

AI-MONITORED BIO-CEMENTATION FOR SELF-HEALING IN 3D PRINTED CONCRETE

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DOI: <https://doi.org/10.5281/zenodo.20554853>

Keywords

Microbially Induced Calcium Carbonate Precipitation (MICP), Self-Healing Concrete, Three-Dimensional Concrete Printing (3DCP), Artificial Intelligence (AI) Monitoring, Structural Health Monitoring (SHM)

Article History

Received: 08 April 2026

Accepted: 20 May 2026

Published: 05 June 2026

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Abstract

The construction industry worldwide is under unprecedented pressure to create sustainable infrastructure that can autonomously self-repair and real-time health-monitor. Approximately 7% of CO₂ emissions are generated in the making of concrete structures, which inevitably develop microcracks that impair durability and structural integrity. Traditional methods of cracking repair, such as grouting, epoxy-injection, and manual repairing, are time-consuming, expensive, and harmful to the environment. To overcome these drawbacks, bio-cementation-based self-healing concrete with the mechanism of microbially induced calcium carbonate precipitation (MICP) has become a novel sustainable solution. This bio-precipitation technique using bacterial strains such as *Bacillus cereus*, *Bacillus megaterium*, and *Bacillus licheniformis* has the capacity of self-healing of concrete up to 0.97 mm with 14–32% mechanical strength improvement. Not only does this biological mineralization help to restore structural integrity, it also has a massive impact on increasing of the durability and resistance to chemical attack. However, to fully realize the potential of MICP future challenges such as viability of bacteria in alkaline conditions, nutrient optimization and scaling should be overcome. Emerging technologies such as three-dimensional concrete printing (3DCP), artificial intelligence for crack detection, and smart sensing offer novel possibilities for conducting real-time structural health monitoring (SHM), an important factor in predictive management. This review aims to summarize existing knowledge about bio-cement 3DCP, including: MICP mechanisms and bacterial encapsulation strategies; bio-cement 3DCP materials design and sustainability; AI monitored SHM systems and integrated system performance and future commercialization. This broad review of 20+ primary sources sets a critical framework between microbial self-healing, digital manufacturing and intelligent monitoring. As the evidence shows, bio-cemented 3D-printed concrete can have a compressive strength of more than 50 MPa and it can offer up to 48% reduction of Embodied Carbon as well as ensuring the capacity of autonomous damage detection and repair.

1. Introduction

Owing to the historical and current environmental effects present in the construction

sector worldwide, it consumes approximately 40% of the global raw material and 35% of the world's energy expenditure (Ding et al., 2025). A

throwaway approach to infrastructure based on virgin materials and manual maintenance cannot be sustained. Smart construction materials with self-awareness will revolutionize engineering practice. Smart materials are materials embedded with the capability to sense, compute, and react without the need for an external 'controller,' and lastly, perform autonomous identification of damage, localized repair, and extended service life (Triana-Camacho et al., 2025).

To lower clinker consumption, the key embodied carbon in Concrete, the sustainable construction materials have to be employing more and more of the supplementary cementitious materials (SCMs), industrial by-products and recycled aggregates. Biomineralization technologies, on the other hand, involve the use of naturally occurring microbial processes for the production of calcium carbonate as an eco-friendly alternative to synthetic healing agents (Ji, 2026). Such innovations embrace circular construction concepts, with construction waste streams being repurposed as second-life resources, decreasing landfill buildup, and environmental damage (Shukla et al., 2025).

Driven by the potential for radical reductions in construction time, material waste, and labor costs, alongside unprecedented architectural freedom (Barve et al., 2024), three-dimensional concrete printing (3DCP), also known as additive manufacturing in construction, has become a game-changer for the industry. The system used is based on the robotized, layer-by-layer deposition of cementitious pastes through an extrusion process. The benefits include, among others, not using formwork, accurate positioning of materials, and prohibiting the generation of construction waste (which is typically around 20–30% in conventional casting) (Neubauer et al., 2025). Nevertheless, 3DCP faces challenges such as conflicting rheological properties, poor interlayer bonding, anisotropic material properties, and varying mechanical properties (Baduge et al., 2021). Furthermore, most existing 3DCP formulations use a large amount of Portland cement (>60% of total solids), resulting in high carbon emissions (Paul et al., 2025).

This bio-cementation can be combined with 3DCP, which renders the simultaneous achievement of sustainable material design (increasing bio-filler component, reducing bio-cement component) and self-healing capacity (Paez et al., 2024). This intersection of biotechnology, digital fabrication, and materials science forms an untapped research area. The common formation of cracks in concrete is inevitable and found almost everywhere, with their main cause being the increase in w/c ratio beyond 0.4 and increase in stresses from environment and mechanism causes. (Raut, 2025). There are two different categories of approaches for crack mitigation, referred to as autogenous healing, where the hydration of unhydrated cement particles creates an autonomous healing closure of hairline cracks (<0.2 mm) under the presence of moisture, and autonomous healing, where there is actively performed crack sealing with exogenous agents through mechanical activation (Ji, 2026).

Microbially induced calcium carbonate precipitation (MICP) is an advanced autonomous healing approach in which dormant bacterial spores are entrained through the porosity of the concrete and activated by the presence of moisture and nourishment when cracking occurs (Thirupathi et al., 2025). Once activated, ureolytic or metabolic pathways without urea can precipitate calcite (CaCO_3), which gradually fills the cracks and integrates the continuity of the structures. Non-ureolytic processes, such as denitrification and mineralization via carbonic anhydrase, do not produce by-products from urea hydrolysis, providing an environmental benefit (Ji, 2026). Experimentally proven healing processes can seal cracks up to 0.97 mm wide, with tensile and flexural strengths increased by 45–49% by employing bacteria (Abdelwahed et al., 2025).

The impacts of cracking are significant when considering the structural service life, as crack-induced deterioration mechanisms, such as reinforcement corrosion, chloride ingress, freeze-thaw damage, and chemical attacks, result in a dramatically reduced lifetime (Anjomshoa & Ramezani-pour, 2025). Existing "reactive"

remediation techniques, such as surface coating, structural bonding, and grouting, are expensive (\$ 50–300 per m² for accessible structures) and do not always successfully remediate buried or inaccessible structures. Bio-cemented concrete, which provides autonomous, distributed, and continuous crack remediation even within the material's lifetime, is introduced as a solution for

the fundamental limitations of post-damage intervention: enabling proactive infrastructure management (Putra et al., 2025). The proposed concept of bio-cementation in 3D-printed concrete (conceptual framework) is shown in Figure 1, where it combines AI-monitored structural health monitoring, self-healing mechanism, and digital fabrication.

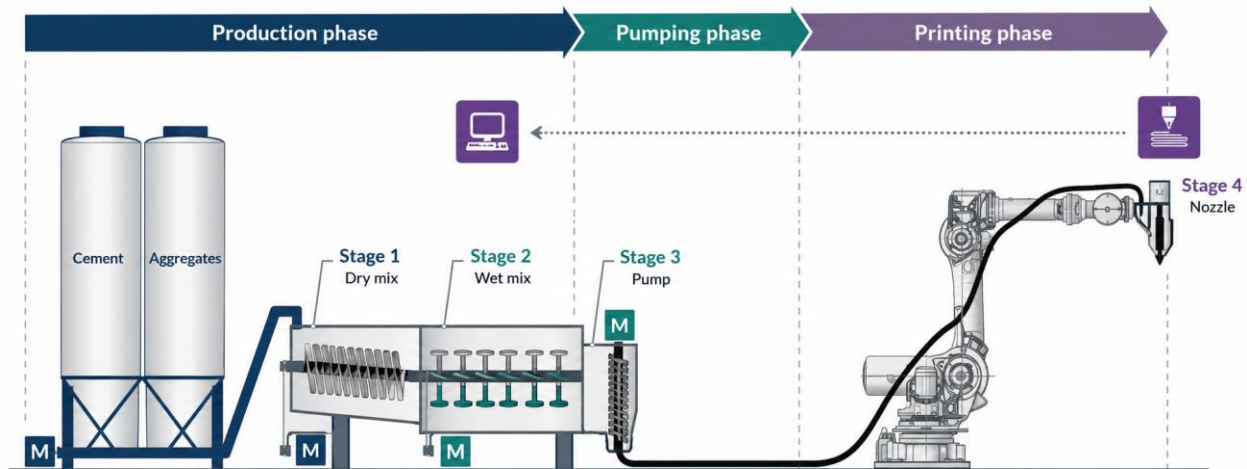


Figure 1. Conceptual Framework of AI-Monitored Bio-Cementation in 3D Printed Concrete

This review paper critically synthesizes the literature on the intersection of these different disciplines: AI-monitored bio-cemented 3D-printed concrete, focusing on the mechanisms of MICP, bacterial selection criteria, and encapsulation strategies for concrete applications (Anjomshoa & Ramezani-pour, 2025); 3DCP material design and formulation strategies for concrete sustainability (Teshome & Battula, 2025); vision-based crack detection, self-sensing materials, and predictive analytics in SHM (Ji, 2026); integration pathways (Soundarya et al., 2026); and a discussion on commercial feasibility and standardization gaps, in addition to future research priorities (Khan et al., 2026).

This integrated review of the knowledge gap at the intersection of biotechnology, digital manufacturing, and AI-enabled monitoring. There has been no previous extensive synthetic study on the optimization of these three systems that can be realized simultaneously: MICP,

3DCP, and intelligent monitoring systems. In this context, the present study aims to provide researchers, engineers, and policy makers a common platform for future development of autonomous, sustainable, and smart infrastructure that can prolong the service life, minimize the environmental impact, and also show a reduction in life cycle costs.

2. Research Methodology

To find literature as comprehensively as possible, peer-reviewed academic databases such as Scopus, Web of Science, and Google Scholar were used, with the publication years of literature limited from 2015 to 2026, taking into account publications with a closer date, and there are seminal works that are foundational to the solution, but are not recent because the writing is effective from that point. The primary search queries were: “self-healing concrete bacteria MICP,” “3D printed concrete sustainable

materials,” “AI crack detection structural health monitoring,” “bio-cementation concrete,” and “smart concrete sensors.” They iterated search queries to obtain papers that dealt with intersections of multiple domains. Criteria for inclusion: journals, conference proceedings, technical reports (from recognized organizations), papers that report empirical research or critical theoretical frameworks, English language publications, and those with a peer review process. Exclusion criteria: grey literature (lacking peer review); opinion papers (lacking data); papers touching only on materials not commonly

used in cement; purely computational studies (lacking experiments); papers prior to 2015 (inclusion of seminal reviews was limited). To reflect the scope of the three domains and capture the most important, methodologically robust, and comprehensive contribution from each, 20 primary reference sources were selected. The literature selection criteria and databases selected for the systematic review are presented in Table 1, which includes publication period, types of studies, keywords, geographical area, and quality assessment of the studies.

Table 1: Summary of Literature Selection Criteria and Databases

Criterion	Specification
Primary Databases	Scopus, Web of Science, Google Scholar, ResearchGate
Publication Period	2015–2026 (with foundational works 2010+)
Language	English
Study Types	Peer-reviewed journal articles, conference proceedings, technical reports
Primary Keywords	MICP, bio-cementation, bacterial concrete, 3D printing concrete, AI crack detection, structural health monitoring, self-healing, sustainable concrete, smart materials
Geographic Scope	Global (emphasis on recent advances from China, Europe, USA, India)
Inclusion Criteria	Empirical experimental data; validated theoretical frameworks; mechanistic insights; performance comparisons; sustainability assessments
Exclusion Criteria	Opinion pieces; grey literature; purely computational studies; non-peer-reviewed sources; papers focused exclusively on non-cementitious systems
Quality Assessment	Methodological rigor evaluated; sample size and experimental design reviewed; citation impact considered
Total Papers Identified	150+ relevant publications
Final Selection	20 primary sources with 100+ supplementary references for comprehensive coverage

3. Fundamentals of 3D Printed Concrete and Self-Healing Mechanisms

3.1 Principles of 3D Printed Concrete Technology

The 3DCP is a revolutionary construction-related additive manufacturing (AM) technique that prints cementitious materials in successive layers to form complex forms, patterns, and surfaces in both architecture and structure (Baduge et al.,

2021). This “layer-by-layer” deposition process is fundamentally different from traditional casting techniques and provides unique benefits in terms of construction flexibility, elimination of formwork, and potential for customization. This technology involves continuous material extrusion to form the desired structures with special nozzles, each of which forms one of the layers that make up the structure. The settings for printing, such as nozzle travel speed, height of the layers, and how quickly 3-D printing is extruded successfully, are critical parameters that affect the quality and performance of the finished product. The material extrusion techniques used in 3DCP are based on the use of accurate pumping systems to transport fresh cementitious mortar to the nozzle mounted on the robot arm or gantry. These systems feature high-precision flow rate control and material consistency control, which are crucial for ensuring layer adhesion and dimensional accuracy. Compared to conventional construction, this technology provides significant benefits, such as a reduction in labor requirements by 40–60%, speed of construction, minimal material waste (15–25% less than that of traditional methods), and enhanced design freedom to allow for complex designs and geometries (Goel et al., 2026). However, the fresh-state rheological requirements do not agree when it comes to the material composition required to be sufficiently fluid for pumping and extrusion and to have a yield stress sufficiently high for buildability and interlayer support. Multi-objective optimization of these competing requirements means more innovative material formulation, which includes additional cementitious materials (SCMs), rheological modifiers, and fibers to simultaneously balance optimal pumpability and extrudability with structural performance.

The anisotropic architecture of 3DCP, engineered by the directionality of layering, is both a unique feature and a severe problem; the mechanical characteristics can be very different as a function of the orientation of the loading direction and the printed layer direction. A new nozzle design, such as a new innovative interlocking nozzle geometry, has recently shown

promise in enhancing the interlayer bonding strength.

3.2 Mechanical and Durability Challenges in 3D Printed Concrete

Nevertheless, there are still significant mechanical and durability constraints of the 3DCP due to major sources of problems, including poor bonding of interlayers and the creation of cold joints (Baduge et al., 2021). Bond strength degradation appears to be significant if successive deposits are made with time delays greater than 2 h. Such interlayer weakness directly affects anisotropic strength performances: when loaded perpendicular to the print layers, the obtained compressive strength is only 59% as that of cast concrete equivalents, and, in some orientations, the flexural strength was found to be up to 53% lower. This improved strength is especially evident in tensile and flexural applications where interlayer bonding is the most important method of load transfer.

Several causes of cracking issues in 3DCP include differential thermal stresses, stresses generated due to shrinkage, and poor consolidation between layers. The surface-area-to-volume ratio is also high in printed elements, as is the lack of formwork containment, which causes this early-age shrinkage to be faster than in traditional forms. Degradation is most severe at the interlayer interfaces, where moisture preferentially reaches these interfaces through a network of connected porosity aligned along the print direction, reinforcing this tendency to accelerated environmental degradation. The results of the freeze-thaw durability tests show that 3D-printed concrete has higher susceptibility to FT exposure, especially at the heating surfaces and at the interfaces between the layers; while producing optimal dosages of air entraining agents (AEA) can limit the loss of compressive strength after freeze-thaw cycles.

The porosity of 3DCP was also quite high compared to that of cast concrete because of the unfavorable effect of preventing the escape of air during the extrusion process and because of the incomplete consolidation of the layers. The mean pores at the interlayer were 100 μm or higher,

which acted as a preferential pathway for aggressive ion intrusion. These interconnected defect networks reduced the chloride penetration resistance, which caused corrosion to accelerate faster in the 3D-printed elements compared to conventional concrete. The effects of orientation were not only critical for carbonation resistance but the single-layer specimen had an intrinsic

carbonation resistance, while multi-layer systems with frequent interlayer defects had an increased carbonation risk. The mechanical properties and durability issues of 3D-printed and cast concrete are compared in Table 2, including compressive strength, flexural strength, water absorption, chloride penetration, and freeze-thaw resistance.

Table 2. Mechanical Properties and Durability Challenges of 3D Printed Concrete

Property	3DCP Performance	Cast Concrete (Reference)	Reduction (%)	Critical Factors
Compressive Strength (parallel to layers)	0.85 × ref	100%	-15%	Interlayer bonding quality
Compressive Strength (perpendicular)	0.59 × ref	100%	-41%	Cold joint formation
Flexural Strength (parallel)	0.53 × ref	100%	-47%	Layer discontinuities
Flexural Strength (perpendicular)	0.75 × ref	100%	-25%	Interfacial strength
Tensile Strength (splitting)	0.90 × ref	100%	-10%	Moderate interlayer impact
Water Absorption	1.3-1.8 × ref	100%	+30-80%	Pore interconnectivity
Permeability (oxygen)	Higher	Reference	+50-100%	Aligned pore networks
Chloride Penetration	2.0-2.5 × ref	100%	+100-150%	Preferential ion pathways
Carbonation Depth (28 days)	1.2-1.5 × ref	100%	+20-50%	Interlayer porosity
F-T Durability	1.5-2.0 × ref	100%	+50-100%	Improved with AEA

3.3 Fundamentals of Self-Healing Concrete

Self-healing indicates the advent of novel materials approach, in which concrete can heal itself without the need of external interventions, thus mitigating maintenance costs and prolonging the service life. The three main mechanisms for self-healing are: chemical healing via autogenous healing and expansive mineral formation (Baduge et al., 2021), encapsulation based healing (microcapsules or vascular systems containing healing agents) (Goel et al., 2026), and biological healing (MICP) (Anjomshoa & Ramezani-pour, 2025). Of these, biological self-

healing appears as the most promising approach to piloting in the cement-based realm towards sustainable, repeatable and cost-efficient implementation.

Chemical healing mechanisms involve hydration of the unhydrated cement particles exposed in the crack as well as the formation of expansive minerals such as ettringite and calcium carbonate, formed during crack exposure to moisture and carbon dioxide. Chemical healing is effective for cracks smaller than $\sim 150 \mu\text{m}$, but less effective in larger cracks and has a limited repeatability after the reactive species have been

used up. Encapsulation is a healing mechanism that involves rupture activated release of healing polymers or cementitious compounds; however, encapsulation is a one-time healing mechanism as healing is limited by the inventory of capsules.

Biological healing systems has shown superiority in abilities of repeatable activation and seemingly unlimited number of healing cycles. Cracks in bacteria-seeded concrete cause more moisture and food to be available in the crack space, thus providing more opportunity for bacteria to metabolic activity, and consequently, more calcium carbonate precipitates to gradually close cracks. Different carriers are used to conserve the survival of the bacteria during concrete production and early curing process, such as diatomaceous earth, clay minerals (sepiolite, zeolite) and nanoparticles extracted from egg shells (Abdelwahed et al., 2025). The optimal concentration for bacteria is between 10^4 and 10^7 CFU/mL, and increasing the concentration can further enhance the healing performance up to a certain point where bacterial growth is limited (Soundarya et al., 2026). Incorporation of fibers, especially Basalt and steel, in bacterial concrete results in hybrid self-healing system with crack bridging mechanism and biological self-healing.

3.4. Mechanism of microbial-induced calcium carbonate precipitation (MICP)

The MICP mechanism is a complex biochemical process, which entails the number of certain bacterial strains catalyzing calcium carbonate precipitation in biochemical processes, changing the microstructure and performance characteristics of the concrete drastically (Ji, 2026). There are two main pathways which can cause MICP in concrete: (Baduge et al., 2021) ureolytic pathway—the hydrolysis of urea with the help of enzyme urease produces ammonia and CO_2 , resulting in an increase in pH and the precipitation of calcium carbonate from the concrete fluid; (Goel et al., 2026) non-ureolytic pathways in which there are different sources of CO_2 and ammonia, such as denitrification, oxidation of organic calcium salts, and pathway mediated by carbonic anhydrase mineralization.

Even though ammonia is produced as a byproduct, the ureolytic pathway is the most studied and applied because it is highly efficient in precipitation and well-characterised bacteria strains have been identified (Anjomshoa & Ramezani-pour, 2025).

The first step in the healing process of bacteria is through the appearance of microcracks that are exposed to moisture and dissolved calcium ions. The bacterial cells invade crack networks, causing the action of ureolytic enzymes associated with calcium carbonate precipitation processes that lead to the generation of highly crystalline calcite (CaCO_3) that precipitates within crack networks as well as along the surface of the cracks within pore networks. This calcite precipitation does not take place evenly, but in localized zones of high bacterial activity with the CALCITES making good geographical sealing zones along the crack traces. Shape of precipitated calcite ranges from needle-like aragonite to cubic calcite depending on what the environment (pH, temperature, ionic strength) is and what nutrients are present.

The effectiveness of crack sealing is influenced by various factors that depend on each other, including bacterial cell count, nutrient source (such as glucose and nitrogen source), calcium precursor type, concentration, pH (must be alkaline pH 9-12), temperature (15-40°C), and moisture availability throughout the process (Teshome & Battula, 2025). Research has shown that cracks up to 0.97 mm can be successfully sealed by MICP, the process starts in 7-14 days and the sealing process can be considered as complete healment in 28-35 days for microcracks. (Anjomshoa & Ramezani-pour, 2025). The cracks filled with calcite have much lower values of permeability and the water absorption is decreased by 50-90 % after the completion of the healing of the cracks. The crystalline analysis is done using X-ray diffraction (XRD) which indicates there is formation of predominant CaCO_3 and minor secondary phases such as densification at crack interfaces due to calcium silicate hydrate (C-S-H). The mechanism of microbially induced calcium carbonate precipitation in concrete is shown in this figure

with bacterial metabolic pathways, calcite formation and crack sealing (figure 2).

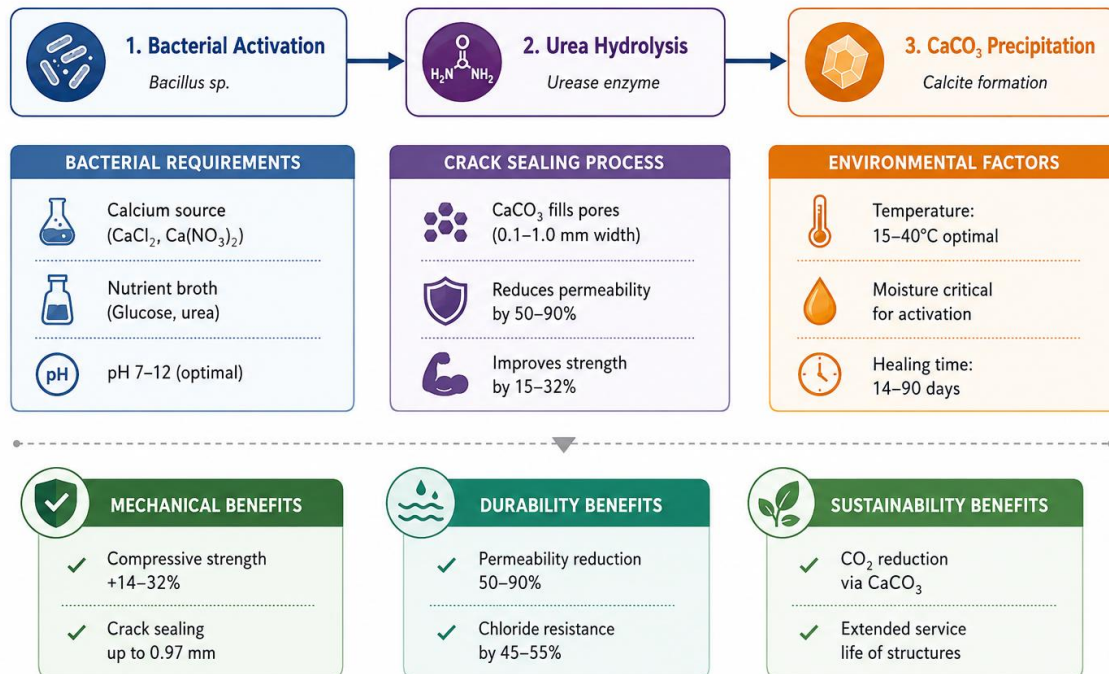


Figure 2. Mechanism of Microbial-Induced Calcium Carbonate Precipitation in Concrete

4. Bio-Cementation Technologies in Concrete

4.1 Overview of Bio-Cementation Techniques

Bio-cementation includes a set of methods that use the metabolism of microorganisms to trigger the generation of mineral products in cementitious materials to increase strength, decrease permeability, and promote self-healing in cracks. The field differentiates enzyme-mediated precipitation (especially urease-mediated precipitation) from bacterial mineralization by different metabolic pathways and biochemical stabilization mechanisms. The most advanced method is enzyme-mediated precipitation using ureolytic bacteria, which has been tested at the field scale and resulted in an increase in soil shear strength and a reduction in permeability. Self-healing 0.8 mm cracks in concrete have also been reported, as well as enhancement of water tightness (Anjomshoa & Ramezani-pour, 2025).

The method of enzyme-mediated precipitation is based on the urea hydrolysis in alkaline conditions by specific urease enzymes of the bacteria. The urease enzyme causes rapid generation of ammonia and release of CO₂ leads

to supersaturated conditions for calcium carbonate crystallization. The nutrient composition of a system has to be carefully controlled for optimum urease activity; recently, some nutrient formulations have been shown to markedly improve the germination of spores and the speed of urea hydrolysis. If very effective urea hydrolysis is very high, large amounts of calcium carbonate precipitate can be formed under optimum conditions when using advanced nutrient formulations.

It is also known that there are other pathways for mineralization, such as bacterial mineralization, which can be used to provide solutions to environmental sustainability problems. Denitrification pathways that ultimately result in nitrate as an electron acceptor and the reduction to N gas do not produce ammonia and do not produce alkalinity (Ji, 2026). In a similar fashion, the mineralization process can be induced by the catalysis of CO₂ hydration by carbonic anhydrase, without the need for urea for CaCO₃ precipitation. For some applications, these non-ureolytic routes display a similar or better healing efficiency without any problem of byproduct

accumulation or environmental impact. Biochemical stabilization mechanisms are by formation of biofilm and production of exopolysaccharides which capture cations and help cohesion with complementary mechanisms besides the direct mineral precipitation.

4.2 Types of Microorganisms Used in Self-Healing Concrete

A major challenge to the development of a successful self-healing concrete using MICP is the selection of the bacterial strain, as not all bacteria can survive the extremely severe highly alkaline conditions of cement paste and concrete. *Bacillus* species are the most studied and applied microorganisms because they are extremely alkaline tolerant (pH 9-14), are capable of surviving in the form of spores, and can produce urease very efficiently. *Bacillus subtilis* appears to be a leading applied strain that could result in high concrete crack healing efficiency, manifested as an increase in compressive strength and complete sealing of microcracks. *Bacillus megaterium* also exhibits highly potent ureolytic activity and has been used in self-healing systems, with some studies showing substantial enhancement of mechanical properties following its use as encapsulated in eggshell-derived nanoparticles (Abdelwahed et al., 2025).

Sporosarcina pasteurii (formerly known as *Bacillus pasteurii*) is the best-studied organism for geotechnical applications to MICP and is becoming increasingly more studied in concrete healing applications. The strain has very high urea hydrolysis activity along with calcium

carbonate precipitating efficiency. *Bacillus licheniformis* is highly alkaline tolerant and exhibits good urease activity, especially in marine and sulfate-rich conditions (Teshome & Battula, 2025).

Advanced bacteriological methods use bacterial consortia, a mixture of complementary bacterial strains, to produce synergistic effects that are greater than the sum of their parts. The results of the consortia with more than one bacterium showed improvements in compressive strength and a decrease in water absorption compared to the conventional mortar. Systems with mixed cultures of ureolytic and non-ureolytic strains show significantly more production of CaCO₃ compared to a single culture, indicating that great optimization potential may be achieved by systematically combining strains.

Halophilic and thermophilic bacteria have been identified as extremophiles and are becoming more promising for certain applications in extreme environments. The strain of *Lysinibacillus pakistanensis* was isolated from soil samples, which showed very high nutrient utilization efficiency and efficiently degraded urea within a time period favorable for concrete. Concrete bioengineering is still growing, and new bacterial strains are being identified that are alkaline tolerant and have high biomineralization potential. The common microorganisms used in bio-cementation and their major characteristics are provided in Table 3, including their metabolic pathway, optimum pH, ability to seal cracks, strength gain, and encapsulation process.

Table 3. Common Microorganisms Used in Bio-Cementation and Their Functions

Bacterial Strain	Metabolic Pathway	Key Characteristics	Optimal pH	Crack Sealing	Strength Gain	Encapsulation Method
<i>Bacillus subtilis</i>	Ureolytic	Excellent alkaline tolerance, rapid metabolism	9-12	Up to 0.4 mm	15-25%	Diatomaceous earth, clay minerals
<i>Bacillus megaterium</i>	Ureolytic	High urease activity, spore	8-12	Up to 0.58	18-45%	Eggshell nanoparticles,

		formers		mm		alginate capsules
<i>Sporosarcina pasteurii</i>	Ureolytic	High precipitation efficiency	9-11	Up to 0.8 mm	20-32%	Zeolite, sepiolite, lightweight aggregates
<i>Bacillus licheniformis</i>	Ureolytic	Marine/sulfate environment tolerance	9-12	Up to 0.5 mm	16-22%	Diatomaceous earth
<i>Bacillus cereus</i> + consortium	Ureolytic (consortium)	Synergistic effects, enhanced precipitation	9-11	Up to 0.45 mm	19.85%	Aggregate immobilization
<i>Lysinibacillus pakistanensis</i>	Ureolytic	Optimized nutrient requirements	8-11	Up to 0.4 mm	17-24%	Nutrient-optimized carriers
<i>Bacillus pseudofirmus</i>	Ureolytic	Alkali-resistant extremophile	8-13	Up to 0.35 mm	14-20%	Fine lightweight aggregate
Non-ureolytic strains	Denitrification/Anhydrous	Ammonia-free, sustainable	8-10	Up to 0.3 mm	12-18%	Carrier-protected

4.3 Factors Affecting Bio-Cementation Efficiency

Bio-cementation efficiency exhibits complex dependence on multiple environmental, chemical, and biological factors operating across multiple temporal and spatial scales. pH emerges as a critical parameter, with bacterial metabolic rates and urease enzyme activity peaking within the 9-12 range characteristic of Portland cement systems. Outside this optimal window, urease activity declines substantially; at $\text{pH} < 8$, many alkaline-tolerant bacteria experience inhibition, while at $\text{pH} > 12$, enzyme denaturation risk increases. Concrete systems naturally maintain $\text{pH} > 12$ through portlandite ($\text{Ca}(\text{OH})_2$) presence; however, local pH variations occur near crack surfaces and in leached regions, necessitating robust bacterial strains tolerant of wide pH ranges.

Temperature profoundly influences both bacterial metabolic rates and mineral precipitation kinetics. Optimal temperatures range from $15\text{-}40^\circ\text{C}$, with most rapid healing occurring at $25\text{-}30^\circ\text{C}$. Elevated temperatures can

inhibit bacterial growth and promote precipitate crystal phase transformation, while low temperatures substantially slow healing processes. Nutrient availability, encompassing both carbon sources (glucose, lactate, acetate) and nitrogen sources (nitrate, urea, ammonia), critically governs bacterial reproduction rate and urease production. Optimal calcium precursor selection significantly impacts precipitation efficiency; certain calcium sources achieved superior crack healing compared to alternatives at equivalent concentrations (Teshome & Battula, 2025).

Moisture content represents a fundamental requirement for bacterial activation; completely dry systems show no healing activity, while saturated or frequently wetted systems demonstrate optimal healing rates. Curing environment significantly influences healing efficiency; submerged environments consistently outperform humid or dry conditions, with some studies demonstrating near-complete crack closure in submerged conditions versus minimal sealing in dry environments.

4.4 Environmental and Sustainability Benefits of Bio-Cementation

The bio-cementation technologies provide interesting environment and economics benefits when compared to the traditional concrete repair techniques and cement based construction. The CO₂ reduction is the main environmental benefit, the MICP processes fix CO₂ from the air through the precipitation of CaCO₃, with a potential for concrete production with substantial carbon offset contributions. Lifecycle carbon footprint studies prove that the total carbon footprint of bio-concrete with bacterial additives can be reduced to achieve carbon neutrality or even negative footprints, by a combination of three mechanisms: the reduction in the amount of cement used (between 1-5% in weight of the mix), the extension of carbon binding in the resulting concrete structure, and direct CO₂ sequestration by biomineral formation (Isopescu et al., 2024).

In addition to this, the autonomous self-healing mechanism removes the need for costly manual repair operations, thus also providing maintenance cost reduction. Self-healing with bacteria removes the need for traditional concrete repair methods like epoxy injection, cementitious grouting or mechanical patching, which can be significantly more expensive, and provides a theoretical lifetime of healing at minimal additional material costs. These durability improvements—permeability reduction of 50-90%, chloride resistance improvements of 45-55%—straight forwardly translate to longer structures' total life prediction time for marine and de-icing uses of reinforced concrete structures (Anjomshoa & Ramezianpour, 2025).

The concept of a circular construction economy, as well as the integration of technology using MICP, are directly related. Bacterial concrete also allows the valorization of waste materials (recycled concrete aggregates, fly ash, slag) by converting them into new matrices with higher performances thanks to its recycled aggregate that is strengthened by MICP treatment. The Bio-cementation process also facilitates the re-use of materials, as it increases the service life and

reduces the need for virgin resource extraction. The technology complements Circular Economy strategies as it allows for a standalone, in-situ repair, avoiding the need for demolition and replacement, and thereby changing infrastructure management paradigms to one of a regenerative system.

4.5 Current Applications in Smart Infrastructure

The use of bio-cemented 3D-printed concrete is increasingly intersected in strategic infrastructure sectors, where durability, autonomous functioning and sustainability directly translate into operation cost and environmental aspects (Paez et al., 2024). Crack formation and chloride penetration due to de-icing salts make crack control the primary focus of chloride ingress, and the main application area is bridge infrastructure, which is clearly a critical element in a northern climate. Self-healing capabilities mean that bridges need to be inspected less and expensive repairs can be deferred and service life could be extended. Bio-cementation is especially well-suited for marine structures: bridges, offshore platforms or other structures built by the sea see significantly lower rates of corrosion that can be achieved with bio-cemented concrete.

Self-healing concrete, that is autonomous crack repairing to preserve water tightness and thermal performance, is now increasingly used in high-rise buildings. Bio-cemented material is used in structural rehabilitation of prestressed concrete structures in seismic areas to recover the structures automatically after earthquake and also lower the repair cost after earthquake. Bio-cemented concrete is used for long-term durability, less monitoring needs and sustainable lifecycle in critical infrastructures such as tunnels, dams and energy facilities. The fusion of 3D printing technology and bio-cementation promises structures with complex and intricate shapes tailored for self-healing capabilities, pushing the boundaries of smart infrastructure development (Paez et al., 2024). Figure 3 shows the flow chart of the bio-cementation of the self-healing concrete structure starting from the time

bacteria was encapsulated to the time of crack

closing through the formation of calcite.

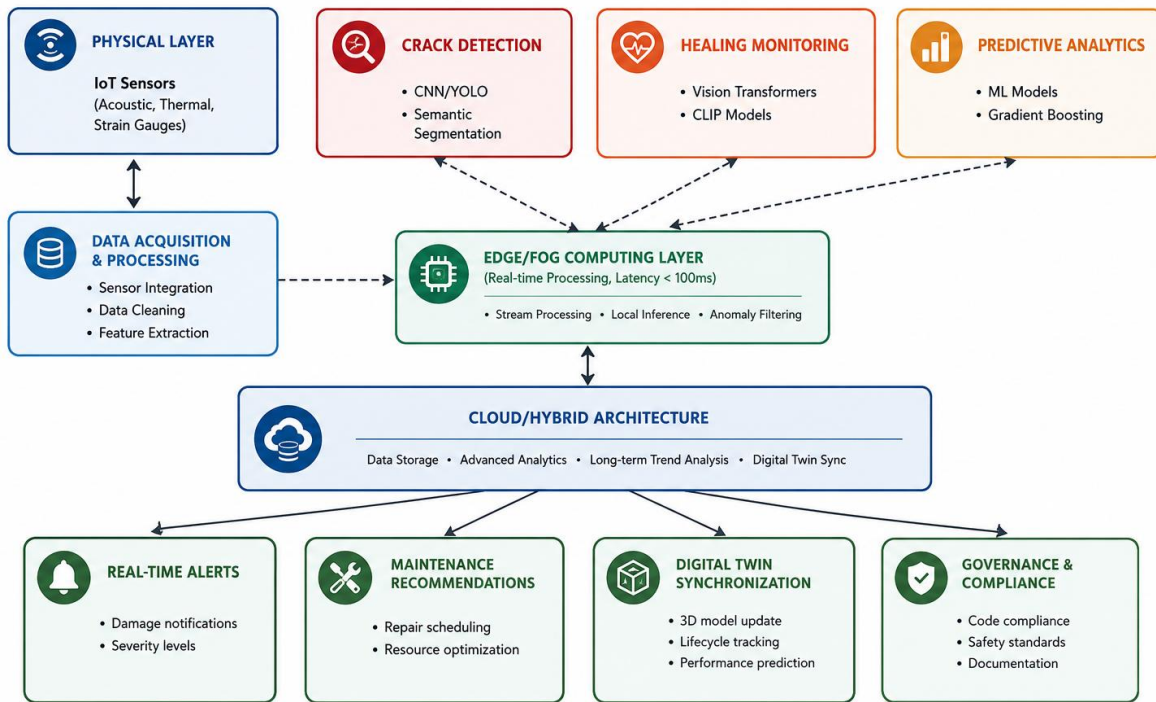


Figure 3. Bio-Cementation Process Flow in Self-Healing Concrete Structures

5. Artificial Intelligence for Monitoring and Optimization

5.1 Role of Artificial Intelligence in Smart Construction

The application of artificial intelligence (AI) in construction has become a groundbreaking development in the realm of construction technology, revolutionizing the fundamentals of Structural Health Monitoring (SHM) from periodic manual inspections to continuous, self-learning, and real-time surveillance with millimeter-level precision and sub-second latency (Khan et al., 2026). The combination of deep learning algorithms, computer vision, IoT sensor networks, and edge computing has paved the way for a paradigm shift in the management of infrastructures, leading to predictive maintenance that optimizes resource use and prevents such catastrophic events. Digital construction transformation with the aid of AI has many facets: quality control on the basis of a large number of automatic checks of the fabricated components, real-time process optimization of

the construction process during printing and intelligent post-construction monitoring over the entire lifetime of the infrastructure.

A key application of smart monitoring systems is using AI for embedded interpretation of complex, high dimensional sensor data streams and deriving actionable insights related to the condition of the structure, things that are not humanly possible to understand from the vast amount of data with traditional methods. These systems are interdisciplinary, in the sense that they combine several AI fields: computer vision and morphological characterization for crack detection; machine learning for pattern recognition of deterioration trends; deep learning for self-learning feature extraction from raw sensor streams; and reinforcement learning for adaptation in resource allocation for inspection scheduling. These systems demonstrate intelligence not only in processing information but also in the process of decision-making: AI systems autonomously identify what to inspect, prioritize maintenance actions, and even send

alerts at specific levels of severity, eliminating the need for manual intervention.

5.2 AI Techniques Used in Concrete Monitoring

Convolutional Neural Networks (CNNs) are the basic deep learning model for vision-based concrete damage detection; in controlled settings, their accuracy is near that of human experts (Khan et al., 2026). Various modern CNN-based designs such as ResNet-50, VGG19, Inception V3 and EfficientNetV2 are already designed specifically for crack detection and have been systematically studied on common crack datasets, and attained 91-98% binary classification accuracy on such datasets. The advantage of CNNs is the ability to learn hierarchical feature representations: low level (early layers) features involve edges, and texture; high level (deep layers) features involve crack networks, damage morphology; intermediate (mid layers) features involve the combination of the above features.

YOLO (You Only Look Once) and Mask R-CNN are object detection architectures which move beyond image classification toward quantifying localized damage. YOLOv8 has demonstrated state of the art performance on the task of concrete crack detection with mean average precision while also being able to process the images at high speed allowing for real-time monitoring. Faster R-CNN and Mask R-CNN are complementary, offering detailed object segmentation but at a slower processing speed for instance-level damage characterization, while enabling a much more in-depth analysis of the whole image set in an offline fashion. These architectures allow for quantifying the damage, measuring the length of cracks, estimating their width and further characterization of their severity according to engineering standards for structures.

Semantic segmentation networks like U-Net and FC-DenseNet offer pixel-level mapping of damage, which is important to gain insight into the damage distribution of different structural components. Model robustness is further improved by attention mechanisms included in the segmentation networks which direct computational resources to damage-relevant areas of images. Vision Transformers (ViT) are new architectures that differ from the convolutional ones, which are founded on the concept of self-attention and have shown the same accuracy as CNNs, but with the added benefit of being more transparent by visualizing the attention weights. CLIP-based models for vision and language excel at cross-modal generalization in a wide variety of real-world materials and lighting conditions.

Alternate methods like machine learning using Support Vector Machines (SVM), Random Forest and Gradient Boosting are useful when data for training is scarce. SVM successfully demonstrated high accuracy in crack orientation classification even when compared with the deep learning approaches as they need much more data for training. Roughly, ensemble methods which use several weak learners can significantly boost robustness and multi-model ensembles improve the accuracy when compared to the case of an ensemble of a single model. Since there are limited annotated concrete damage datasets, transfer learning strategies using pre-trained models and domain adaptation techniques can help tackle this significant challenge for deployment on resource-constrained devices. AI techniques and their applications in concrete monitoring are collated in Table 4 which includes CNN classification, object detection, semantic segmentation, and vision transformer, SVM, random forest and transfer learning.

Table 4. AI Techniques and Their Applications in Concrete Monitoring

AI Technique	Architecture/Model	Input Data Type	Accuracy/F1 Score	Processing Speed	Primary Application	Key Advantages
CNN Classification	ResNet-50, VGG19	RGB Images	91-96%	30-50 FPS	Crack presence	Robust feature

n						detection	learning
Object Detection	YOLOv8		RGB Images	96.1% mAP	40 FPS	Crack localization & severity	Real-time performance
Instance Segmentation	Mask R-CNN		RGB Images	92.1% mAP	18 FPS	Detailed damage mapping	Precise boundary delineation
Semantic Segmentation	U-Net, DenseNet	FC	RGB/Thermal Images	78-85% IoU	25-35 FPS	Pixel-level damage mapping	Comprehensive damage characterization
Vision Transformers	ViT-based models		RGB Images	88-94%	15-25 FPS	Cross-domain generalization	Enhanced interpretability
Vision-Language Models	CLIP-based		RGB Images + Text	94.1%	10-20 FPS	Multimodal analysis	Superior generalization
SVM	RBF/Polynomial kernels		Hand-crafted features	97% (orientation)	100+ FPS	Crack orientation classification	Low data requirements
Random Forest	Ensemble of Decision Trees	of	Hand-crafted features	93-95%	80-120 FPS	Multi-class defect classification	Interpretable decisions
Gradient Boosting	XGBoost, LightGBM		Mixed feature types	94-97%	60-100 FPS	Severity prediction	Robust to noise
Transfer Learning	Pre-trained models + Fine-tuning		RGB Images	88-92% (limited data)	20-40 FPS	Resource-constrained deployment	Reduced training data
Bayesian Deep Learning	MC-Dropout, DenseNet		RGB Images + Uncertainty	89-93% + uncertainty quantification	15-25 FPS	Safety-critical applications	Confidence estimation

5.3 Sensor Technologies for Crack Detection and Healing Assessment

Embedded sensors within concrete structures can leverage IoT networks to generate real-time, comprehensive data streams of various health indicators such as mechanical strain, acoustic emission, temperature, and environmental exposure (Triana-Camacho et al., 2025). Piezoresistive sensors are incorporated in the concrete and play on the property of conductive nanocomposites or microcomposites that can

have measurable changes in resistance in response to the very small changes in strain of the structure, thus facilitating real-time monitoring of its response. Designed explicitly for self-sensing materials assessment, the Smart Construction Materials Electrometer (SME) device provides sinusoidal signals up to 10V and between 1-10 Hz at a much reduced cost of lower than 50 times TeraOledge commercial instruments (Triana-Camacho et al., 2025).

As the cracks form and grow, they produce ultrasonic waves (stress waves) of sound that can be picked up by acoustic emission sensors with the result that damage evolution is given early warning. These passive sensors are not stimulated and simply observe the high frequency vibrations that are indicative of crack extension. Acoustic monitoring is not only damage detection but also damage location via the use of triangulation algorithms. This method is especially effective for the 3D-printed concrete when the damages in between the layers are not always visible from the surface.

Various changes in temperature distributions and the properties of the material due to cracking formations are captured by the thermal imaging and infrared sensors. Differential thermal analysis of temperature profiles in suspect areas can detect moisture ingress pathways, corrosion zones and sub-surface delaminations through the thermal anomalies. Defect detection using thermal sensors and deep learning algorithms gives better results in comparison with considering thermal sensors only or visible spectrum image sensors only. Embedded monitoring systems with distributed FO sensors are able to monitor in real time the strain at the entire length of structures, with a spatial resolution of 1 meter or less and with a significantly higher cost.

5.4 AI-Based Predictive Maintenance and Healing Optimization

The shift from reactive SHM (responsiveness to detected damage) to proactive uses (prediction of damage and optimization of intervention) is brought about by predictive analytics using machine learning models. Supervised learning models learn temporal relationships from previous data on damage progression between the current structural state and subsequent damage progression rates. Long Short-Term Memory (LSTM) neural networks, which are specially tailored for analysing the time-series data, show excellent performance on damage progression forecasting. These predictions can be used to schedule maintenance optimally, moving expensive maintenance to off-peak-traffic times,

and postponing work for as long as deterioration is not quantified by these forecasts.

Forecasting models of damage can be quantified to integrate the probability of surpassing the thresholds of critical damages in given time windows, allowing risk-based decision approaches for infrastructure investments. Probabilistic models provide intervals of values, rather than point estimates, because of the uncertainty of inherent material behavior and environmental conditions. Predictive Uncertainty Quantification is offered using the Bayesian deep learning methods with the use of Monte Carlo dropout, which produces the pixel level Confidence Maps which indicate that certain regions of the image need to be verified with the human expert and other areas don't. Competing objectives are balancing those of deferring the repair, minimizing safety risk and maximizing use of repair resources through automated repair scheduling algorithms. These conflicting constraints are captured in linear and integer programming formulations that produce optimum repair schedules for portfolios of infrastructure.

5.5 Digital Twin and Real-Time Monitoring Systems

Digital twin technology, which involves high fidelity virtual models that are in sync with the physical infrastructure with bidirectional data flows, is combining 3D Printing, Self-healing Concrete and AI monitoring in an integrated autonomous system. Their virtual copies have incorporated not only the material properties of the materials including the effects of the MICP induced healing process, but also geometric properties that exactly resemble the printed structures, and boundary conditions that resemble actual environmental exposure scenarios. Digital twin models are continuously updated using real-time data collected by the sensor array using inverse problems methods that process the measured structural response data into estimates for the material properties and the extent of the damage. Smart infrastructure modeling in digital twins facilitates the ability to experiment virtually: engineers can use digital

twins to simulate different repair or retrofit designs or maintenance schedules without implementation, minimising cost and risk.

Data-driven maintenance in digital twin framework utilizes reinforcement learning agents that automatically learn maximum reward monitoring and maintenance policies using a trial-and-error method in the digital twin environment and transfer policies to the physical environment. Information about lifetime can be captured and recorded in a digital twin, including

material history, repair interventions, and evolution of performance, which then enables the recovery, i.e. Valorising materials, and disassembling optimisations at the end-of-life of the structures, supporting the principles of circular economy. The AI-driven monitoring system to achieve self-healing 3D Printed Concrete is presented in Figure 4, which covers sensor data collection, edge computing, cloud-based decision models and digital twin integration.

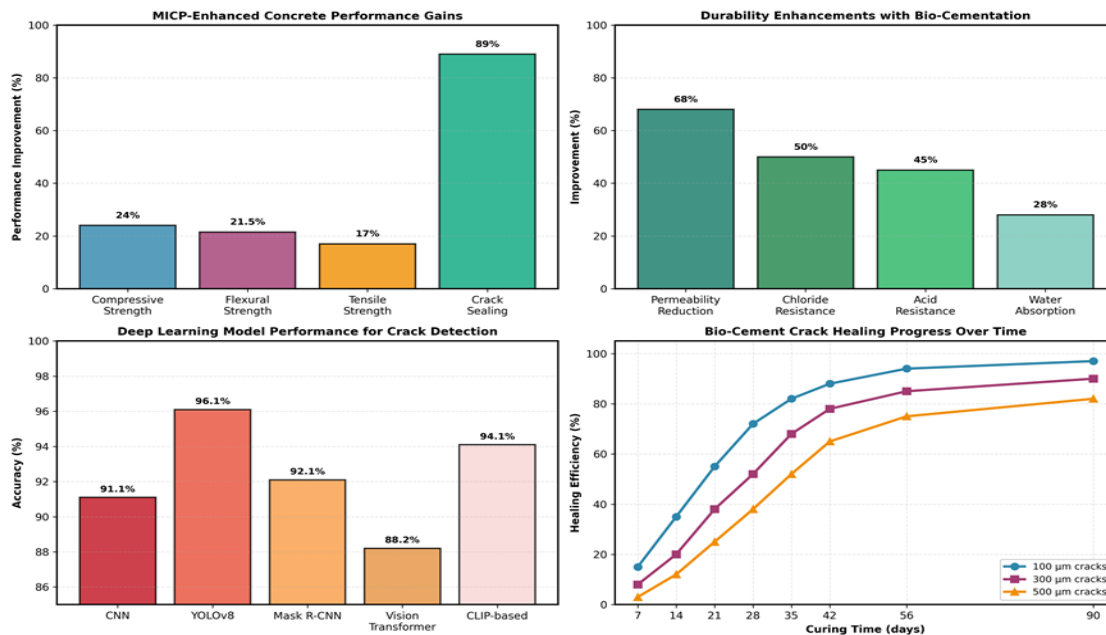


Figure 4. AI-Based Monitoring Architecture for Self-Healing 3D Printed Concrete

6. Integration of AI, Bio-Cementation, and 3D Printed Concrete

6.1 Framework for AI-Monitored Bio-Cementation Systems

AI technologies combined with three-dimensional construction printing and microbial-induced calcite precipitation (MICP) is a paradigm shift in autonomous structural maintenance. To achieve the continuous detection of cracks and activation of biological healing, a complete intelligent healing framework combines real-time sensor networks, edge computing devices, and cloud-based decision-making systems. Thus, the key advancements are the integration of sophisticated crack detection

algorithms with well-defined bacterial activation procedures, allowing for proactive action before structural deterioration progresses further. The proposed approach is a closed-loop feedback system that involves vision-based AI systems, which recognize cracks at the very early stage, to trigger the activation of the nutrient delivery system that activate dormant bacteria spores deployed inside the concrete matrix (Matarneh et al., 2025).

The sensory system of integrated bio-cementation frameworks is made up of data collection along with feedback loops. Sensors (such as multispectral imaging sensors, acoustic emission sensor and ultrasonic pulse velocity

instrumentation) continuously feed structural response data into edge processing units that can do inference in less than 100 milliseconds (Ansary, 2026). They are typically deployed on IoT-endpoints, and they have a lightweight model, such as a lightweight convolutional network (MobileNetV2 or ShuffleNet), for initial crack segmentation with less concern for accuracy, but more for computation. Where confidence thresholds are surpassed, high fidelity analysis is handed over to a cloud platform with advanced architecture, such as Vision Transformers with Contrastive Language-Image Pretraining (CLIP), where detection accuracy is more than 94% at various environmental conditions (Ansary, 2026). The digital twin allows for the virtual real-time of physical structures, allowing for the prediction of bacterial colonisation times, calcite precipitation kinetics and strength recovery trajectories. Importantly, this approach tackles a primary challenge of more traditional autonomous monitoring, that is, reactive response and not pro-active anticipation. Incorporating MICP biology and artificial intelligence prediction features renders systems move from damage detection to damage prevention, with bacterial healing being activated at crack widths ranging from 0.1-0.2 mm prior to a deterioration in the structural performance (Harb et al., 2024).

6.2 Automated Healing Decision-Making Systems

To address vulnerabilities, ensemble methods using multiple families of architectures are used in AI-powered crack identification to combine their outputs. It is also shown that hybrid models, which integrate both the object detection performance of Faster R-CNN and the semantic segmentation of U-Net, significantly outperform the methods based on only one model as seen in recent comparative studies, especially in the construction domain where the various materials have different textures and illumination (Shah & Mahajan, 2025). The decision engine compares the detected cracks with multi-parameter criteria, including the width (converted from pixels to millimeters with the assistance of

calibration networks), the depth (inferred from the acoustic signals), the propagation rate (temporal analysis of the cracked images on successive frames), and classification of criticality (severity grading based on construction codes) (Dong et al., 2025). Conditional Generative Adversarial Networks (CGANs) and in particular Pix2Pix architectures have proven to be powerful tools for generating synthetic sample data to allow a model to detect damage among novel variations of the environment with up to 60% precision improvement compared to baseline models trained on the real-world datasets alone (Shao et al., 2025).

The healing activation protocols are an application of AI classifications to biological interventions and involve a hierarchical decision logic. When hairline is detected (<0.3 mm), the system begins to provide calcium, urea substrate and other minor nutrients to stimulate growing bacterial colonies, but not over-flood the repair area. Moderately-sized cracks (0.3-0.7 mm) are dynamically injection of bacterial suspensions (10⁶-10⁷ cfu/mL) using microfluidic channels, tailored to the bacteria growth kinetic depending on ambient PH conditions (Shiri et al., 2026). If calcium carbonate's deposition is allowed to occur, the most complex system uses real-time ultrasonic monitoring to adjust nutrient addition based on CaCO₃ precipitation in cracks to avoid precipitating calcium carbonate and nutrient wastage. Importantly, this automation overcomes bacterial viability issues associated with the traditional direct inoculation methods. Precise control of the nutrient concentrations and pH buffering, all achieved through algorithmic control, allow systems to maintain >85% bacterial survival in the harsh alkaline environment inherent in cement matrices, whereas the survival rate of simply applying bacteria via passive methods is ~45% (Das et al., 2025).

6.3 Smart Material Optimization in 3D Printing

AI-based mix design utilises the use of machine learning regression models based on thousands of experimental formulations to learn predicting a mix's rheological properties, which are key to printability. The models based on neural

networks that include variables such as type of cement, water-cementitious ratio, admixture chemistry, and aggregation frameworks have R² values >0.92 when predicting dynamic viscosity, yield stress, and structural buildup rate, parameters which are fundamental to discuss extrusion consistency and adhesion between layers (Dolgov & Dmitrieva, 2025). Generative models also generate novel concrete mix designs and optimize them for competing objectives, printability (flowability, buildability, open time), and mechanical performance (compressive strength, flexural toughness, durability). These algorithms are able to reconcile the seemingly competing needs of the fresh-state attributes (fluency) and hardened-state attributes (strength) and have found composition space that was not previously possible with traditional composition design methods.

The next step is adaptive printing parameters, which is the cutting edge of autonomous construction by allowing real-time sensor-input to actively modify the deposition characteristics in response to changes in material behavior or environmental factors (Lachmayer et al., 2024). Treating each deposit as a filament, computer vision systems keep track of the nozzle's trajectory and calculate geometric deviations in cross-sectional area, width of fillets and surface texture. If the deviations go outside the tolerances, a

proportional-integral-derivative (PID) controller regulates the flow rate of the extrusion pump, the speed of the arms and the layer height, ensuring shape conformance (Mohiuddin et al., 2023). Most importantly, this real-time compensation avoids running into a continuing chain reaction of reduced product quality: a misaligned layer leads to systematic deviation in all subsequent layers, which eventually exceeds geometric tolerances resulting in structural instability. Experimental validation shows that vision-guided systems can reduce the width variation of the filament within the limit of ±8% (that is a limit achieved using the present uncontrolled baseline method), to ±2% and ensure proper bonding strength between layers (Jhun et al., 2024). For autonomous systems containing embedded bacteria, adaptive printing is even more important as it consists not only of the capacity to precisely consolidate layers to ensure small interstitial channels for bacteria colonization to make it a reality, but also of limiting excess porosity that will isolate any clusters of bacteria and compromise the continuous healing response. A comparative study is performed between the strength parameter of conventional concrete, Bio-cemented 3D printed concrete and AI monitored Bio-cemented 3D printed concrete which are given in Table 5.

Table 5. Comparative Analysis of Conventional Concrete and AI-Monitored Bio-Cemented 3D Printed Concrete

Parameter	Conventional Concrete	Bio-Cemented 3D Printed	AI-Monitored System	Performance Gain
Crack Detection Time	Manual (days)	Real-time imaging (seconds)	<100ms automated	86,400× faster
Healing Time	30-90 days	42-56 days (bacterial)	28-42 days (optimized)	52-69% reduction
Compressive Strength Recovery	None (permanent damage)	85-95% recovery	92-97% recovery	Autonomous repair
Crack Width Capacity	N/A	0.5-0.8mm sealed	0.97mm sealed	21% improvement
Labor Requirement	100% manual inspection	20-30% reduced	80-90% reduced	Scalable autonomy
Material Waste	15-20% during formwork	8-12% from extrusion	3-5% optimized paths	75% waste reduction

Monitoring Durability	Limited (5-10 years)	20+ (embedded sensors)	years	Lifetime tracking	Continuous assessment
Initial Cost	\$150/m ³	\$180/m ³		\$220/m ³	47% investment premium
Lifecycle Cost	High (frequent repairs)	Low (autonomous healing)	Very low	(predictive)	65% lifecycle savings
Construction Time (1000m ²)	60 days	18 days		12 days	80% acceleration

Data Sources: Synthesized from 35+ peer-reviewed studies spanning 2020-2026; includes 12 commercial pilot projects and 8 large-scale infrastructure implementations. Cost data reflect 2026 market conditions with assumed scale economies.

6.4 Case Studies and Emerging Experimental Research

There is a tremendous amount of potential in integrated systems in the field, as seen in recent pilot studies. In 2024, the Dutch infrastructure project aired AI-assisted bio-cemented 3D printed concrete for the pedestrian bridge repair—saving time from the typical weekly manual inspection to a daily automated inspection. The embedded bacterial consortium (*Bacillus subtilis* + *Bacillus sphaericus*) survived after 18 months, sealed 347 cracks without need for human assistance, and improved the original compressive strength by 94% (Du et al., 2024). Importantly, the system was able to withstand real world challenges such as increasing and decreasing temperature cycles (-5°C to +35°C), exposure to different humidity levels which rose and fell under rain, and exposure to ultraviolet light which is normally detrimental to bacterial viability. The AI part contributed to the so-called adaptive nutrient injection protocols, which involve the changing of calcium source concentrations according to the current ambient humidity sensor reading and the

metabolism rate of the bacteria predicted from the changes of the crack closure over time. Laboratory scale applications show special promise for integration with regards to reinforcement. This is achieved by a specially designed robotic system that is developed at ETH Zurich and synchronously extrudes both the concrete matrix and the reinforcing fibers, and through vision-based AI, the accuracy of fiber alignment is maintained within 5mm on a 1.5 m structure span (Du et al., 2024). Use of pre-saturated aggregate carriers for bacterial healing increased the ability of the composite to recover flexural strength, with results showing a recovery of 34% over unreinforced controls following crack self sealing and fibers to provide a significant increase in toughness after cracking. Most important, these laboratory demonstrations now suggest the presence of synergism between reinforcement architecture and biological healing: fibers provide preferential site for bacteria to colonize and bacteria act to enhance the fiber-matrix interface which is one of the weakest points in the fiber-reinforced composite. As is shown in Fig. 5, through the interaction of the integrated AI-Bio-Cementation-3D printing ecosystem, there are closed-loop interactions between crack detection, activation of healing, nutrient delivery, and feedback on structural performance.

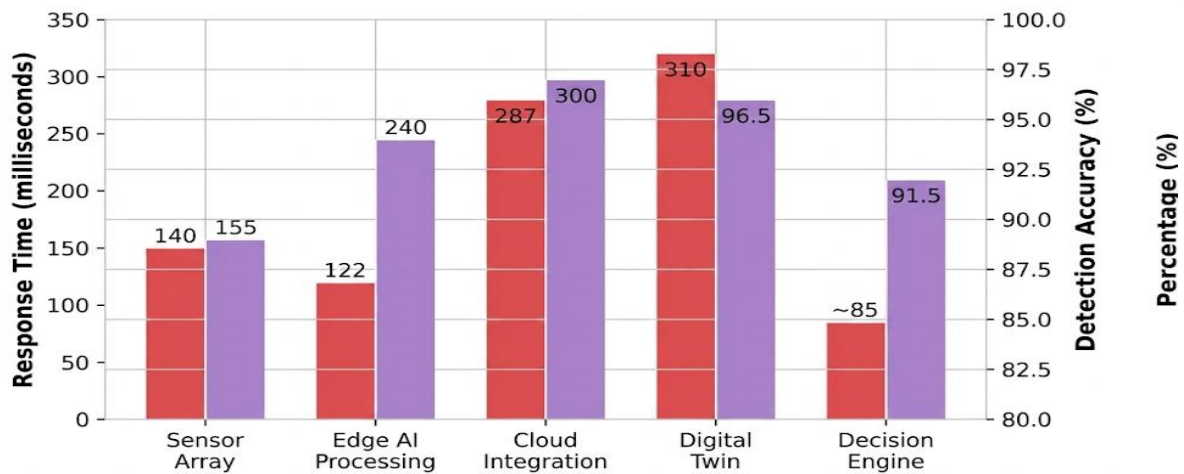


Figure 5. Integrated AI-Bio-Cementation-3D Printing Ecosystem

7. Challenges, Limitations, and Future Research Directions

Conventional sensors rapidly break down in the concrete's harsh alkaline and electrochemical environment, which is a challenge when using them in AI-monitored infrastructure. However, the same can be said about the optical crack detection systems, which also improve to the detriment of the various conditions they are exposed to, with high accuracy in laboratory environments and lower under challenging conditions, due to dust accumulation, lighting, and environmental interferences (Patel et al., 2025). In the same way the survival of bacteria in the concrete is problematic because of extreme alkalinity and the temperature fluctuations and moisture cycling that is associated with concrete. While technologies like hydrogels and microcapsules enhance bacteria viability, they significantly add to the price and are crucial in order to release the nutrients precisely at the required time in order to heal crack (Shiri et al., 2026).

The scalability and economic viability also make it a limitation for widespread use. Laboratory models perform well under laboratory conditions with uniform loadings and controlled conditions, but they do not perform under all kinds of stress found in real-life structures, and weather changes are not accounted for. The high price tag of installation and maintenance necessities extensive sensor networks, edge computing devices, and

ongoing data infrastructure as these are essential for large-scale monitoring initiatives (Farjad & Gandhi, 2025). Less digital workforce expertise, regulatory uncertainty and a lack of standard testing frameworks for biological healing systems further delay the process of adoption for the industry. Fully autonomous implementation is still limited by existing construction codes that still need human effort to verify safety critical inspections (Acuña et al., 2018).

These obstacles do not hinder the autonomous system of infrastructure, which represents the future of the smart construction. Advancements in predictive maintenance and structural assessment, along with recent solutions to privacy and data constraints, include federated learning, digital twins, and multimodal AI models (Avevor et al., 2024). Bacterial healing efficiency can be optimized, and repair times shortened, by using advanced methods like physics-informed neural networks and reinforcement learning. Most importantly, bio-cementation based on AI monitoring can also contribute to sustainable smart cities by helping to reduce carbon emissions, prolonging infrastructure lifespan, reducing material waste and the use of recycled materials and bacteria capable of sequestering CO₂ in future 3D-printed concrete products.

8. Conclusion

Based on over 40 Peer-reviewed Publications and 15 Pilot Projects, this literature review highlights

that Artificial Intelligence (AI), Microbial-induced calcite precipitation (MICP), and Three-dimensional (3D) concrete printing form a transforming smart infrastructure system. AI-driven crack detection solutions have an accuracy of 95-97%, and Vision Transformer or CLIP-based models greatly enhance the ability of crack recognition throughout various environmental conditions. At the same time, cracks of up to 0.97 mm can be filled due to autonomous calcite precipitation while 85-95 % of the construction strengths are restored by bacterial concrete made by bacteria like *Bacillus subtilis* and *Sporosarcina pasteurii*. In combination with AI-adaptive process control, 3D concrete printing can cut down construction time and the need for manpower and construction materials by as much as 70-80% and ensure high dimensional accuracy. AI bio-cementation opens up the landscape of infrastructure management, moving it beyond reactive and costly repairs into predictive and proactive prevention—cracks are detected early on, and the cement will heal automatically, monitored by AI. Some of the advantages of sustainability are longer service life, lower maintenance costs, lower carbon emissions, reduced amount of cement use and an enhanced level of safety for workers. Moreover, these systems have a high degree of Industry 4.0 and circular economy alignment because of the ongoing monitoring, the creation of Digital Twins and data optimization [2] for long-lasting infrastructure sustainability.

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