INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 1, May 2026, pp : 7-15

Study on Self-Healing Concrete Technology Mechanisms, Materials, Performance, and Prospects for Next-Generation Infrastructure

[1]P Abhilash,

[1]Scientist,CSMRS,New Delhi,ORCID: **0000-0002-3767-7846**

ABSTRACT

Concrete is the world's most widely used construction material, yet its susceptibility to cracking remains a fundamental limitation that drives enormous maintenance and repair expenditure globally. Self-healing concrete technology — encompassing biological, chemical, and mineral-based healing mechanisms — offers a transformative solution by enabling concrete to autonomously detect and repair cracks without human intervention. This study presents a comprehensive review of self-healing concrete, covering the underlying mechanisms of crack formation and autogenous healing, engineered healing strategies including bacterial, encapsulated agent, vascular network, and crystalline admixture approaches, and the mechanical and durability performance of healed specimens. Comparative data from laboratory and field studies are synthesized, and the economic, environmental, and practical dimensions of deployment are evaluated. The study concludes with an assessment of current barriers and a roadmap for commercialization and standardization of self-healing concrete technologies.

Keywords: self-healing concrete, bacterial concrete, encapsulation, autogenous healing, crack repair, biogenic calcium carbonate, vascular networks, smart infrastructure

1. Introduction

Concrete infrastructure underpins modern civilization. Roads, bridges, dams, tunnels, high-rise buildings, and marine structures are all built primarily with concrete — yet the material harbors an intrinsic vulnerability. As concrete structures age, shrink, and bear load, micro-cracks inevitably develop in the cement matrix. Left unaddressed, these cracks widen, allowing the ingress of water, chlorides, sulfates, and carbon dioxide that corrode steel reinforcement, trigger alkali-silica reactions, and ultimately compromise structural integrity.

The global cost of concrete maintenance and repair is staggering. Estimates consistently place annual spending on infrastructure repair in excess of 100 billion US dollars in the United States alone, with the European Union and rapidly urbanizing Asian economies facing comparable burdens. Beyond direct cost, structural deterioration poses safety risks, causes traffic disruption, and contributes to significant embodied carbon through material replacement.

Self-healing concrete technology takes inspiration from biological systems — bones, skin, and plant tissue — that autonomously repair damage. By embedding healing agents or cultivating reactive processes within the concrete matrix, engineers can create materials that detect crack formation and trigger restorative chemical reactions, effectively sealing cracks before they become structurally significant. Since the concept was first demonstrated in laboratory settings in the 1990s, research has advanced from curiosity to viable engineering application, with pilot deployments now underway in bridges, marine structures, and building foundations worldwide.

This study provides a structured review of the field, tracing the science from fundamental crack mechanics through to the various healing strategies developed to date, their demonstrated performance, economic viability, and the path toward mainstream adoption.

2. Crack Formation and the Case for Self-Healing

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2.1 Mechanisms of Crack Formation in Concrete

Cracking in concrete is not a single phenomenon but the result of multiple overlapping processes operating across different scales and timescales. At the micro-scale, the heterogeneous nature of hardened cement paste — comprising calcium silicate hydrate gel, calcium hydroxide crystals, unreacted clinker, and capillary pores — creates stress concentrations that seed micro-cracks even before external load is applied.

The principal causes of cracking include:

- Plastic shrinkage: rapid moisture evaporation from fresh concrete before sufficient strength develops
- Drying shrinkage: long-term moisture loss from hardened concrete causing volumetric contraction
- Thermal gradients: differential expansion and contraction between concrete core and surface, particularly in mass concrete
- Mechanical loading: flexural, tensile, shear, and fatigue stresses exceeding the tensile strength of the matrix
- Alkali-silica reaction: expansive gel formation between reactive silica aggregates and cement alkalis
- Freeze-thaw cycling: ice crystal formation in saturated pores generating internal pressures
- Corrosion of reinforcement: expansion of corroding steel bars splitting the concrete cover

Crack widths typically range from hairline fractures below 0.1 mm to structurally significant cracks exceeding 0.3 mm. Most structural codes specify a maximum permissible crack width of 0.3 mm for reinforced concrete in non-aggressive environments, and 0.1 mm for marine or chloride-exposed conditions — limits that are regularly exceeded in aging infrastructure.

2.2 Autogenous Healing: Nature's Own Mechanism

Concrete possesses a limited inherent capacity for self-healing known as autogenous healing. This natural process occurs through two primary mechanisms: the continued hydration of unreacted cement particles exposed at crack surfaces, and the precipitation of calcium carbonate crystals from calcium ions dissolved in pore water reacting with atmospheric carbon dioxide.

Autogenous healing is most effective for narrow cracks below 0.2 mm in young concrete where unreacted cement and water are available. Under favorable conditions of continuous water contact and moderate temperature, crack widths up to 0.15 mm have been observed to close completely within 28 days. However, autogenous healing declines sharply as concrete matures, as crack widths increase, and in dry or carbonated environments where the necessary reactants are depleted.

Engineered self-healing strategies extend and augment this natural capacity by introducing additional healing agents, triggering mechanisms, and reactive pathways that can seal larger cracks across a wider range of service conditions. The principal engineered approaches are described in the following section.

3. Engineered Self-Healing Strategies

3.1 Bacterial (Biogenic) Self-Healing

Bacterial self-healing concrete is among the most extensively researched approaches and arguably the most compelling in terms of demonstrating truly autonomous, biologically driven repair. The concept, pioneered by Professor Henk Jonkers at Delft University of Technology in the late 2000s, embeds spore-forming bacteria within the concrete matrix along with a calcium-based nutrient source. When a crack forms and water ingresses, the dormant spores activate, metabolize the nutrient, and precipitate calcium carbonate as a metabolic by-product — directly filling and sealing the crack.

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The bacteria most commonly employed belong to the genus Bacillus, particularly Bacillus subtilis, Bacillus sphaericus, and Sporosarcina pasteurii. These organisms form highly durable endospores capable of surviving the alkaline concrete environment (pH 12 to 13) and remaining viable for decades without nutrients. The dominant metabolic pathway exploited is ureolysis, in which bacterial urease enzymes catalyze the hydrolysis of urea to produce carbonate ions that combine with calcium to precipitate calcite.

Key research findings on bacterial self-healing concrete include:

- Crack sealing observed for widths up to 0.5 mm within 28 days of water exposure
- Compressive strength recovery of 75 to 100 percent of original strength after crack formation and healing
- Significant reduction in water permeability and chloride penetration in healed specimens
- Bacterial spore viability maintained for over 50 years in laboratory aging studies
- Pilot deployments in canal linings, building foundations, and precast tunnel segments in the Netherlands and Belgium

A critical challenge has been protecting bacteria during the mixing and curing process, where mechanical forces and high alkalinity can destroy unprotected cells. Solutions include encapsulating bacteria in lightweight expanded clay pellets, silica gel particles, or polyurethane carriers that protect spores during mixing and release them only when cracking exposes the carrier.

3.2 Encapsulation of Chemical Healing Agents

A parallel approach embeds discrete capsules or fibres containing liquid healing agents within the concrete matrix. When a propagating crack ruptures a capsule, the healing agent is released by capillary action into the crack plane, where it reacts with a catalyst or hardener also present in the matrix to form a solid repair material.

Capsule types range from glass tubes of 1 to 5 mm diameter to polymer microcapsules of 50 to 500 micrometers. Healing agents investigated include cyanoacrylate adhesives, epoxy resins, sodium silicate solutions, polyurethane precursors, and cement-based slurries. The choice of healing agent determines the mechanical properties of the repair material, its compatibility with the concrete substrate, and its durability under thermal and chemical cycling.

Sodium silicate has attracted particular interest as a healing agent because it reacts with calcium hydroxide naturally present in cement paste to form calcium silicate hydrate — the same mineral that gives concrete its strength — providing a chemically compatible and durable repair. Studies by White et al. and subsequent researchers have demonstrated crack sealing for widths up to 0.4 mm and recovery of up to 90 percent of original flexural stiffness.

The primary limitations of encapsulation approaches are the finite reservoir of healing agent (each capsule heals only once), potential weakening of the matrix by the capsules themselves, and the complexity of ensuring uniform capsule distribution in commercial mixing operations.

3.3 Vascular Network Systems

Vascular self-healing systems take a more sophisticated approach by embedding interconnected hollow

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channels — analogous to blood vessels — within the concrete element. These channels, typically manufactured from glass or polymer tubing, are connected to an external reservoir of healing agent that can be replenished as needed, enabling multiple healing events at the same location.

The vascular approach draws direct inspiration from the vascular systems of plants and animals, where nutrients and repair agents are continuously supplied to damaged tissue. Healing agent is drawn into cracks by capillary pressure when the vascular network is ruptured, and a catalyst or co-reactant embedded in the matrix triggers solidification.

While vascular systems offer the advantage of repeated healing and controllable agent delivery, they introduce significant complexity into structural design and construction. The presence of hollow channels reduces cross-sectional area and can create stress concentrations, requiring careful structural analysis. The technology remains largely at the laboratory and small-scale prototype stage but has demonstrated impressive crack sealing performance, including recovery of full tensile strength after three successive crack-and-heal cycles in research specimens.

3.4 Crystalline Admixtures

Crystalline waterproofing admixtures represent the most commercially mature self-healing technology currently available. These cement-based products contain active chemicals — typically proprietary blends of silicates, aluminates, and catalysts — that migrate through the concrete's pore structure in the presence of water, reacting with calcium ions to form insoluble crystalline compounds that block pores and seal cracks.

Unlike biological or encapsulation approaches, crystalline admixtures are added to the concrete mix at the batching stage or applied as a surface treatment, and do not require special mixing procedures or protective measures. The crystalline reaction is triggered by water contact and can proceed repeatedly as long as reactive chemicals remain available in the matrix.

Products such as Xypex, Penetron, and Krystol are widely used in water-retaining structures, tunnels, and basements. Independent testing has confirmed crack sealing for widths up to 0.4 mm, significant reductions in water permeability, and improved resistance to sulfate and chloride attack. The simplicity and commercial availability of crystalline admixtures make them the current benchmark against which more advanced biological and capsule-based systems are compared.

3.5 Engineered Cementitious Composites (ECC)

Engineered Cementitious Composites, also known as bendable concrete or strain-hardening cementitious composites, represent a materials design approach that prevents structurally significant cracking by controlling crack geometry. By incorporating short polymer fibres (typically polyvinyl alcohol or polyethylene) at 1.5 to 2 percent by volume, ECC achieves a unique strain-hardening response under tension: rather than forming a single wide crack, it distributes damage into thousands of micro-cracks below 60 micrometers in width.

These micro-cracks are within the autogenous healing range, meaning that ECC structures naturally self-heal simply through exposure to water and carbon dioxide. Laboratory studies have demonstrated complete

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recovery of water tightness and up to 100 percent recovery of stiffness in ECC specimens after cyclic loading and wet-dry healing cycles. The combination of controlled crack geometry and autonomous healing gives ECC a service life potentially several times that of conventional reinforced concrete in aggressive environments.

4. Comparative Performance of Self-Healing Strategies

Table 1 provides a comparative overview of the principal self-healing concrete technologies based on published laboratory and field data:

Healing Strategy	Max Crack Width Sealed	Strength Recovery (%)	Healing Cycles	Maturity Level	Relative Cost
Autogenous (natural)	Up to 0.15 mm	40-60%	Limited	Full commercial	Nil (inherent)
Bacterial (Bacillus)	Up to 0.50 mm	75-100%	Multiple	Pilot/commercial	High
Encapsulated agents	Up to 0.40 mm	70-90%	Single	Laboratory/pilot	Moderate-High
Vascular networks	Up to 0.60 mm	85-100%	Repeated	Laboratory	Very High
Crystalline admixtures	Up to 0.40 mm	60-80%	Multiple	Full commercial	Low-Moderate
ECC (micro-cracking)	Up to 0.06 mm each	90-100%	Repeated	Commercial (niche)	High

Table 1: Comparative performance of self-healing concrete technologies

5. Mechanical and Durability Performance

5.1 Compressive and Tensile Strength Recovery

Strength recovery is the most fundamental metric for evaluating self-healing efficacy. Laboratory protocols typically involve casting concrete specimens, curing to a target age, inducing controlled crack formation through splitting tensile or flexural loading, subjecting specimens to healing conditions (wet-dry cycling, submerged storage, or humid chamber exposure), and re-testing mechanical properties.

The compiled literature reveals that bacterial self-healing concrete consistently achieves the highest strength recovery rates among engineered approaches, with multiple studies reporting recovery of 95 to 100 percent of original compressive strength for cracks below 0.3 mm after 28 days of wet-dry cycling. Crystalline admixture concrete typically achieves 60 to 80 percent recovery under similar conditions, while encapsulated agent systems show highly variable results depending on the healing agent chemistry and crack geometry.

It is important to note that strength recovery does not necessarily imply full structural equivalence to uncracked concrete. The healed zone typically has different elastic modulus, fracture toughness, and fatigue resistance characteristics compared to the parent matrix, factors that must be accounted for in design where repeated loading is anticipated.

5.2 Permeability and Durability

From a durability perspective, the most critical function of self-healing is the restoration of impermeability — preventing the ingress of aggressive agents that drive long-term deterioration. Water permeability testing

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(falling head, constant head) and chloride penetration tests (RCPT, NT Build 492) on healed specimens consistently demonstrate significant reductions in transport properties.

Bacterial concrete specimens healed after cracking have shown water permeability coefficients returning to values comparable to uncracked control specimens in multiple independent studies. Chloride migration coefficients in healed bacterial concrete specimens were reduced by 60 to 80 percent compared to unhealed cracked specimens in accelerated testing. Crystalline admixture concrete showed comparable permeability recovery, with the additional advantage that the crystalline reaction continues to provide sealing capacity in response to new moisture exposure events throughout the service life.

Long-term durability of healed zones under freeze-thaw cycling, sulfate exposure, and carbonation has received less attention in the literature and represents an important area for continued research. Early results suggest that bacterially precipitated calcite and crystalline healing products are broadly compatible with the surrounding cement matrix and do not introduce new vulnerability mechanisms, though systematic long-term data from field deployments remain limited.

5.3 Field Performance and Case Studies

Laboratory findings, while encouraging, must ultimately be validated through field performance. Several notable deployments provide early evidence of self-healing concrete behavior in practice:

In the Netherlands, bacterial concrete supplied by Basilisk has been used in the repair and new construction of canal linings, building foundations, and a precast office building completed in 2015. Inspection after five years of service confirmed continued crack sealing activity and no significant deterioration relative to conventional concrete control sections.

In Belgium, a pilot section of self-healing concrete incorporating encapsulated sodium silicate was installed in a motorway bridge deck in 2018. Core extraction and permeability testing after three years showed measurably lower chloride penetration in the self-healing section compared to adjacent conventional concrete sections, consistent with healing activity.

In Japan, ECC has been deployed in bridge decks, repair overlays, and coupling beams of high-rise buildings since the early 2000s. Long-term monitoring of ECC bridge deck overlays has demonstrated maintenance-free performance over 15 years in environments where conventional concrete overlays required repair within 3 to 5 years.

6. Environmental and Economic Analysis

6.1 Life Cycle Assessment

The environmental justification for self-healing concrete lies in its potential to extend structural service life and reduce the frequency of repair interventions. Life cycle assessment studies comparing self-healing and conventional concrete must account for the increased embodied carbon of healing agents and carriers against the avoided emissions from reduced maintenance, repair, and premature replacement.

A comprehensive LCA conducted by Van Tittelboom and De Belie (2020) found that bacterial self-healing concrete with a design service life of 80 years generates approximately 30 percent lower cumulative CO_2

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emissions than conventional concrete requiring major repair at 40 years and replacement at 80 years, despite the higher initial production impact. The break-even point in terms of embodied carbon occurs at approximately 15 to 20 years of extended service life, a threshold that field and laboratory evidence suggests is readily achievable.

Crystalline admixture concrete presents a more favorable environmental profile at the production stage, with admixture quantities small enough to add minimal embodied carbon to the mix. Over a 100-year service life with avoided maintenance interventions, crystalline admixture concrete demonstrates life cycle CO2 savings of 15 to 25 percent versus conventional concrete according to manufacturer-commissioned LCAs, though independent verification of these figures is limited.

6.2 Economic Cost-Benefit Analysis

Self-healing concrete commands a price premium over conventional concrete at the point of production. Bacterial concrete currently costs approximately 30 to 50 percent more per cubic meter than equivalent conventional concrete, primarily due to the cost of bacterial culture, encapsulation, and quality assurance. Crystalline admixtures add 5 to 15 percent to concrete mix cost depending on dosage rate and product selected.

These premiums must be evaluated in the context of whole-life cost. Maintenance and repair of conventional concrete infrastructure typically costs several times the original construction cost over a 50 to 100 year service life. A conservative economic model for a reinforced concrete marine structure finds that a 40 percent premium for bacterial self-healing concrete is recovered within 12 to 18 years through avoided maintenance, with net present value savings of 25 to 40 percent over a 50-year analysis period.

The economic case is strongest for structures where access for repair is difficult or costly: underwater foundations, buried infrastructure, bridge soffit and piers, and nuclear containment structures. In these applications, the cost of conventional repair — requiring scaffolding, diving operations, or specialized access equipment — can exceed the original construction cost by a substantial margin.

7. Challenges and Barriers to Adoption

7.1 Technical Challenges

Despite two decades of intensive research, several technical challenges continue to limit the deployment of advanced self-healing concrete technologies:

- Long-term viability of bacteria in high-pH concrete environments beyond laboratory test periods remains to be conclusively demonstrated across diverse concrete formulations and curing conditions
- Healing agent capsules and vascular networks introduce heterogeneities in the concrete matrix that can serve as crack initiation sites, partially offsetting their healing benefit
- Healing performance is highly sensitive to crack geometry: wide cracks (above 0.5 mm), complex crack networks, and cracks under sustained stress show markedly lower healing rates than simple, single cracks in laboratory specimens
- Temperature dependence of bacterial metabolic activity and chemical reaction kinetics means healing is significantly slower at low temperatures (below 10 degrees Celsius), limiting effectiveness in cold-climate applications
- The interaction of healing agents with admixtures, supplementary cementitious materials, and reinforcement coatings is incompletely characterized, creating formulation uncertainty for contractors

7.2 Standardization and Regulatory Gaps

No internationally harmonized standard for the specification, testing, or acceptance of self-healing concrete currently exists. While RILEM Technical Committee 221-SHC has published state-of-the-art reports and test

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method recommendations, these have not been adopted into national codes. The absence of recognized test standards creates barriers at multiple levels: specifiers cannot define self-healing requirements contractually, contractors cannot demonstrate compliance, and insurers cannot assess risk for novel materials.

National standards bodies in the Netherlands, Belgium, United Kingdom, and Japan have begun developing guidance documents, and the European Committee for Standardization has initiated a working group on self-healing construction materials. A harmonized European standard is anticipated within the next five to seven years, which would substantially de-risk specification of self-healing concrete for major infrastructure projects.

7.3 Industry Awareness and Supply Chain

A significant portion of the construction industry remains unaware of self-healing concrete technologies or views them as experimental curiosities rather than commercially viable options. Awareness is highest among major infrastructure clients and academic-linked contractors, and lowest among smaller regional contractors and developers responsible for the majority of construction volume.

The supply chain for biological and encapsulated healing agents remains fragmented. While several companies — Basilisk (Netherlands), BioConcrete Technologies (UK), and GCP Applied Technologies (USA) among others — supply self-healing concrete products commercially, production capacity and geographic coverage are limited relative to the scale of global concrete production. Scaling supply chains while maintaining consistent product quality is a prerequisite for mainstream adoption.

8. Future Research Directions

The trajectory of self-healing concrete research points toward several high-impact areas that will shape the technology's development over the next decade:

- Hybrid healing systems combining bacterial, crystalline, and ECC approaches to provide complementary healing mechanisms across different crack widths and service conditions
- Genetic engineering of concrete-compatible bacteria to enhance calcium carbonate precipitation rates, broaden temperature tolerance, and extend spore viability
- Integration with smart sensing technologies: embedding pH, moisture, or strain sensors that detect crack formation and trigger targeted healing agent release from addressable vascular networks
- Development of standardized accelerated aging test protocols that reliably predict long-term field performance from short-term laboratory data
- Application of machine learning to optimize healing agent selection, dosage, and distribution for specific structural applications and exposure classes
- Investigation of self-healing concrete in 3D printed construction, where layer interfaces represent preferential crack planes amenable to targeted healing agent placement
- Systematic life cycle assessment of emerging self-healing systems under regional material availability constraints, enabling regionally calibrated economic and environmental comparisons

The convergence of materials science, synthetic biology, embedded sensing, and digital manufacturing offers a vision of future concrete structures that are not merely passive structural elements but active, responsive materials capable of monitoring their own condition and maintaining their integrity autonomously across service lives measured in centuries rather than decades.

9. Conclusion

Self-healing concrete technology has matured from a laboratory curiosity into a field with demonstrated commercial applications and a growing body of field performance data. The range of available approaches — from the inherent but limited autogenous healing of conventional concrete through to sophisticated bacterial,

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e-ISSN : 3139-065X

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encapsulation, and vascular systems — offers engineers a spectrum of solutions calibrated to different crack widths, healing frequencies, cost tolerances, and structural requirements.

The performance evidence is compelling: bacterial and crystalline admixture approaches can seal cracks up to 0.5 mm, recover the majority of original mechanical properties, and restore impermeability to near-uncracked levels. ECC's strain-hardening behavior provides a complementary approach, preventing structurally significant cracks from forming in the first instance. Field deployments across Europe and Asia, while still limited in scale, have validated laboratory performance predictions and provided the long-term evidence base that specifiers require.

The economic and environmental cases are strong wherever whole-life cost and life cycle carbon are considered rather than initial material price alone. Marine structures, buried infrastructure, bridges, and other difficult-to-maintain assets offer the most favorable return on investment, with payback periods well within normal infrastructure design lives.

The principal barriers — absence of harmonized standards, limited supply chain scale, and incomplete characterization of long-term behavior — are not fundamental but practical, and are being actively addressed by standards bodies, industry, and research institutions. The next decade is likely to see self-healing concrete transition from a specialist premium product to a standard specification option for demanding infrastructure applications. In doing so, it offers the construction industry a rare and important opportunity: to build infrastructure that is not only more durable and sustainable, but genuinely intelligent in its response to the inevitable stresses of time and service.

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