

SELF-HEALING CONCRETE COMBINED WITH NANOMATERIALS: A COMPREHENSIVE REVIEW

Afsheen^{*1}, Ashfaq Hussain Kaka², Muhammad Azeem³, Junaid Ahmed⁴,
Suhail Ahmed Abbasi⁵

¹Faculty of Engineering Science & Technology, Indus University, Karachi, Pakistan.

²Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan.

³Hydraulics, Irrigation and Drainage, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan.

⁴Department of civil Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan.

⁵Department of Civil Engineering, The University of Larkano, Larkano, Sindh, Pakistan.

^{*}eng.afsheen@gmail.com

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Corresponding Author: *
Afsheen

Abstract

Self-healing concrete offers independent fracture repair characteristics that increase buildings lifespan and lower maintenance costs, marking an evolutionary change in building materials. The incorporation of nanoparticles has become a revolutionary strategy that improves the mechanical characteristics and healing effectiveness of cementitious processes. The methods, categories, current developments, and potential future paths of nanomaterial-infused self-healing concrete are all examined in this paper. With an emphasis on nanotechnology such as carbon nanotubes, graphene, silicon dioxide, and bio-nanocarriers, we examine autogenous and autonomous healing mechanisms. Recent advances show that bacteria trapped by nanoparticles may mend cracks up to 1.71 mm, with gains in compressive strength surpassing 45%. Although there are still issues with adaptability, cost-effectiveness, and sustainability verification the synergistic coupling of nanotechnology and biotechnology offers hitherto unheard-of possibilities for robust, sustainable infrastructure.

1. INTRODUCTION

Although concrete is still the most commonly used building material in the world [1-4], there are serious durability issues because to its vulnerability to fracture under mechanical stress, heat fluctuations, and exposure to the atmosphere. Conventional repair techniques are expensive, time-consuming, and frequently reactive rather than predictive. These restrictions are addressed by self-healing concrete (SHC), which uses intrinsic or extrinsic processes to automatically patch fractures as soon as they occur.

The advancement of SHC has been completely transformed by the introduction of nanotechnology. Substances with a minimum of one size between 1 and 100 nm are known as nanomaterials (NMs). Because of their special qualities, such as high surface area-to-volume ratios, increased reactivity, and quantum effects, NMs are excellent candidates for applications as agents of healing and performance improvements [5, 6]. This study highlights recent developments and highlights significant research needs in the

field of integrated nanotechnology self-healing concrete.

2. Classification of Self-healing System,

2.1 Autogenous Self-Healing

The continuous hydration of unprocessed cement particles and the resulting carbonation of calcium hydroxide (CH) while water seeps through fractures are essential for autogenous healing [6-8]. The process includes:

- **Prolonged hydration:** More calcium-silicate-hydrate (C-S-H) gel is created when unused cement fragments interact with incoming water.
- **Carbonation:** Calcium carbonate (CaCO_3) is produced when soluble CH interacts with ambient CO_2 .
- **Crystallization:** Fracture volumes are filled by the growth of hydration products. Autogenous healing is restricted by accessibility to water, fracture breadth, and mortar age; however, it works well for microcracks (less than 0.2 mm).

2.2 Autonomous Self-Healing

Additional healing substances are included into autonomous structures and become active when cracks appear [9, 10]. Among them are:

- Microencapsulated materials.
- Mineral additives (crystalline additives, expanding agents).
- Spores from bacteria are examples of biological agents.
- Nanotechnology carriers.
- Nanomaterials are mostly found in autonomous technologies, serving as transporters or facilitators of various healing processes or as primary healing agents.

3. Nanomaterials in Self-Healing Concrete

3.1 Nano-Silica

The majority studied nanomaterial for practical uses is nano silica [11]. It exhibits notable impacts on self-healing ability at doses of 1-3%.

Action Mechanism:

- **Nucleation sites:** A large specific surface area offers many of places where C-S-H can develop.
- **Pozzolanic action:** Densifies the mixture by reacting with CH to produce more C-S-H.

- **Filler impact:** Physically seals small cracks and tiny voids.

- **Accelerator:** Promotes quicker autogenous repair by accelerating hydration kinetics.

According to the latest findings, based on the dose and mix with other substances, nano SiO_2 -modified concrete can boost compressive strength by 12–50% and flexural strength by 15–55% [12]. The combined actions result in a 22.86% raised compressive strength and a 40.74% enhancement of flexural strength while paired with nano- CaCO_3 at 2% for each [12].

Enhancement of Self-Healing: According to 2025 research on hydrophilic nano- SiO_2 -modified tiny capsules, n SiO_2 can enhance rheological characteristics while controlling hydration kinetics, maintaining cementitious composites' capacity for self-healing [13]. By densifying the ITZ between aggregate and the paste of cement, the nanoparticles decrease the number of locations where cracks can start.

3.2 Carbon Nanotubes (CNTs)

CNTs [14-18] support self-healing concrete in a number of ways:

- Crack monitoring and detection.
- High tensile strength (up to 200 GPa) prevents the spread of cracks.
- Capable of carrying therapeutic agents.

A 5% CNT inclusion increases the compressive strength, flexural strength, and tensile strength of alkali-activated slag concrete pavements by 15%, 9%, and 15%, respectively [12]. The cylindrical shape produces networks that may speed up autogenous healing procedures by facilitating ion transfer.

3.3 Graphene Oxide (GO)

Materials from the graphene family (GFMs) have developed into multipurpose additives:

- **Mechanical improvement:** 2D GO [19-22] in construction offers outstanding support.
- **Barrier characteristics:** impervious to ions and water, lowering the drivers of crack development.

- **Platform for functionalization:** GO's oxygen-containing groups [23-25] allow for chemical interaction with therapeutic substances. "Eco-Nanoseal" graphene oxide composites made from aquaculture waste represents a significant advancement [26]. Without the need of external polymerization chemicals, this substance quickly forms inside cement fissures to create strong, impenetrable obstacles. Superior bonding, mechanical suitability, and superior sustainability parameters are all displayed by the sealant.

3.4 Nano-TiO₂

Nano-TiO₂ is used in various applications [27-29].

In addition to its self-cleaning photocatalytic qualities, nTiO₂ promotes healing:

- **Photocatalytic activation:** In photo-responsive systems, UV light can initiate healing processes.
- **Refinement of microstructure:** Like nSiO₂, it increases density and occupies tiny spaces.
- **Combined capabilities:** Self-healing and self-cleaning properties in one ingredient. Research shows that adding 1% nTiO₂ to self-cleaning concrete increases its compressive strength by 10.90% and its flexural strength by 33.33% [12].

4. Mechanisms of Nanomaterials Enhanced Healing

4.1 Physical Mechanisms

The physical mechanisms for nanomaterials are summarized in Table 1.

Table 1: Physical Mechanisms of nanomaterials

Mechanism	Description	Key Nanomaterials
Nucleation enhancement	Increased C-S-H and CaCO ₃ formation sites	nSiO ₂ , nCaCO ₃
Pore filling	Physical blockage of transport pathways	All nanomaterials
Crack bridging	Mechanical reinforcement across cracks	CNTs, graphene
Barrier formation	Impermeable layers preventing ingress	GO

4.2 Chemical Mechanisms

The chemical mechanisms summarized few properties as mentioned below:

- Pozzolanic reactions: nano SiO₂ + CH → C-S-H.
- Carbonation acceleration: CO₂-Ca²⁺ interactions using nanotechnology catalysts.
- Biomineralization: Nanoparticle-mediated bacterial CaCO₃ precipitation.

- Ion interchange: Chitosan and nano clay control ion transportation and humidity.

5. Performance Matrices and comparative Analysis

5.1 Healing Efficiency

The healing efficiency of various nano-materials are summarized in Table 2.

Table 2: Healing Efficiency

References	System	Max Crack Width Healed	Healing Time	Strength Regain
[6]	Autogenous (control)	0.2-0.3 mm	28-90 days	60-80%
[12]	nSiO ₂ enhanced	0.3-0.5 mm	14-28 days	80-90%
[30]	Bacteria + GNP	0.81-1.3 mm	28 days	85-91%
[31]	Bacteria + IONPs	0.45-0.5 mm	28-120 days	91%
[30]	Bacteria + EShN	0.5-0.8 mm	28 days	90-95%
[26]	Chitosan-GO hydrogel	0.3-0.5 mm	Immediate-7 days	85%

5.2 Mechanical Properties Enhancement

Fundamental attributes are regularly improved by nanomaterials:

- 10–50% rise in compressive strength (ideal at 1-3% dose).
- The enhancement in flexural strength was recorded by 15–55%.
- 12–30% increase in tensile strength.
- 90% less water flow due to decreased permeability.

6. Challenges and Limitations

6.1 Dispersions and Agglomeration

Getting uniform dispersion is the main obstacle in the application of nanomaterials. Because of their high surface energy and van der Waals forces, nanomaterials have a tendency to aggregate, which decreases their efficacy and may result in the creation of weak zones.

Remedies:

- Pre-dispersion in chemicals or liquids.
- Techniques for ultrasonic blending.
- Functionalization of the surface.
- Hydrophilic transformation using silane coupling compounds.

6.2 Cost and Scalability

GO and CNTs are still too costly for massive construction. Nevertheless, inexpensive substitutes are provided by waste-derived nanoparticles (rice husk ash, eggshell) [30].

6.3 Standardization

Comparing different research is made more difficult by the absence of standardized testing techniques for self-healing effectiveness. Although recommendations are being developed by the

RILEM and ASTM committees, consistent standards are still unattainable.

7. Conclusions

A revolutionary development in construction technologies is the incorporation of nanoparticles into self-healing concrete. Important findings consist of:

- **Synergistic improvement:** By resolving many performance requirements with an individual inclusion, nanomaterials concurrently increase mechanical characteristics, longevity, and healing efficiency.

- **Bio-nano convergence:** Using waste-derived substances, the integration of bacterial healing with nanoscale carriers yields the best healing efficiency (cracks >1 mm) whereas preserving ecological integrity.

- **Dosage optimization:** Because of their agglomeration, various nanomaterials function best around 1-3% by cement weight, with declining benefits and possible adverse effects at greater percentages.

- **Sustainability demands:** In order to facilitate greater acceptance, future advancement must give priority to cost minimized, waste consumption, and life-cycle evaluation.

Nanomaterial-based self-healing concrete is moving from experimental development to practical use. The upcoming generation of robust, low-maintenance infrastructure—which is crucial for environmentally friendly urban development—will be made possible by these components with ongoing studies on uniform distribution, durability, and standardization.

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