

SELF-HEALING CONCRETE: PRODUCTION, IMPROVEMENT, AND EFFICIENCY FOR LONG-TERM STRUCTURAL INTEGRITY OF CONCRETE INFRASTRUCTURE

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Анотація

У статті проаналізовано сучасні підходи до розроблення самовідновлювального бетону та оцінено їх ефективність у підвищенні довговічності бетонних конструкцій. Розглянуто автогенні та автономні механізми самовідновлення, зокрема використання мікрокапсул, бактеріальних систем, полімерних і мінеральних добавок. Визначено основні переваги самовідновлювального бетону: зменшення тріщиноутворення, подовження строку експлуатації, підвищення водонепроникності та зниження витрат на обслуговування. Результати досліджень підтверджують перспективність застосування самовідновлювального бетону в сучасному будівництві.

Ключові слова: самовідновлювальний бетон; автономне відновлення; мікрокапсули; бактеріальні системи; довговічність; контроль тріщин.

Abstract

This paper analyzes modern approaches to the development of self-healing concrete and evaluates their effectiveness in improving the long-term durability of concrete infrastructure. Both autogenous and autonomous healing mechanisms are considered, including microcapsules, bacterial systems, polymers, and mineral additives. The main advantages of self-healing concrete are reduced crack propagation, increased service life, improved water tightness, and lower maintenance costs. Experimental data confirm the high potential of self-healing concrete for ensuring long-term structural integrity in modern construction.

Keywords: self-healing concrete; autonomous healing; microcapsules; bacterial systems; durability; crack control.

Introduction

Concrete is the primary construction material for modern infrastructure; however, its long-term operation is accompanied by the formation of microcracks that gradually develop into more severe defects, reducing the strength, durability, and safety of structures. Traditional repair methods not only require significant financial resources but often fail to fully restore structural integrity. Against this background, the development of self-healing concrete (SHC), capable of autonomously repairing damage without human intervention, has become an intensive research direction. Such materials significantly extend the service life of structures and reduce maintenance costs, making them highly relevant in modern civil engineering.

Research results

One of the key approaches to creating self-healing concrete is the use of **autogenous healing mechanisms**, which rely on the natural ability of cementitious materials to recover microcracks through carbonation and continued hydration processes when moisture is present. Autogenous healing does not require additional additives but has limited effectiveness and only works for cracks up to 0.2–0.3 mm. Therefore, current research focuses on enhancing this mechanism by modifying cement mixtures with mineral activators (such as silica fume, ground granulated blast-furnace slag, or pozzolans) which intensify secondary hydration and promote the formation of additional healing products.

A more advanced and promising approach involves **autonomous self-healing systems**, which include:

- encapsulated polymeric or mineral healing agents,
- bacterial systems that induce calcium carbonate precipitation,
- superabsorbent polymers (SAPs),
- fiber-reinforced systems and smart composites.

One of the most widely studied solutions is **microencapsulated polymer-based healing agents**. When a crack forms, the microcapsule ruptures, releasing the polymer, which fills the crack and solidifies. Numerous experimental studies demonstrate that this method can restore mechanical strength by 60–90%, depending on

capsule composition and size. However, such systems remain costly and challenging to scale for industrial use.

Particular attention has been given to **bacterial self-healing concrete**, which relies on spore-forming bacteria (commonly *Bacillus* spp.) capable of producing calcite within cracks. Bacteria are encapsulated with nutrients in granules or capsules that remain dormant within the concrete for long periods. When exposed to moisture, the bacteria activate and initiate biocalcification, effectively sealing cracks up to 0.6–0.8 mm. Studies show that this type of concrete significantly enhances water tightness, reduces salt penetration, and increases resistance to freeze-thaw cycles.

An important aspect of SHC development is the **optimization of production technologies**, as incorporating capsules or bacterial granules into the cement matrix requires strict control over their distribution, compatibility with cement hydration, and mechanical stability during mixing. Recent studies highlight the effectiveness of using stronger polymer shells, mineral carriers (e.g., zeolite, diatomite), or lightweight aggregates as protective containers for healing agents. These methods improve both the durability of healing components and the rheological properties of fresh concrete.

Evaluation of SHC performance and durability includes compressive and flexural strength testing, water permeability tests, absorption measurements, and accelerated aging cycles. According to modern research, self-healing concrete systems significantly reduce crack propagation and provide a 20–40% increase in long-term compressive strength compared to conventional concrete after damage cycles. Water permeability is improved by 2–10 times, which is essential for infrastructure exposed to moisture and aggressive environments.

However, several challenges hinder the widespread adoption of SHC:

1. high costs associated with capsules or bacterial additives;
2. difficulties in scaling production and ensuring uniform distribution of healing agents;
3. lack of standardized methods for evaluating self-healing performance;
4. potential long-term changes in mechanical properties due to added capsules or porous carriers.

These challenges guide future research aimed at cost reduction, composition optimization, and improvement of healing system reliability.

A promising emerging concept is **hybrid self-healing concrete**, which combines multiple healing mechanisms – such as microcapsules, mineral admixtures, and superabsorbent polymers – enabling multiscale healing of cracks under various conditions. Some studies report the ability to repair cracks wider than 1 mm using multi-component systems.

Given the increasing demands for safe, durable, and sustainable infrastructure, self-healing concrete has become a key innovative material capable of significantly reducing CO₂ emissions by minimizing repair work, extending service life, and reducing the need for cement production. This makes it an important element in green construction and sustainable development strategies.

In conclusion, self-healing concrete represents a highly promising direction in the modernization of the construction industry, combining technological innovation, material engineering advancements, and practical advantages for long-term infrastructure performance. Future research should focus on composition optimization, cost reduction, and improving quality control methods to support the widespread adoption of self-healing concrete in transportation, hydraulic, and civil engineering structures.

Conclusions

Self-healing concrete is a promising material for enhancing the durability and reliability of infrastructure structures. Through autogenous and autonomous healing mechanisms, it can reduce crack propagation, improve water tightness, and partially restore mechanical strength. The most effective systems are those using microcapsules and bacterial agents, which can heal cracks up to 0.6–1.0 mm wide. Despite their high efficiency, industrial implementation is limited by cost and the need for standardized testing methods. Future development of more affordable and stable self-healing systems will facilitate wider adoption of these technologies in construction.

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