A Comprehensive Review on Self- Healing Concrete Technology

Anshul Mathur[1], Tarachand Kumawat[2], Samiksha Kumawat[3], Anuradha Kumawat[4]
[1]*HOD, Rajasthan College of Engineering for Women, Jaipur, India*
[2]*Assistant Professor, Department of Civil Engineering, Rajasthan College of Engineering for Women, Jaipur, India*
[3,4]*Students, Department of Civil Engineering, Rajasthan College of Engineering for Women, Jaipur, India*

Abstract—Self-healing concrete (SHC) is an emerging material technology capable of autonomously repairing cracks and improving structural durability. This review explores the recent developments (2020–2024) in self-healing concrete, focusing on three primary mechanisms: chemical, natural, and biological. The paper also discusses material design strategies, limitations, and future research directions. A conceptual figure is included to illustrate the three self-healing pathways.

Keywords—Self-healing concrete, chemical healing, biological healing, natural healing, crack repair, durability.

I. INTRODUCTION

Concrete, the most widely used construction material, suffers from cracking due to shrinkage, thermal effects, and mechanical loads. Cracks reduce structural integrity and allow ingress of harmful agents, leading to corrosion and reduced lifespan.

Traditional repair methods are costly and labor-intensive. Self-healing concrete (SHC) is an innovative approach inspired by natural healing processes in biological organisms.

SHC autonomously repairs cracks, enhancing durability and sustainability [1]–[3].

Recent research (2020–2024) has focused on designing SHC using chemical, natural, and biological methods. Each mechanism exhibits unique advantages and challenges depending on material composition, environmental conditions, and desired performance.

II. SELF-HEALING MECHANISMS

A. Chemical Self-Healing

Chemical self-healing relies on encapsulated or pre-mixed agents that react with water or CO_2 to precipitate minerals and seal cracks. Common methods include:

1. Microcapsules containing adhesives (epoxy, polyurethane) that rupture upon cracking.Hollow fibers and vessel networks for active delivery of healing agents.
2. Autogenous healing through unhydrated cement particles reacting with water to form additional C-S-H gel.

Advantages include controlled healing and immediate crack sealing.

Limitations involve reduced effectiveness for large cracks and complex encapsulation methods [4]– [6].

B. Natural Self-Healing

Natural healing utilizes supplementary cementitious materials (SCMs) and admixtures to promote autogenous crack repair. Examples include:

- Fly ash and slag enhancing long-term hydration and reducing permeability.
- Mineral additives like bentonite or limestone powders that expand upon water ingress.

Natural self-healing is environmentally friendly and cost- effective but may require longer times for complete crack closure [7]–[9].

C. Biological Self-Healing

Biological self-healing employs bacteria or enzymes capable of precipitating calcium carbonate to seal cracks. Key strategies include:

- Bacterial spores embedded in concrete, activated by moisture.
- Nutrient carriers like calcium lactate to sustain

microbial activity.
● Enzyme-induced mineralization as an alternative pathway.
Advantages include long-term sustainability and potential for repeated healing. Challenges involve bacterial survivability under high pH, limited nutrient availability, and ensuring uniform distribution [10]–[13].

III. RECENT ADVANCES (2020–2024)

Recent studies have reported significant improvements in SHC performance:
● Chemical SHC: Smart microcapsules with dual-agent systems improve crack sealing efficiency up to 90% for cracks <0.5 mm [14].
● Natural SHC: Enhanced autogenous healing using bio- based mineral admixtures increased durability and reduced permeability in marine environments [15].
● Biological SHC: Genetically engineered Bacillus strains demonstrated improved calcium carbonate precipitation under alkaline conditions [16].
Integration of multi-mechanism SHC (chemical + biological) has shown synergistic effects, providing rapid initial sealing and long-term durability [17].

IV. CHALLENGES AND FUTURE DIRECTIONS

Despite advances, several challenges remain:
[1] Scalability: Large-scale production of bacteria or capsules remains costly.
[2] Crack size limitation: Most methods effectively seal cracks <1 mm.
[3] Environmental durability: Performance under freeze-thaw cycles, aggressive chemicals, and high temperatures needs improvement.
[4] Standardization: Lack of uniform testing protocols hinders commercialization.
Future research should focus on hybrid self-healing systems, nanotechnology-enhanced healing agents, and eco-friendly sustainable materials [18]–[20].

V. CONCLUSION

Self-healing concrete represents a transformative approach to durable and sustainable construction. Chemical, natural, and biological mechanisms offer complementary advantages for autonomous crack repair. Recent research (2020–2024) demonstrates the potential of SHC for real-world applications, but challenges remain in scalability, durability, and standardization. Continued interdisciplinary research is crucial for widespread adoption of SHC technologies.

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