintenance costs, and increase overall durability. This makes it a promising solution for constructing more sustainable and durable structures (Meraz et al., 2023).

In conclusion, SHC is a new type of material that can fix cracks on its own and partly regain its mechanical qualities. It is an environmentally friendly way to build today.

1.1 Definition of SHC

SHC is a kind of concrete that has the capacity to autonomously repair itself after any form of injury, hence improving its overall strength and lifespan. This self-healing process can occur autonomously or through external methods like embedding hollow tubes with healing agents. To repair concrete cracks, vascular, capsule-based, shape memory alloy, and microbial self-healing employing calcium carbonate precipitation have been created. The goal is to reduce the need for manual detection and repair, improving the material's resilience and reducing maintenance costs over time. (Amran et al., 2022)(Meraz et al., 2023).

1.2 Commercial microorganism SHC mixing system

An optimal blending system that considers the feeding capacity, mixing duration, and feeding order is essential for the production of uniform and superior microbial SHC. The creation of microbial SHC involves three processes, with the first step being the measurement of raw components. The second phase involves arranging all raw elements in a certain sequence, and the last step is mixing them for a duration of 2-3 minutes to produce microbial SHC. Figure 3 displays the precise stirring mechanism (X. Zhang & Qian, 2020).

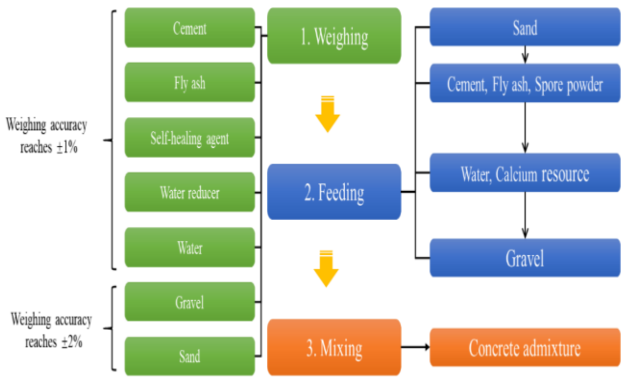

Figure-1: Integration of a SHC system with microorganisms (X. Zhang & Qian, 2020)

2. Overview of Self-healing bacterial concrete

Concrete is now everywhere used in construction industry that is prone to cracking and damage due to various environmental factors, such as temperature fluctuations, humidity, and chemical attacks. Traditional repair methods can be time-consuming, costly, and may not fully enough for the structural designing of the concrete. To overcome this issue, researchers have been exploring the concept of SHC, which incorporates bacteria that can repair cracks and damages autonomously (Rajczakowska et al., 2019).

2.1 Importance of sustainable infrastructure development for self-healing bacterial concrete

The use of self-healing bacterial concrete in sustainable infrastructure development is crucial for enhancing the longevity and durability of structures while reducing maintenance costs and environmental impact. This innovative concrete technology offers significant advantages for sustainable construction practices:

1. Durability and Longevity: Self-healing bacterial concrete has the unique ability to autonomously repair cracks, ensuring the structural integrity of buildings and infrastructure over an extended period. By addressing cracks promptly, this concrete enhances the overall durability of structures, reducing the need for frequent repairs and maintenance.
2. Cost-Effectiveness: The self-healing properties of bacterial concrete can lead to cost savings in maintenance and repair expenses. By minimizing the need for manual interventions to fix cracks, this concrete technology offers a more sustainable and cost-effective solution for infrastructure maintenance.
3. Environmental Sustainability: Bacterial concrete contributes to environmental sustainability by reducing the carbon footprint associated with concrete production and maintenance. Its self-healing mechanism helps prolong the lifespan of structures, reducing the overall environmental impact of construction activities.
4. Improved Performance: The use of self-healing bacterial concrete enhances the compressive and tensile strengths of structures, making them more resilient to stress and wear. This improved performance ensures that infrastructure can withstand harsh conditions and maintain structural integrity over time.
5. Reduced Corrosion: By sealing cracks and preventing water ingress, self-healing bacterial concrete helps mitigate corrosion of steel reinforcement within structures. This corrosion resistance contributes to the longevity and safety of infrastructure, especially in environments prone to moisture and chemical exposure.

2.2 Development of new bacterial strains(Alemu et al., 2022),(Balajirao & Kalurkar, 2020)

The development of new bacterial strains for SHC involves several future directions to enhance the crack-healing efficiency and overall performance of bacterial concrete. Key areas of focus include:

1. Optimization of Bacterial Strains and Mix Designs:

Continued Research: Further research is needed to optimize bacterial strains and mix designs to improve the self-healing properties of bacterial concrete.
Selecting Superior Bacteria: Selecting bacteria with superior calcite-producing abilities and optimizing nutrient delivery mechanisms will enhance the self-healing capabilities of bacterial concrete.

2. Advanced Materials and Technologies:

Nanomaterials Integration: Incorporating nanomaterials, such as nanoparticles and nanofibers, into bacterial concrete matrices can improve crack-sealing efficiency and enhance resistance to environmental stressors.

3. Integration of Bacterial Concrete into Building Codes:

Collaborative Efforts: Collaborative efforts between industry stakeholders, researchers, and regulatory agencies are necessary to integrate bacterial concrete into building codes and standards.
Guidelines Development: Developing guidelines for the design, construction, and maintenance of bacterial concrete structures will promote its acceptance and adoption in construction projects.

4. Field Trials and Performance Monitoring:

Longitudinal Studies: Conducting field trials and long-term performance monitoring of bacterial concrete in real-world construction projects is essential to assess its durability, resilience, and cost-effectiveness.
Data Collection: Longitudinal studies will provide valuable data on the behavior of bacterial concrete under different environmental conditions and loading scenarios, informing future design and construction practices.

5. Sustainability and Environmental Impact:

Eco-Friendly Production: Research efforts should focus on improving the sustainability of bacterial concrete production processes and minimizing its environmental impact.
Eco-Friendly Nutrient Sources: Exploring eco-friendly alternatives for nutrient sources and optimizing production methods to reduce energy consumption and greenhouse gas emissions will enhance the sustainability of bacterial concrete.

By addressing these future directions, the development of new bacterial strains for SHC can be accelerated, leading to more effective and sustainable construction materials.

3. Critical Literature Review

`**(X. Zhang & Qian, 2020)** study explores the use of microbial SHC in ship lock engineering. They developed self-healing agents containing microbial spores and calcium sources, which were tested in a spray drying method. The concrete, applied to the ship lock side wall, showed complete crack healing after 60 days. The study also introduced a commercial SHC production system for mass production.

The research by **(Shafiei-Pourkamali & Esmaeil, 2022)** looked into bacteria-based SHC. They used metakaolin instead of calcium lactate as a preparation and found that the concrete had better compression strength.

The study by **(Luo & Qian, 2016)** suggests that bacteria-based additives can create self-healing cementitious material systems. Type 1 additives, including calcium lactate and bacteria spores' powder, decreased compressive strength after curing, while Type 2 increased it.

(Milla et al., 2017) research examined the healing properties of calcium nitrate tetrahydrate in concrete. The study modified microencapsulation and mix design to improve microcapsule-containing concrete's mechanical qualities. Microcapsule concentrations of 0.25 to 0.50% by cement weight increased mechanical qualities, according to the research.

(Chen et al., 2019) study explores the use of microbial techniques, specifically using Bacillus pasteurii, to repair concrete cracks. The researchers found that lightweight aggregates can increase bacterial survival and restore strain vitality, improving the feasibility and success rate of bacterial mineralization in concrete.

(Lauch et al., 2023) study explores the self-healing properties of aged concrete using crystalline admixture and expansive agent, showing self-healing during healing periods but high residual strength in mechanical recovery.

The study by **(Luo et al., 2022)** examines mortars with AFA-encapsulated bacteria's self-healing. XRD, FTIR, TG, and SEM with an energy dispersive spectrometer were employed to characterize crack-healing products. On shallow and deep fracture walls, $CaCO_3$ was the major healing product.

The review by **(Souradeep & Kua, 2016)** emphasizes the significance of crack width and micro-capsule protection in self-healing techniques for concrete structures. It suggests further research on controlling crack width and highlights eight key factors for self-healing by encapsulation: robustness during mixing, crack probability, curing time, empty capsule effect, healing agent release controllability, stability, sealing ability, and repeatability.

The review by **(He et al., 2020)** bio concrete, bio cement, and biological surface treatments are three biological concrete pavement options. These technologies might improve pavement durability, but they lack long-term impacts and performance assurances, thus they have not been extensively used. Cost, energy, and environmental consequences should be reduced while maintaining building efficiency.

(Han et al., 2020) tested coated and uncoated concrete with calcium carbonate-producing microorganisms. Bacteria in the cement composite were protected from high temperature and pH by the styrene-acrylic coating. Only 5% difference was discovered between uncoated and coated concrete, indicating styrene acrylic coating may self-heal similarly.

(Abdelatif et al., 2022) gum arabic (Hashab gum) may immobilize Bacillus subtilis on coarse sand for SHC. After mixing bacterial spores, gum arabic powder, and calcium lactate in a flask, they evaluated mortar prisms for crack healing. Spore-coated sand pellets boosted healing efficiency without compromising prism strength.

Self-healing granules and polyvinyl acetate fibers increased concrete recovery, permeability, and surface crack closure while decarbonizing the atmosphere and minimizing erosive impacts **(C. Zhang et al., 2023)** In stress failure, PVA fibers inhibited fracture propagation and improved self-healing, according to the research.

The study by **(Luo et al., 2024)** bio-mineralization modified recycled aggregate (RA) can be used as a bacterial carrier to create SHC, improving workability, compressive strength, durability, and self-healing performance by filling surface pores and microcracks with bio-calcium carbonate.

The study by **(Yan et al., 2024)** examined the mineralization properties of microorganisms at low temperatures and the adsorption and charge characteristics of expanded perlite as microbial carriers in concrete specimens, finding that 0.6-1.2 mm microbial self-healing agents improve freeze-thaw resistance and self-healing.

The study by **(Fang et al., 2023)** examines how self-healing aggregates maintain concrete's mechanical strength and permeability. A revolutionary self-healing technology comparable to traditional concrete preparation improves performance and flexural and compressive strength.

(Meraz et al., 2023) examines SHC fracture repair methods and chemicals. Mineral admixtures and fibres outperform biomimetic materials. Bacillus-based SHC heals millimeter fractures better. More research required.

(Tan et al., 2016) created a silica sol microencapsulated SHC repair material. After microcracking, size and smoothness optimization boosted compressive and bending strengths. Silica sol, a cheap healing agent, was employed in the synthesis, and the improved microcapsules are extremely scalable, allowing commercialization.

3.1 Outcomes from Literature Review

1. The development and widespread adoption of bacterial SHC contribute to the creation of more sustainable and durable infrastructure, reducing the need for frequent repairs and replacements.
2. Literature explores the environmental benefits of bacterial SHC, such as its potential to reduce carbon emissions by extending the lifespan of buildings and infrastructure, thus lowering the overall environmental footprint of construction.
3. Studies investigate the economic implications of using bacterial SHC, including cost savings from reduced maintenance and repair expenses, as well as the potential for job creation and economic growth in the construction industry.
4. Literature examines how bacterial SHC enhances the resilience of structures against natural disasters, such as earthquakes and floods, leading to improved safety and reduced damage in vulnerable regions.
5. Literature discusses the scientific advancements and innovations in material science that have enabled the development of bacterial SHC, highlighting its potential for further breakthroughs in construction materials.
6. Studies investigate the impact of bacterial SHC on urban development, including its role in revitalizing aging

infrastructure, promoting sustainable urbanization, and improving the overall liability of cities.

7. Bacterial SHC contributes to public health and safety by reducing the risk of structural failures, enhancing the reliability of critical infrastructure, and creating healthier built environments for communities.

4. Case study

4.1 Case Study -1 (Qianhai Tunnel, a smart tunnel in Shenzhen, China) (Ma et al., 2023)

As demonstrated in Fig. 13, the smart Shenzhen Qianhai Tunnel uses SHC. The moist air near the Lingdingyang Estuary may enhance the possibility of corrosive ions entering and shattering material (Ma et al., 2023).

Therefore, this project employed epoxy resin (EP) SHC. The shell comprised ureaformaldehyde resin and the healing agent epoxy resin E-51. The healing agent and curing agent reaction, MC120D (epoxy resin E-51), was received from Guangzhou Kawai Electronic Materials Ltd. Company.

Prior to experimentation, the laboratory conducted a comprehensive investigation into five specific elements of capsule-based self-healing materials (Ma et al., 2023):

1. microcapsule physical characteristics,
2. compressive strength of concrete cubes,
3. chloride migration coefficient,
4. reduction in size with time, and
5. specimen microstructure.

The experiments showed that the microcapsule-based approach considerably boosted materials' inherent ability to repair after breaking. Concrete impermeability increased significantly.

However, these microcapsules changed the material's microstructure, reducing compressive strength by 20% to 30%. The results suggested supporting the tunnel using SHC. Strain monitoring and experimental measurements examined EP microcapsule concrete slab behaviour (Ma et al., 2023).

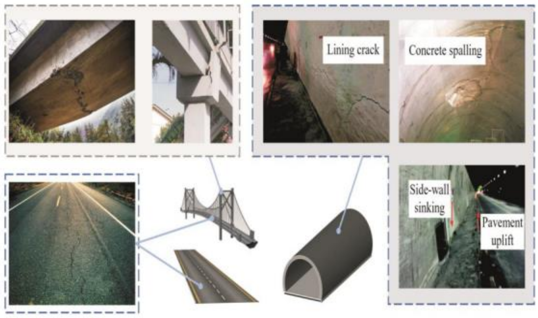

Figure-2: Qianhai Tunnel, a smart tunnel in Shenzhen, China (Ma et al., 2023)

4.2 Case Sudy-2 (Beijing-Hangzhou Canal, China) (X. Zhang & Qian, 2020)

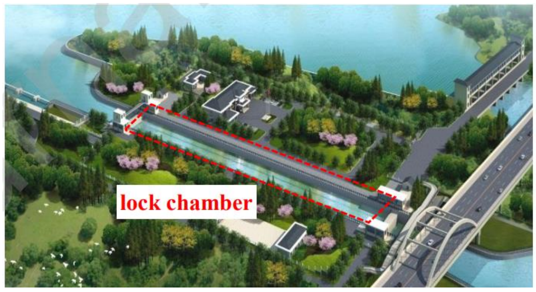

Figure-3: Top view of Beijing-Hangzhou Canal, China

The Beijing-Hangzhou Canal is an important Chinese inland canal. The Beijing-Hangzhou Canal's Hangzhou section diversion channel and the South-to-North Water Transfer Project's east route principal water delivery channel. Drainage, flood management, and water transportation are project goals. Mangdao River ship lock is a major navigational facility in Yangzhou City, Jiangsu Province, China (Figure 14) (X. Zhang & Qian, 2020).

Figure 4. (a) Interior view of lock chamber (b) A construction 3d section of lock channel (X. Zhang & Qian, 2020).

A 300 mm thick layer of SHC was poured using a horizontal layered continuous pouring technique. Two days after the concrete was poured symmetrically and evenly upwards, demolding was done. Artificial watering and geotextile covering were two maintenance techniques used to provide thermal insulation and lessen temperature stress. By keeping the concrete's surface moist during the water curing process, shrinkage cracks were avoided, and early cracks were repaired by mineralization. (X. Zhang & Qian, 2020).

Figure 5. (a) Pouring of SHC (b) Curing of SHC (X. Zhang & Qian, 2020)

Temperature stress and bottom concrete shrinkage will eventually cause cracks in side wall concrete. Both self-healing and regular concrete had surface cracks, and after 65 days, the normal concrete's surface remained unrepaired. However, SHC had blocked the connectivity and no more water leaked. An area of crack's ability to mend itself depends on the speed at which water passes through it. There are various chemical profiles of the calcium carbonate that bacteria produce, so methods for reducing the loss of self-healing products must be refined (X. Zhang & Qian, 2020).

5. CONCLUSIONS

In conclusion, self-healing bacterial concrete has emerged as a revolutionary technology in the construction industry, offering a novel solution to the long-standing problem of concrete degradation. This innovative material has been shown to possess exceptional durability and sustainability, with the ability to repair cracks and damages autonomously. The potential benefits of self-healing bacterial concrete are numerous, including reduced maintenance costs, extended service life, and minimized environmental impact. As the construction industry continues to evolve and face new challenges, the development of self-healing bacterial concrete is poised to play a significant role in shaping its future. Future research and development should focus on scaling up the production process, improving the uniformity and consistency of the bacterial cultures, and exploring new applications for this technology. Furthermore, the integration of self-healing bacterial concrete with other advanced construction materials and technologies, such as smart sensors and nanomaterials, holds immense potential for creating intelligent, adaptive, and sustainable infrastructure. As the construction industry continues to adopt this innovative technology, we can expect to see significant improvements in the quality, durability, and sustainability of buildings and infrastructure. In conclusion, self-healing bacterial concrete is a game-changing technology that has the potential to transform the construction industry. With its unique properties and benefits, it is poised to play a crucial role in shaping the future of construction and infrastructure development.

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