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Review

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Bio-inspired Self-Healing Concrete for Sustainable Structures: A Critical Review

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ABSTRACT

Cracks provide pathways for water, chlorides, sulfates, and carbon dioxide to penetrate reinforced concrete, while conventional crack repairs are often costly, disruptive, and environmentally burdensome. Bio-inspired self-healing concrete incorporates bacteria, enzymes, fungi, or vascular networks to promote autonomous crack sealing and extend service life. This critical review addresses four research questions: (i) how bio-inspired healing compares with autogenous and non-biological engineered healing; (ii) how biological-agent selection, encapsulation and mix design influence trade-offs among healing performance, mechanical properties and cost; (iii) how reliable and comparable laboratory and field evidence is; and (iv) under which conditions self-healing concrete provides environmental and economic benefits. Literature retrieved from Scopus and Web of Science was screened using predefined criteria and critically synthesised, with emphasis on experimental and field evidence. Microbially induced calcium carbonate precipitation (MICP) generally seals cracks 0.3–0.5 mm wide, although laboratory studies report closure of cracks up to 0.8–0.97 mm and reductions in water permeability exceeding 90%. However, healing-agent production can increase embodied carbon by 36% per m³ in one recent assessment. Environmental benefits therefore depend on achieved service-life extension, avoided repairs and targeted application. Reported life-cycle benefits range from approximately 12% to 75%, depending on assessment boundaries and assumptions. Major limitations include non-standardised testing, uncertain long-term bacterial viability and repeated-healing capacity, limited field evidence and regulatory uncertainty. Research priorities include standardised testing, long-term field monitoring, hybrid healing systems, predictive modelling and engineered living materials.

1. Introduction

Concrete is the most widely used construction material because of its availability, strength, durability and relatively low cost, forming the foundation of bridges, tunnels, dams and buildings [1]. However, cement manufacturing contributes approximately 8% of anthropogenic CO_2 emissions, making it a major industrial contributor to climate change [2]. Extending the service life of existing concrete structures is therefore as important as reducing emissions from new construction [3].

Concrete can develop cracks through plastic shrinkage, thermal gradients, freeze-thaw cycles, chemical attack and mechanical loading [4]. These cracks facilitate the ingress of water, chloride ions, sulfates and atmospheric CO_2, accelerating deterioration processes such as reinforcement corrosion,

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carbonation and, under suitable conditions, alkali-silica reaction, ultimately reducing structural capacity and service life [5]. Conventional repair materials, including epoxy resins and polymer sealants, may exhibit limited compatibility with cementitious matrices, introduce additional environmental burdens, and primarily address visible, accessible cracks [6], [7].

Self-healing construction materials draw inspiration from biological processes, including wound healing and bone remodelling. Microbially induced calcium carbonate precipitation (MICP) is the most extensively investigated bio-inspired approach. It employs alkali-tolerant, spore-forming bacteria, including *Bacillus subtilis*, *Lysinibacillus sphaericus* (formerly *Bacillus sphaericus*) and *Sporosarcina pasteurii*, to precipitate calcium carbonate within cracks [8], [9]. Bacterial spores can remain dormant until moisture enters a crack, creating conditions that support germination and biomineralisation. Crack-closure efficiencies exceeding 88%, alongside improved mechanical properties and reduced permeability, have been reported for bacteria-based concrete [10].

Research on bio-inspired self-healing concrete has expanded considerably over the past two decades, producing several categories of reviews. These include (i) mechanism-specific reviews addressing bacteria [11-13], non-ureolytic bacteria [14], fungi [15] and encapsulation [16], [17]; (ii) bibliometric studies examining publication trends, authorship and keyword clusters, with limited technical appraisal [18-20]; and (iii) broader reviews covering self-healing technologies in which biological systems represent one component [1], [2], [4], [6], [21].

Nevertheless, an integrated critical assessment connecting biological mechanisms, mix design, evidence reliability, and life-cycle sustainability remains necessary, particularly to distinguish laboratory performance from demonstrated field outcomes. Quantitative claims concerning healing capacity, carbon savings, and costs are also frequently repeated without sufficient consideration of testing conditions or assessment boundaries.

Accordingly, this review addresses four research questions (RQs):

- RQ1: How do the healing capacity, rate, and repeatability of MICP, enzyme-induced precipitation, fungal mineralisation, and biomimetic vascular networks compare with autogenous and non-biological engineered healing?
- RQ2: How do bacterial selection, encapsulation, and mix design influence trade-offs among healing efficiency, mechanical performance, and cost?
- RQ3: How reliable and comparable is the reported performance evidence, and to what extent can laboratory outcomes be transferred to field applications?
- RQ4: Under which conditions does self-healing concrete provide environmental and economic benefits?

The review contributes a comparative assessment using consistent evaluation criteria, critically examines reported performance ranges and identifies exposure conditions and testing methods as major sources of variability. It also reconciles life-cycle assessment (LCA) findings by distinguishing production-stage environmental penalties from use-phase benefits. An evidence-maturity assessment further connects current limitations with research priorities. Collectively, these contributions support the development of sustainable, lower-carbon infrastructure aligned with the United Nations Sustainable Development Goals (SDGs).

2. Methodology

This study adopts a structured critical-review approach rather than a systematic or bibliometric review. Relevant literature was identified and selected through a transparent search and screening protocol, followed by qualitative synthesis and comparative analysis addressing RQ1-RQ4. The

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emphasis is on technical interpretation and evidence appraisal rather than bibliometric mapping, as recent studies have already characterised the publication landscape of self-healing concrete [18-20].

2.1 Data Sources and Search Protocol

Scopus and the Web of Science Core Collection were searched because they index peer-reviewed literature across materials science, civil engineering, and microbiology. Searches covered titles, abstracts, and author keywords using the following Boolean string: ("self-healing" OR "self-sealing" OR "crack healing") AND (concrete OR mortar OR cementitious) AND (bacteria OR microbe OR MICP OR "calcium carbonate precipitation" OR enzyme OR urease OR fungi OR vascular OR biomimetic OR bio-inspired). Supplementary searches incorporated the terms "life cycle assessment", "cost", "field application" and "standardization". The initial search was conducted in May 2025 and updated in 2026 to capture additional publications from 2021-2026. Backward and forward citation tracking of key reviews complemented the database searches.

2.2 Eligibility Criteria

Studies were eligible if they (i) were peer-reviewed journal articles, review articles or full conference papers published between 1994 and 2026; (ii) addressed autogenous, engineered or bio-inspired self-healing of cementitious materials, including testing, sustainability or field applications; and (iii) provided sufficient methodological information, such as crack width, healing conditions and evaluation methods, to support interpretation. Editorials, errata, non-peer-reviewed reports, studies involving non-cementitious matrices and non-English publications were excluded. Earlier studies were retained where they established foundational mechanisms or testing methods.

2.3 Screening, Data Extraction and Synthesis

Records were screened for duplicates, followed by title and abstract screening and full-text eligibility assessment. For each included study, information was extracted on the healing mechanism, agent and carrier, crack width, exposure conditions, evaluation method, healing or recovery performance, testing scale (laboratory, pilot or field), and relevant life-cycle assessment (LCA) or cost assumptions.

Numerical ranges represent values reported by individual studies rather than pooled estimates; no meta-analysis was performed. Results obtained under idealised conditions, such as continuous water immersion, are identified where relevant. Evidence maturity was classified according to laboratory, pilot/demonstration or field validation, as discussed in Section 9.

3. Fundamentals of Self-Healing Concrete

This section examines autogenous and engineered self-healing as benchmarks for evaluating bio-inspired approaches. Figure 1 provides a hierarchical classification of self-healing concrete mechanisms distinguishing autogenous from engineered approaches, and intrinsic from extrinsic healing agent integration strategies; this classification is used consistently in Table 2 and Section 4.

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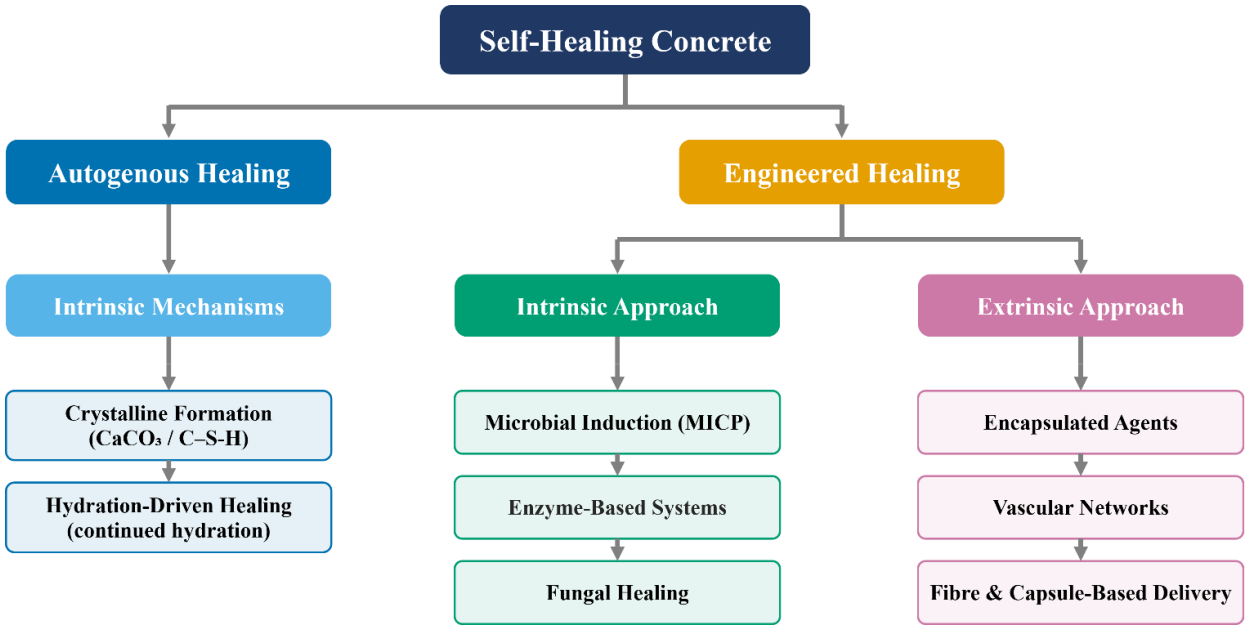


Figure 1. Hierarchical classification of self-healing concrete mechanisms (Created by the authors).

3.1 Autogenous Self-Healing

Autogenous self-healing refers to the ability of cementitious materials to seal cracks through physicochemical processes without intentionally added healing agents. The phenomenon was recognised in the nineteenth century through observations of spontaneous crack closure in water-retaining structures [22]. Its principal mechanisms include continued cement hydration, calcium carbonate precipitation, swelling of hydration products, and mechanical blockage by debris [23].

3.1.1 Continued Hydration of Unhydrated Cement

Portland cement does not necessarily hydrate completely, leaving unhydrated grains within the hardened matrix. When water enters a crack, these grains undergo further hydration, producing calcium silicate hydrate (C-S-H) and calcium hydroxide that can partially fill narrow cracks. Consequently, younger concrete generally exhibits greater hydration-driven healing potential than mature concrete because it contains larger reserves of unhydrated cement. The principal reactions can be expressed using conventional cement chemistry notation:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \quad (1)$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \quad (2)$$

Here, C_3S denotes tricalcium silicate, C_2S denotes dicalcium silicate, H represents water, and CH represents calcium hydroxide.

Huang et al. [24] demonstrated that continued hydration contributes substantially to early-age crack closure, although its importance declines as unhydrated cement reserves decrease. In mature concrete, calcium carbonate precipitation becomes increasingly important, making healing strongly dependent on age and exposure conditions [7], [23].

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3.1.2 Calcium Carbonate Precipitation

Calcium carbonate precipitation is a major autogenous healing mechanism in mature concrete. Calcium hydroxide dissolves at crack surfaces and reacts with atmospheric carbon dioxide or dissolved carbonate species:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

Sustained moisture exposure can promote carbonate precipitation and seal cracks approximately 0.1 mm wide. This process requires available calcium and carbonate species and chemical conditions favouring precipitation over dissolution [23]. Higher temperatures and narrower cracks can accelerate reductions in water flow [25]. Exposure conditions are also important: wet-dry cycling generally promotes healing more effectively than continuous immersion or dry storage by facilitating alternating ion dissolution and carbonate precipitation [26]. Characterisation of healing products in strain-hardening cementitious composites has identified calcium carbonate as the predominant crystalline phase [27].

3.1.3 Limitations of Autogenous Healing

Despite its demonstrated potential, autogenous healing has limitations in structural applications. Crack width is a major constraint: effective healing generally occurs below approximately 0.1 mm and becomes substantially less efficient above 0.2 mm. A practical limit of 0.15 mm has been suggested for engineered cementitious composites [26]. Healing may also require weeks or months, depending on crack width and exposure conditions [25], [26], making it unsuitable where rapid functional recovery is essential.

Moisture availability is another critical requirement. Granger et al. [28] reported mechanical recovery in cracked ultra-high-performance concrete specimens only when they were maintained in water. Furthermore, calcite generally contributes less to mechanical strength recovery than newly formed C-S-H. Differences in strength recovery between reference and capsule-containing specimens further demonstrate the limitations of relying on autogenous healing alone [29]. Table 1 summarises these mechanisms and constraints.

Table 1. Characteristics and limitations of autogenous self-healing mechanisms (indicative ranges).

Mechanism	Primary products	Effective crack width (mm)	Time required	Environmental requirements	Strength recovery (%)
Continued hydration	C–S–H, $Ca(OH)_2$	< 0.05	7–28 days	High moisture; young concrete	20–40
Carbonation	$CaCO_3$ (mainly calcite)	< 0.1	4–12 weeks	Cyclic wetting; CO_2 availability	15–30
Combined autogenous	Mixed products	< 0.15	4–16 weeks	Optimal moisture cycling	25–45

Note: Indicative values compiled from [23]–[29]; actual values depend strongly on concrete age, crack width, exposure regime, and test method.

3.2. Engineered Self-Healing Approaches

Engineered self-healing involves deliberately modifying the cementitious matrix or incorporating healing agents to address cracks beyond the effective range of natural healing.

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These approaches can be classified by healing-agent integration (intrinsic or extrinsic) and activation mechanism (autonomic or non-autonomic).

3.2.1 Intrinsic vs. Extrinsic Healing Mechanisms

Intrinsic approaches modify the matrix itself to promote healing without separately stored agents. A common example involves crystalline admixtures containing reactive silicates and aluminates, which react with water and cement hydration products to form insoluble crystalline deposits within cracks. Ferrara et al. [30] demonstrated that crystalline admixtures can reduce porosity and promote self-healing, while Roig-Flores et al. [31] showed that their effectiveness depends strongly on exposure conditions, with the greatest benefits observed under water immersion. Supplementary cementitious materials, including fly ash, slag, silica fume, and expansive minerals, can also promote crack healing through delayed pozzolanic or expansive reactions that densify the affected region [32], [33]. Superabsorbent polymers (SAPs) swell upon contact with water, physically sealing cracks while providing moisture for continued hydration [34], [35].

Extrinsic approaches store healing agents in separate containers that release their contents when intersected by a crack. Van Tittelboom et al. [29] demonstrated that capsule rupture releases polyurethane, substantially reducing crack permeability. Common capsule-shell materials include melamine–formaldehyde and urea–formaldehyde, which can withstand mixing and curing while remaining susceptible to crack-induced rupture [17]. Alternatively, vascular systems distribute healing agents through embedded hollow channels. Dry [36] first demonstrated adhesive release from hollow fibres into matrix cracks, followed by developments involving embedded concrete networks [37] and three-dimensional printed channels [38].

3.2.2 Autonomic vs. Non-Autonomic Systems

Autonomic systems initiate healing following damage without external detection or intervention. Capsule-based systems rely on crack-induced rupture, making capsule strength and brittleness important design parameters. Kanellopoulos et al. [39] optimised polymeric microcapsules to withstand mixing while rupturing during cracking. Bacteria-based systems can also operate autonomically when moisture activates dormant spores. Jonkers et al. [8] demonstrated bacterial crack healing through spore germination and subsequent mineral precipitation under suitable conditions.

Non-autonomic systems require external stimulation, such as heat, chemicals or mechanical activation. Although this provides greater control, it increases operational complexity. Thermally activated shrinkable polymer tendons [40], hybrid shape-memory polymer tendons [41] and knotted shape-memory polymer fibres [42] have demonstrated improved crack closure. However, thermal activation requires a feasible means of delivering heat. Conventional manual repairs similarly require damage detection, access and skilled application of epoxy or grout. Table 2 classifies engineered approaches by mechanism, healing agent, activation mode and healing-cycle capacity.

Table 2. Classification of Engineered Self-Healing Approaches.

Classification	Mechanism	Healing agent	Activation	Healing cycles	References
Intrinsic/autonomic	Crystalline admixtures	Reactive silicates	Water ingress	Multiple, while unreacted admixture remains	[30], [31]

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Classification	Mechanism	Healing agent	Activation	Healing cycles	References
Intrinsic/autonomic	Mineral additions	Pozzolanic or expansive materials	Water + $Ca(OH)_2$	Limited by reactants	[24], [32]
Extrinsic/autonomic	Encapsulation (capsules)	Polymers, bacteria	Capsule rupture	Single per capsule	[29], [39]
Extrinsic/autonomic	Vascular networks	Various liquids	Channel rupture	Multiple (refillable)	[37], [43]
Extrinsic/non-autonomic	Shape-memory materials	Polymer/alloy tendons	Thermal activation	Multiple	[40], [41]

3.2.3 Performance Metrics and Evaluation Standards

Comparable performance metrics are essential for evaluating self-healing technologies, although testing standardisation remains incomplete [6], [44]. Healing efficiency is commonly expressed as the percentage reduction in crack width or area:

$$\eta_{\text{healing}} = \frac{W_{\text{initial}} - W_{\text{final}}}{W_{\text{initial}}} \times 100\% \quad (4)$$

Interlaboratory studies [44] and reviews [6], [23] emphasise reporting initial crack width, healing duration and exposure conditions alongside efficiency. Mechanical recovery can be expressed through the strength recovery ratio:

$$R_{\text{strength}} = \frac{\sigma_{\text{healed}}}{\sigma_{\text{virgin}}} \times 100\% \quad (5)$$

Consistent pre-cracking procedures are necessary to ensure comparable initial damage [7], [29]. Controlled crack-opening methods can improve repeatability. Functional sealing is assessed through water or gas permeability, using:

$$HR_{\text{perm}} = \frac{k_{\text{cracked}} - k_{\text{healed}}}{k_{\text{cracked}} - k_{\text{uncracked}}} \times 100\% \quad (6)$$

This measure is particularly relevant to durability protection. Tziviloglou et al. [45] evaluated bacterial crack sealing through water-flow measurements. Repeated damage-healing tests are equally important for long-lived infrastructure, although evidence remains limited. Justo-Reinoso et al. [46] reported that previously healed bacterial specimens did not demonstrate renewed healing when recracked after 20 months.

International initiatives, including RILEM and COST Action SARCOS, have addressed variability in specimen preparation, crack induction, healing exposure, and performance evaluation through methodological recommendations and interlaboratory investigations [44]. Nevertheless, substantial methodological heterogeneity persists [6], [21]. Table 3 summarises commonly applied assessment metrics.

Table 3. Performance metrics commonly used to evaluate self-healing concrete.

Metric	Definition	Measurement method	Indicative benchmark*	Reference standard for guidance
Healing efficiency	Crack width or area reduction (%), Eq. (4)	Optical microscopy; image analysis	> 80% for cracks < 0.3 mm	RILEM/SARCOS recommendations [6], [44]
Strength recovery	Healed/virgin strength ratio, Eq. (5)	Flexural testing after controlled pre-cracking	> 70%	RILEM/SARCOS recommendations [6], [44]

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Metric	Definition	Measurement method	Indicative benchmark*	Reference standard for guidance
Stiffness recovery	Healed/virgin modulus ratio	Resonant frequency	> 65%	ASTM C215
Permeability healing ratio	Flow-rate reduction (%), Eq. (6)	Water flow through the crack	> 85%	No standard; set-ups compared in [44]
Durability restoration	Recovery of chloride resistance	Rapid chloride permeability or migration	> 80%	ASTM C1202; NT Build 492

*No harmonised acceptance criteria exist; values are indicative benchmarks used in the literature to denote effective healing.

4. Bio-Inspired Self-Healing Mechanisms

This section examines four principal families of bio-inspired healing systems: microbial, enzymatic, fungal and vascular approaches, followed by a comparative assessment.

4.1 Microbially Induced Calcium Carbonate Precipitation (MICP)

4.1.1 Mechanism and Biochemistry

MICP is among the most extensively investigated biological healing mechanisms for cementitious materials. De Muynck et al. [9] described the principal bacterial metabolic pathways capable of promoting calcium carbonate precipitation (Figure 2). The most widely studied is ureolysis, in which bacterial urease catalyses urea hydrolysis:

$$CO(NH_2)_2 + H_2O \xrightarrow{\text{urease}} 2NH_3 + CO_2 \quad (7)$$

Ammonia increases local alkalinity, while dissolved carbon dioxide contributes carbonate species that precipitate in the presence of calcium ions:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \text{ (calcite)} \quad (8)$$

Jonkers et al. [8] reported crack sealing within days under favourable conditions. However, ammonia generation during ureolysis raises environmental and application-specific durability concerns [47]. An alternative pathway involves aerobic oxidation of organic calcium salts, such as calcium lactate, as discussed by Wiktor and Jonkers [48]:

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5H_2O + 5CO_2 \quad (9)$$

The generated carbon dioxide can react with portlandite to produce additional calcium carbonate [14]. Unlike ureolysis, this pathway does not generate ammonia and consumes oxygen that might otherwise contribute to reinforcement corrosion [48]. Erşan et al. [49], [50] also investigated denitrification by nitrate-reducing bacteria, which can promote carbonate formation under oxygen-limited conditions when suitable nitrate and nutrient sources are available. The three pathways (ureolytic hydrolysis, aerobic calcium lactate oxidation and anaerobic denitrification) are illustrated in Figure 2.

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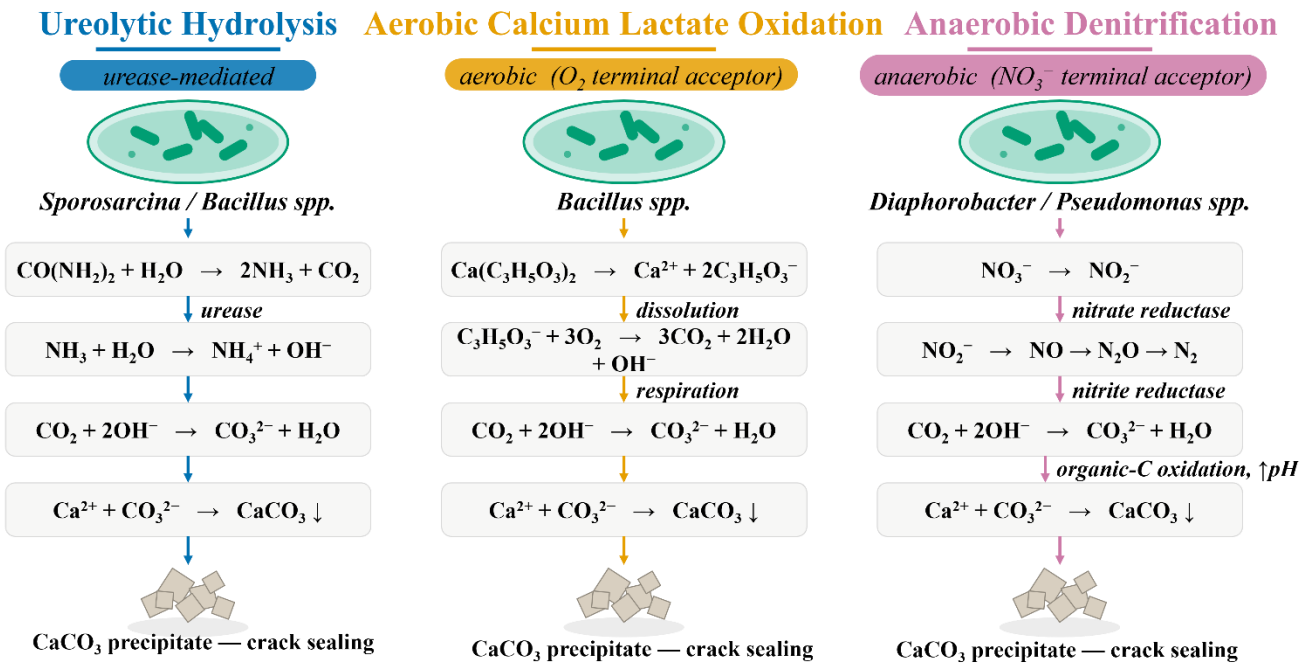


Figure 2. Three metabolic pathways enabling bacterial calcium carbonate precipitation: ureolytic hydrolysis, aerobic calcium lactate oxidation, and anaerobic denitrification (Created by the authors).

4.1.2 Bacterial Species Selection

Bacteria selected for self-healing concrete must survive within the cementitious matrix and promote calcium carbonate precipitation. Sharma et al. [51] identified four principal selection criteria: tolerance of highly alkaline conditions (pH >12), ureolytic or alternative precipitation-inducing metabolic activity, non-pathogenicity, and endospore formation for prolonged dormancy. *Lysinibacillus sphaericus* (formerly *Bacillus sphaericus*) produces alkali-resistant spores and exhibits urease activity following germination, making it suitable for ureolytic systems [52], [53]. *Sporosarcina pasteurii* (formerly *Bacillus pasteurii*) also exhibits strong urease activity and has demonstrated effective calcite precipitation when immobilised in polyurethane [54], although its compatibility with highly alkaline concrete requires consideration [5].

Non-ureolytic pathways involving species such as *Bacillus subtilis* offer alternatives that avoid ammonia generation [8], [55] and can reduce permeability through mineral precipitation within pores [56]. Healing performance also depends on bacterial species, concentration, and nutrient availability [57], [58]. Intarasoontron et al. [59] further showed that the delivery form (vegetative cells or microencapsulated spores) influences healing efficiency.

4.1.3 Encapsulation Strategies

Encapsulation protects bacteria against the high alkalinity of fresh concrete and mechanical damage during mixing. Carrier selection must balance protective efficiency, healing performance, cost, and scalability [16], [17]. Figure 3 illustrates four principal strategies: (A) protection within expanded-clay pores, (B) crack-induced microcapsule rupture, (C) hydrogel swelling and release, and (D) adsorption onto diatomaceous earth.

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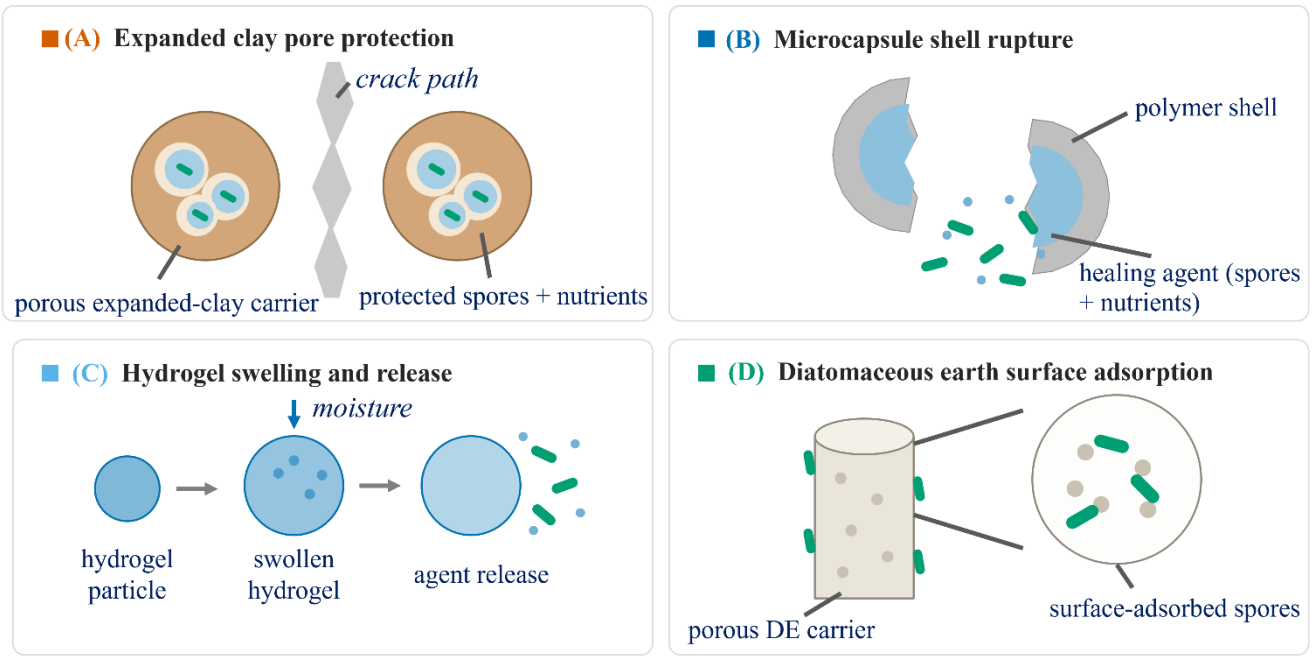


Figure 3. Schematic illustration of bacterial encapsulation and release mechanisms (Created by the authors).

Expanded clay is among the more developed carrier materials. Wiktor and Jonkers [48] demonstrated its ability to protect bacteria while remaining compatible with conventional concrete production; the system was later applied in a field repair pilot [60]. Hydrogels and superabsorbent polymers (SAPs) retain moisture, supporting bacterial activity and continued healing. Examples include the pH-responsive chitosan-based hydrogel developed by Wang et al. [61] and SAP-assisted moisture supply to cracks [34].

Wang et al. [53] reported bacterial-spore encapsulation within melamine-based microcapsules and healing of cracks up to 0.97 mm wide. Kanellopoulos et al. [39] developed microcapsules with mechanical properties designed to withstand mixing but rupture during cracking. More recently, layer-by-layer (LbL) single-spore encapsulation has been proposed to protect bacteria while minimising changes to the cementitious matrix [62].

Lower-cost porous minerals provide additional carrier options. Diatomaceous earth has demonstrated bacterial protection [63], while expanded perlite has also been investigated as a carrier [64], [65]. Lower-alkalinity cementitious materials offer another strategy for improving bacterial survival [66]. Table 4 compares the principal carrier systems.

Table 4. Comparison of bacterial carriers.

Carrier	Protection mechanism	Relative protection	Relative cost	Scalability	Typical application	References
Expanded clay	Spores and nutrients held in porous ceramic aggregate	High	Low	High	General infrastructure; field repair systems	[48], [60], [67]
Microcapsules	Polymer shell ruptured by the crack	Very high	High	Medium	High-value or critical elements	[39], [53], [62]

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Carrier	Protection mechanism	Relative protection	Relative cost	Scalability	Typical application	References
Hydrogels / SAPs	Water uptake, moisture retention and release on swelling	Medium–high	Medium	Medium	Moisture-variable environments	[34], [61]
Diatomaceous earth	Adsorption in natural siliceous pores	Medium	Low	High	Cost-sensitive applications	[63]
Expanded perlite	Spores and nutrients held in porous volcanic glass	High	Low	High	General infrastructure	[64], [65]

Note: Ratings are qualitative comparisons synthesised from the cited studies; survival rates and costs are not reported in a comparable way across studies and are therefore not tabulated.

4.2 Enzyme-Based Self-Healing

Enzyme-based approaches employ biological catalysts rather than living microorganisms to induce calcium carbonate precipitation, potentially improving process reproducibility. Enzyme-induced carbonate precipitation (EICP) commonly uses free urease, which can be extracted from plant sources, to hydrolyse urea through a mechanism similar to bacterial ureolysis [68]. Eliminating the requirement for cell survival simplifies biological control and may facilitate more consistent dosing [57]. However, EICP has primarily been investigated for soil stabilisation rather than concrete crack healing [68].

Another pathway uses carbonic anhydrase to catalyse carbon dioxide hydration, producing bicarbonate that can contribute to carbonate precipitation [69]. Gilmour et al. [70] proposed engineering *Bacillus subtilis* with carbonic-anhydrase-related functionality to promote calcium carbonate formation and explore lower-carbon cementitious materials.

Enzyme stability remains a major limitation. Unlike bacterial spores, free enzymes cannot regenerate and may lose activity in highly alkaline pore solutions or during cement hydration. Immobilisation and encapsulation could extend their functional lifetime, but long-term evidence of enzyme-mediated healing in concrete remains limited.

4.3 Fungal-Based Self-Healing

Fungal self-healing combines calcium carbonate precipitation with physical crack bridging by filamentous mycelial networks. Although fungal systems have received considerably less research attention than bacterial approaches, their potential is increasingly recognised [15]. Luo et al. [71] demonstrated that *Trichoderma reesei* spores could germinate under concrete-like conditions and promote calcium carbonate precipitation.

Fungal hyphae form interconnected three-dimensional networks that provide scaffolds and nucleation sites for mineral deposition, potentially facilitating the closure of wider cracks [15]. However, most fungal species cannot grow at pH values above 11, while oxygen deficiency within deeper concrete regions further restricts development. Screening studies have identified species with improved compatibility and healing potential [72], although their reported performance remains below that of optimised bacterial systems.

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4.4 Biomimetic Vascular Networks

Biomimetic vascular networks resemble biological circulatory systems, using embedded hollow channels to transport healing agents towards damaged regions. Unlike single-use capsules, these networks can potentially be replenished, enabling repeated healing throughout a structure's service life.

Minnebo et al. [37] developed concrete vascular networks in which crack formation opens embedded channels, allowing healing agents to reach the damaged region. Gardner et al. [73] investigated passive capillary transport, while pressurised delivery can be achieved through networks such as the three-dimensional printed systems investigated by De Nardi et al. [38] and Davies et al. [43]. Gravity-fed delivery provides another possible configuration.

Healing-agent selection strongly influences durability restoration and mechanical recovery [74]. Acoustic emission has also been investigated for monitoring damage and subsequent healing in vascular systems [75]. Table 5 compares the four bio-inspired healing families with autogenous and conventional capsule-based approaches.

Table 5. Comparison of bio-inspired healing mechanisms with autogenous and capsule-based healing (synthesis of reported laboratory evidence).

Mechanism	Healing product or action	Typical crack width healed*	Repeated healing	Main advantages	Main limitations	Key references
Autogenous	C–S–H, $CaCO_3$; swelling, blocking	≤ 0.1–0.15 mm	Limited	No additives or added cost	Narrow cracks only; slow; needs water	[23], [26]
Polymer capsules	Polyurethane, epoxy or similar agent	Wider than autogenous; depends on capsule size	Single per capsule	Fast; independent of cement chemistry	Capsule survival during mixing; cost; polymer footprint	[29], [39]
MICP (bacteria)	$CaCO_3$ (mainly calcite)	≈ 0.3–0.5 mm; up to 0.8–0.97 mm in the laboratory	Possible but uncertain	Matrix-compatible product; dormant spores	Viability; nutrients; ammonia (ureolytic); needs water and O_2	[46], [53], [76]
EICP (enzymes)	$CaCO_3$	Few data for concrete	Limited (enzyme decay)	No viability issue; defined composition	Enzyme stability at high pH; urea by-products	[68], [69]
Fungi	$CaCO_3$ on a hyphal scaffold	Few data; potential for wider cracks	Unknown	Crack bridging; no ammonia	Low alkali tolerance; O_2 demand	[15], [71], [72]
Vascular networks	Liquid agent supplied through channels	Wide cracks possible	Multiple (refillable)	Repeated healing; free choice of agent	Casting complexity; channel blockage	[37], [38], [43]

*Indicative values that depend strongly on exposure, healing time and evaluation method.

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5. Materials and Mix Design Considerations

Mix design must facilitate self-healing while maintaining the required fresh and hardened properties of concrete. Figure 4 illustrates the balance among healing efficiency, mechanical performance, and cost.

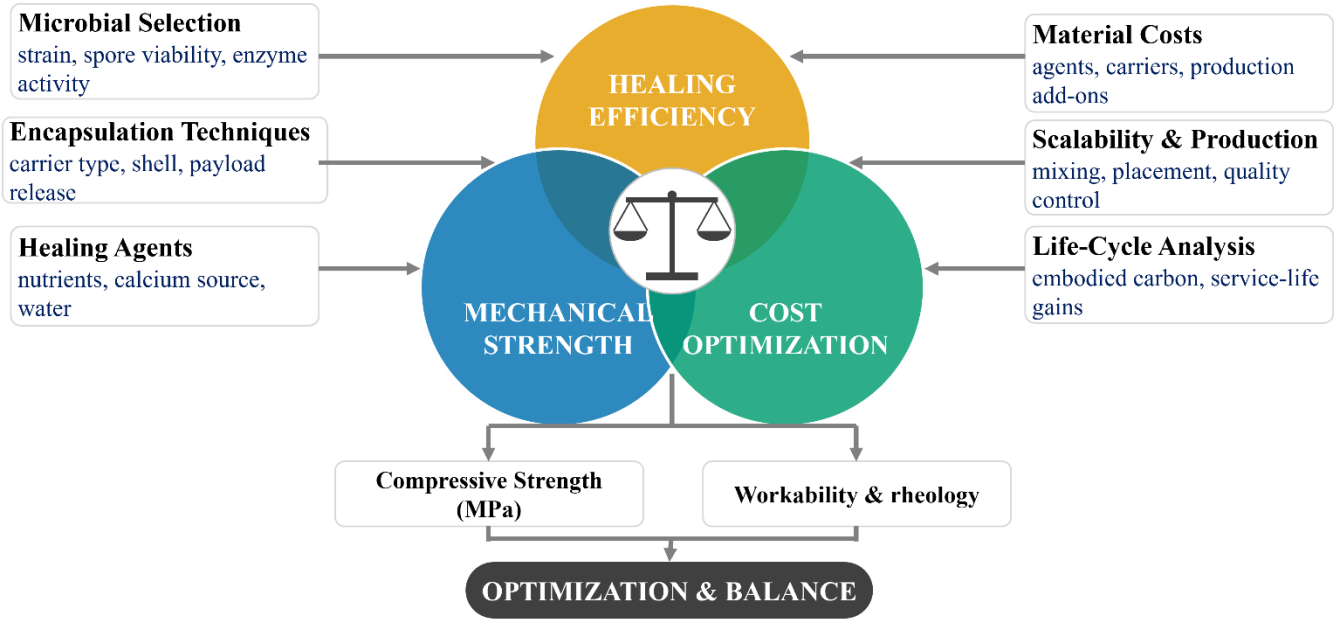


Figure 4. Framework for optimising the mix design of self-healing concrete (Created by the authors).

5.1 Concrete Matrix Compatibility

Biological agents and protective carriers influence both fresh and hardened concrete properties. Porous carriers absorb mixing water and may reduce slump at dosages required for sufficient bacterial loading [77]. Hydrogels and superabsorbent polymers (SAPs) absorb water during mixing and release it during curing, potentially requiring adjustments to water content or superplasticiser dosage [34], [61]. Organic nutrients may adversely affect setting and strength. Jonkers et al. [8] reported that directly adding yeast extract and peptone reduced strength, whereas calcium lactate exhibited better compatibility. This supports encapsulating nutrients alongside bacterial spores [78].

Reported compressive-strength responses vary. Some studies indicate reductions of approximately 5-15% at typical dosages, primarily associated with carrier-induced porosity [79]. Others report strength improvements resulting from pore densification through bacterial mineral precipitation [55], [80]. Tensile and flexural properties may remain comparable to control specimens when formulations are optimised [81], [82]. Bacterial concentration also requires optimisation: insufficient loading limits healing, while excessive loading may compromise concrete properties [58], [83]. Reported calcium lactate dosages commonly range from 0.5% to 2.0% by cement mass [47].

5.2 Healing Agents and Nutrients

The selection of calcium sources and nutrients determines healing efficiency, compatibility, and cost. Calcium lactate is among the most extensively investigated substrates for bacterial healing [8], [48]. It is highly soluble, has a near-neutral pH and supports ammonia-free metabolic pathways. However, its cost and nutrient-production impacts can increase the environmental burden [84]. Nutrient composition also influences healing kinetics [85].

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Under oxygen-limited conditions, denitrifying bacteria can utilise calcium nitrate as a calcium source and nitrate substrate [49]. Although calcium nitrate is commercially available as a concrete admixture, Justo-Reinoso et al. [84] identified it as an important contributor to the environmental footprint of bacteria-based concrete. Calcium acetate offers another alternative, although Zhang et al. [65] reported approximately 15% lower healing efficiency than calcium lactate, attributed to slower metabolic kinetics.

Urea is commonly added at approximately 1-3% of cement mass to support ureolytic precipitation. Its concentration influences precipitation rates [54], but excessive addition may increase ammonia generation [47]. Yeast extract can improve spore germination [51], although its dosage requires control to avoid adverse effects on setting and strength. Table 6 compares the principal healing agents and nutrients.

Table 6. Comparison of healing agents and nutrients.

Compound	Function	Typical dosage (% bwc)	Relative cost	Healing efficiency	Considerations
Calcium lactate	Calcium + carbon source	0.5–2.0	High	Very high	No ammonia; high solubility
Calcium nitrate	Calcium + nitrogen source	1.0–3.0	Low	High	Suits denitrification; high LCA burden [84]
Calcium acetate	Calcium + carbon source	0.5–2.0	Medium	Medium–high	Balance of cost and efficiency
Urea	Nitrogen + carbon source	1.0–3.0	Low	High	Ammonia generation
Yeast extract	Complex nutrients	0.2–0.5	Medium	Supporting (enhancer)	Accelerates germination; may retard setting

bwc = by weight of cement. Dosages and ratings are indicative values compiled from [8], [47], [49], [51], [54], [65].

5.3 Protective Carriers

Carrier selection affects bacterial survival, controlled release, and compatibility with the cementitious matrix, requiring trade-offs among protection efficiency, cost, and practical feasibility (Table 4). Expanded clay is among the more developed options and can partially replace conventional aggregates with relatively limited changes to concrete production [48]. Its influence on spore viability under cold and freeze-thaw exposure has also been investigated [67].

Microcapsules provide controlled, crack-triggered release [39], [53], although manufacturing complexity and cost constrain their use in price-sensitive applications. Hydrogels offer an intermediate approach by protecting bacteria during mixing and supplying moisture to damaged regions. pH-responsive formulations can additionally respond to chemical changes associated with cracking [61]. Diatomaceous earth provides a lower-cost alternative but offers less control over pore characteristics and bacterial protection [63].

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6. Performance Evaluation and Characterisation

This section examines the principal methods used to quantify crack healing, mechanical recovery, durability restoration and microstructural changes (Figure 5).

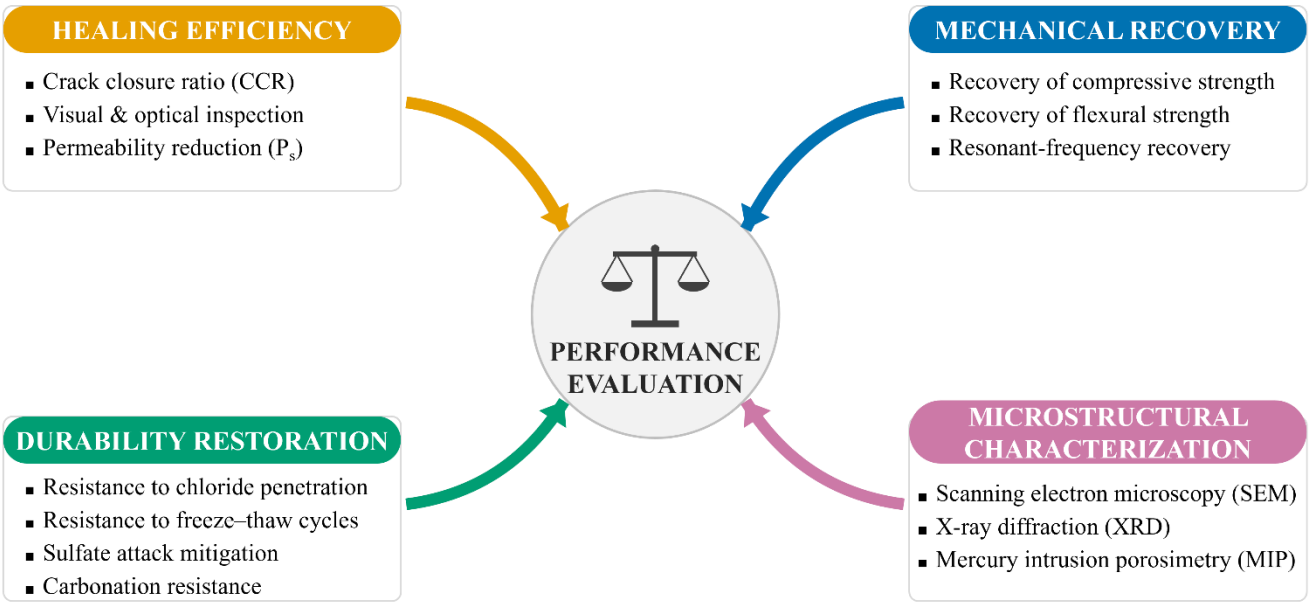


Figure 5. Integrated performance evaluation framework (Created by the authors).

6.1 Crack Healing Efficiency

Crack-healing efficiency is a primary performance indicator. Optical microscopy provides direct evidence of crack closure, while standardised imaging [48] and digital image analysis [86] enable measurements over time. Measurements at multiple positions along each crack are recommended to account for spatial variability [44]. Percentage crack-width reduction, calculated using Equation (4), provides a common basis for reporting geometric closure.

However, visible closure does not necessarily demonstrate functional recovery. Tziviloglou et al. [45] assessed restored watertightness through water-flow measurements, while Van Mullem et al. [87] reported sealing efficiencies of at least 90% in water-permeability tests on laboratory control specimens from a large-scale application. Methodological differences remain substantial, particularly regarding exposure conditions. Results obtained under continuous immersion cannot be directly extrapolated to structures exposed to wet-dry cycling or humid air [21], [23]. Du et al. [88] quantified the effects of initial crack width and healing duration and proposed a kinetic model to improve performance interpretation and reporting consistency.

6.2 Mechanical Recovery

Mechanical recovery is commonly evaluated through flexural-strength testing involving controlled pre-cracking, healing and subsequent reloading, typically using three-point bending [48]. Optimised bacterial systems have demonstrated reported recovery ratios of approximately 60-95%, depending on initial crack width, healing duration and exposure conditions [53], [89]. Resonant-frequency measurements can also provide non-destructive estimates of stiffness recovery [86].

Restored impermeability does not necessarily indicate equivalent mechanical recovery because healing products may bond weakly to crack surfaces. Fatigue behaviour remains less extensively investigated, with reported recovered fatigue lives of approximately 40-70% relative to virgin specimens

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[90]. Healing-product crystallinity and bonding characteristics are important influencing factors. Performance under sustained loading is particularly relevant to practical structures. Ehsan Khan et al. [91] investigated bacterial mortar healing under sustained tensile loading in marine environments. Table 7 summarises the reported mechanical-recovery ranges.

Table 7. Reported Mechanical Recovery Ranges from Literature.

Property	Recovery range (%)	Favourable conditions	Limiting factors	References
Flexural strength	60-95	Immersion; 28 days	Crack width; bonding of healing products	[53], [89]
Compressive strength	65-90	High humidity; 56 days	Crack density; nutrient availability	[77]
Stiffness (elastic modulus)	55-85	Continuous moisture	Partial healing; interfacial bonding	[86]
Fatigue life	40-70 (of virgin)	Rest periods between loading	Crystallinity of healing products	[90]

Note: Ranges are values reported by individual studies under different test conditions and are not directly comparable.

6.3 Durability Restoration

Durability testing evaluates whether self-healing restores the barrier functions that protect steel reinforcement. Water-permeability measurements provide a direct means of assessing crack sealing, with laboratory studies reporting reductions exceeding 90% for bacteria-based systems [53], [87]. In marine environments and areas exposed to de-icing salts, resistance to chloride penetration is particularly important because chloride ingress can initiate reinforcement corrosion. Van Belleghem et al. [92] demonstrated reductions of 75% or more in chloride ingress through cracked regions treated with encapsulated polyurethane. Cappellesso et al. [93] compared bacteria-based healing and crystalline admixtures for limiting chloride ingress and corrosion under marine exposure. Chloride migration tests have also been used to assess encapsulated polymer-based healing agents [94], while ureolytic microbially induced calcium carbonate precipitation (MICP) has demonstrated potential to inhibit reinforcement corrosion [95]. Commonly used test methods include the rapid chloride permeability test (ASTM C1202) and the non-steady-state chloride migration test (NT Build 492).

In cold climates, healing products must withstand freeze-thaw exposure to maintain their effectiveness. Cappellesso et al. [96] assessed bacteria-based self-healing concrete for resistance to frost salt scaling. Ivaškė et al. [67] investigated the viability of non-ureolytic bacteria immobilised in expanded clay under low-temperature and freeze–thaw conditions, while Palin et al. [97] developed a bacteria-based composite for low-temperature marine environments. Resistance to sulfate attack has also been investigated for bacteria-induced healing systems and crystalline admixtures [98].

6.4 Microstructural Analysis

Microstructural characterisation helps explain healing mechanisms and identify the products responsible for crack closure. Wang et al. [53] used scanning electron microscopy (SEM) to examine calcite morphology, bacterial cells, healing products and crack–matrix interfaces. Energy-dispersive X-ray spectroscopy (EDS) provides elemental maps that help establish the distribution of calcium and other constituents, although elemental composition alone cannot confirm a specific mineral phase. X-ray diffraction (XRD) identifies crystalline phases, including calcite, aragonite and vaterite, whose

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formation depends on precipitation conditions and whose properties may influence healing performance [9], [45].

Lors et al. [99] investigated precipitates formed by MICP during the repair of microcracks that remained after autogenous healing. X-ray computed microtomography (micro-CT) offers non-destructive three-dimensional imaging of crack networks and internal healing products. Snoeck et al. [34] used X-ray micro-CT to investigate autogenous healing promoted by SAPs. Table 8 summarises the principal characterisation techniques and their applications.

Table 8. Microstructural characterisation techniques for self-healing concrete.

Technique	Information obtained	Spatial resolution	Sample requirements	References
SEM/EDS	Morphology; elemental composition	1-10 nm	Dried; coated	[53]
XRD	Crystalline phase identification	Bulk average	Powdered	[9]
Micro-CT	3D crack and healing visualisation	1-50 μm	Intact specimen	[34]
TGA	$CaCO_3$ content quantification	Bulk average	Powdered	[99]
Confocal microscopy	Bacterial distribution; viability	200-500 nm	Stained sections	-

7. Sustainability Assessment

This section critically examines life-cycle assessment (LCA), economic viability and the contribution of self-healing concrete to the United Nations Sustainable Development Goals (SDGs).

7.1 Life Cycle Assessment

LCA results for self-healing concrete are highly sensitive to the system boundary and functional unit. Cradle-to-gate assessments, which compare materials at the factory gate, capture production impacts but exclude potential benefits during service. Justo-Reinoso et al. [84] reported that bacteria-based self-healing concrete had an 85% higher overall environmental impact and a 36% higher embodied-carbon footprint per cubic metre than conventional concrete, primarily because of calcium nitrate and polyvinyl acetate in the healing system. Garces et al. [100] found that microcapsule-based self-healing geopolymer concrete had a lower global warming potential (GWP) than Portland cement concrete but higher impacts in other categories, owing to capsule production. Van den Heede et al. [101] reported that adding 1% (by mass) of SAPs to a self-healing engineered cementitious composite (ECC) contributed impacts equivalent to 4-52% of those of the cement, and that polyvinyl alcohol microfibres added substantially to the burden; nevertheless, if complete crack healing was assumed, a self-healing ECC slab had lower impacts over 100 years than a conventional concrete slab requiring cover replacements.

Including service-life effects can change these comparisons. Under marine exposure, Van Belleghem et al. [92] predicted service lives of 60-94 years for self-healing reinforced-concrete slabs, compared with seven years for conventional cracked slabs. Their assessment indicated environmental

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benefits of 56-75% across ten impact indicators. Justo-Reinoso et al. [84] reported potential impact reductions of 12-50% when bacteria-based concrete was used selectively and wider design crack widths reduced reinforcement requirements. The magnitude of these benefits depends on the impact category, repair frequency, exposure conditions, and assumed service life. Results from different studies should not be averaged directly because their functional units and system boundaries differ. Table 9 summarises the LCA evidence, and Figure 6 illustrates the trade-off conceptually.

Table 9. Summary of life cycle assessment studies on self-healing concrete.

System assessed	Scope / functional unit	Key result	Reference
Bacteria-based concrete (encapsulated non-ureolytic spores)	Cradle-to-gate; 1 m^3	+85% overall impact and +36% embodied carbon compared with conventional concrete	[84]
Same system used selectively in a reinforced concrete structure	Structure level; less crack-control steel	12-50% improvement depending on impact category; up to 51 kg CO_2-eq/m^3 saved	[84]
Encapsulated polyurethane; marine slab	Service-life based; chloride exposure	Service life 60-94 vs 7 years; 56-75% lower impacts	[92]
Microcapsule-based self-healing geopolymer concrete	Cradle-to-gate; 1 m^3	Lower GWP than Portland cement concrete; higher impacts in other categories	[100]
ECC with superabsorbent polymers	Cradle-to-gate	1% SAP adds 4-52% of the cement impact; PVA fibres add substantially; lower slab impacts than conventional concrete if full healing is assumed	[101]

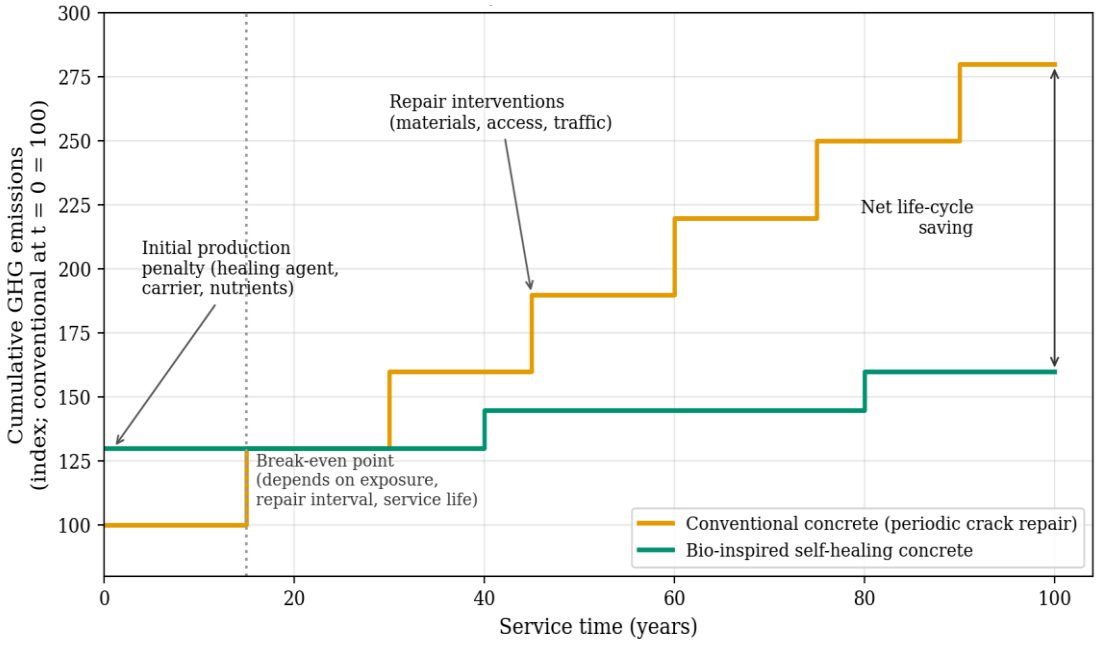


Figure 6. Conceptual life-cycle carbon trajectories of self-healing and conventional concrete, showing the initial production penalty offset by avoided repairs (Created by the authors).

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As Figure 6 illustrates, whether and when self-healing concrete breaks even depends on the size of the production penalty, the frequency and carbon intensity of the avoided repairs, and the service life considered.

7.2 Economic Viability

Published cost data remain limited, although existing studies identify the healing agent, nutrients and protective carriers as major contributors to the initial cost premium. Manufacturing at larger scales may reduce these costs [57], [102]. Selective application in crack-prone, inaccessible or expensive-to-maintain components can improve economic feasibility [84]. In watertight structures, self-healing may also reduce reinforcement requirements associated with crack-width control, depending on the design approach [76]. Potential savings arise primarily from avoided repairs, reduced maintenance disruption and less downtime, particularly in structures that are difficult to inspect or repair [2], [92]. However, published life-cycle cost analyses remain scarce, and many reported savings are estimates rather than verified outcomes. Long-term field data are needed to establish actual costs and savings.

7.3 Alignment with Sustainable Development Goals

Self-healing concrete may contribute to several SDGs when its life-cycle benefits are demonstrated in practice. Extending structural service life and reducing material demand can support SDG 13 (Climate Action) by contributing to lower emissions from cement and concrete infrastructure [3]. Reduced material consumption aligns with SDG 12 (Responsible Consumption and Production), while more durable and reliable infrastructure can support SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities) [2], [4]. Figure 7 illustrates the potential links between the environmental, economic and social dimensions of self-healing concrete and the relevant SDGs. These contributions depend on verified durability improvements, responsible material selection and demonstrable life-cycle benefits.

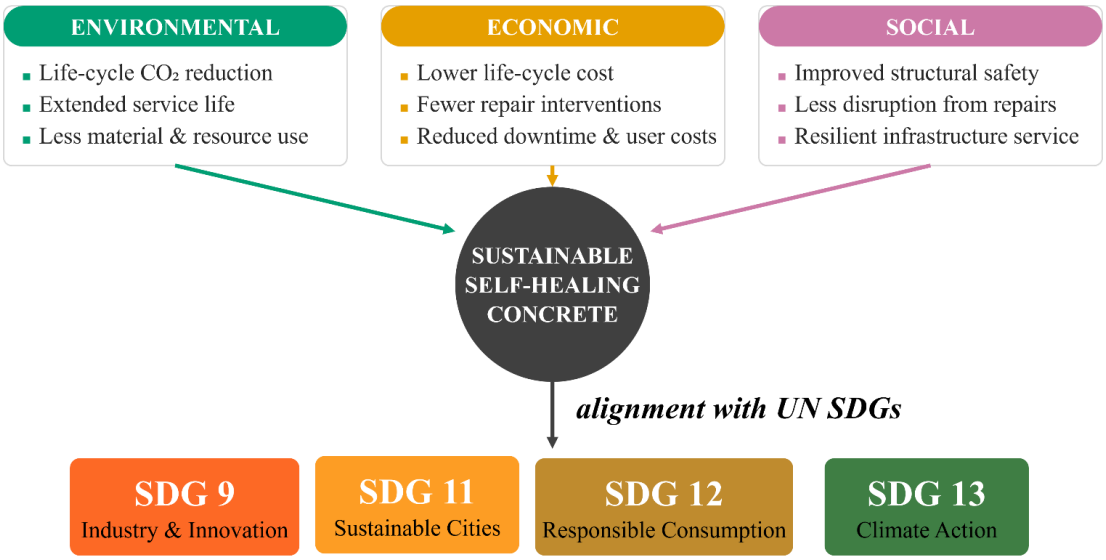


Figure 7. Integrated sustainability framework illustrating environmental, economic, and social contributions of self-healing concrete with SDG alignment pathways (Created by the authors).

8. Applications and Case Studies

Evidence of real-world performance remains limited, with only a small number of short-term demonstration projects and relatively few applications supported by comprehensive monitoring data.

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8.1 Infrastructure Applications

Wiktor and Jonkers [60] investigated a bacteria-based repair system in a parking garage in the Netherlands. Mors and Jonkers [76] evaluated the Delft bacteria-based healing agent in four full-scale repair-mortar and concrete construction projects. Their findings indicated that the bacterial agent could be incorporated safely without adversely affecting concrete properties, while laboratory tests demonstrated healing of cracks up to 0.8 mm wide. Van Mullem et al. [87] constructed the roof slab of an inspection pit using bacterial self-healing concrete. Laboratory control specimens from the same concrete batch achieved at least 90% crack-sealing efficiency.

Al-Tabbaa et al. [103] reported the first UK field application of microcapsule-based self-healing concrete, while Davies et al. [104] documented the design, construction and testing of large-scale field trials involving several self-healing technologies. For marine and tunnel applications, evidence remains predominantly laboratory-based. Research has investigated bacteria-based composites for low-temperature marine environments [97], healing under sustained tensile loading in seawater [91], and the optimisation of tunnel-lining concrete for self-healing performance [105]. Table 10 summarises documented field applications.

Table 10. Documented field and demonstrator applications of self-healing concrete.

Application	Healing system	Country	Main findings	Reference
Parking garage repair (pilot)	Bacteria-based repair system	Netherlands	Field performance of a bacteria-based repair system demonstrated	[60]
Repair mortar and concrete demonstrators (four projects)	Bacterial spores with lactate	Netherlands	Agent added safely with no adverse effect on concrete properties	[76]
Roof slab of an inspection pit	Mixed ureolytic culture (MUC+)	Belgium	Slab in normal operation; control specimens sealed ≥ 90%	[87]
Field trial	Microcapsules	United Kingdom	First UK field application of microcapsule-based self-healing concrete	[103]
Large-scale field trials	Several autonomic healing technologies	United Kingdom	Design, construction and testing at structural scale	[104]

8.2 Field Trials and Performance Analysis

Moisture availability is a major factor governing healing under field conditions [6], [21]. Effective quality control also requires verification of bacterial viability and uniform carrier distribution [64], as well as appropriate moist curing [61]. Long-term field performance remains insufficiently documented because monitoring periods are generally limited and quantitative in-situ measurements of healing are scarce.

8.3 Smart Infrastructure Integration

Integration with smart infrastructure could improve the verification of self-healing performance. Acoustic-emission monitoring has been used to investigate cracking and healing in vascular self-healing concrete [75]. Predictive models estimate crack-healing percentages from mixture composition and exposure conditions [106], [107], while models of microbially induced calcium carbonate

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precipitation (MICP) [108], bacteria-based healing [102], and reactive transport within cracks [109] continue to develop. Integrating these models with structural-monitoring data in digital twins is promising, but its practical effectiveness remains to be demonstrated.

9. Challenges and Limitations

9.1 Bacterial Viability and Repeated Healing

The widely repeated claim that bacterial spores can survive in concrete for decades has not yet been substantiated by long-term field data. Jonkers et al. [8] observed declining viability of spores added directly to cement paste after several months, potentially because of pore-structure refinement. This limitation encouraged the development of protective carriers. Crack depth also influences spore germination because oxygen and moisture availability may decrease away from the exposed surface [110]. Low temperatures and freeze–thaw cycles may further reduce spore viability [67]. Repeated healing is another concern: Justo-Reinoso et al. [46] reported that cracks healed at an early age did not re-heal when reopened in the same location 20 months later, even under favourable conditions, whereas new cracks formed elsewhere did heal, indicating that the encapsulated spores remained viable.

9.2 Crack-Width Limitations

Most bacteria-based systems effectively seal cracks approximately 0.3-0.5 mm wide, although laboratory studies have reported sealing of cracks up to 0.8-0.97 mm [53], [76]. Healing capacity depends partly on bacterial concentration and nutrient availability [83]. Wider cracks may therefore require hybrid healing mechanisms or vascular delivery systems to provide sufficient healing products [21], [43].

9.3 Lack of Standardisation

Comparisons across studies remain difficult because specimen geometry, crack-induction methods, exposure conditions and healing-assessment techniques vary considerably [1], [6], [44]. Water immersion can produce better healing than wet-dry cycling or exposure to humid air, yet many studies assess healing under immersion alone [21]. Harmonised testing protocols and acceptance criteria are needed to support reliable performance assessment and structural design.

9.4 Scale-Up, Quality Control and Regulation

Industrial fermentation could support the cost-effective production of bacterial strains suitable for concrete applications [57]. However, rapid methods for verifying bacterial viability in fresh concrete remain necessary. Regulatory requirements for living additives in construction materials are also unclear, particularly for engineered living materials that do not fit neatly within existing regulatory frameworks [111].

9.5 Critical Synthesis and Research Priorities

Table 11 links each major limitation to the maturity of the available evidence and the corresponding research priorities. MICP mechanisms are reasonably well understood, and laboratory evidence is substantial. However, major gaps remain in long-term bacterial viability, repeated healing, performance under realistic exposure conditions, and life-cycle effectiveness. Enzyme-based and fungal systems remain largely at the laboratory stage, whereas bacteria-based, capsule-based and vascular systems have progressed to various levels of demonstration. Nevertheless, the existence of demonstrator projects does not establish long-term structural reliability or commercial readiness [76], [103], [104].

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Future research should prioritise long-term field monitoring, standardised performance testing, scalable production, reliable quality control and independently verified life-cycle benefits.

Table 11. Evidence maturity and research priorities for bio-inspired self-healing concrete.

Aspect	Current evidence	Maturity	Research priority
MICP mechanisms and healing capacity	Extensive laboratory data; cracks of ≈ 0.3–0.5 mm sealed	High (laboratory)	Report crack width, exposure and method consistently
Long-term viability and repeated healing	Few studies; failure to re-heal after 20 months reported	Low	Multi-year field monitoring; accelerated ageing protocols
Performance under realistic exposure	Strong dependence on moisture; immersion overstates performance	Medium	Testing under wet–dry, humid-air and loaded conditions
Enzyme-based and fungal systems	Proof-of-concept studies	Low	Alkali-stable enzymes; alkali-tolerant fungal strains
Field application	A few demonstrators; monitoring of a few years	Low–medium	Instrumented field trials with quantitative healing data
Life-cycle environmental benefit	Few LCAs; production penalty; benefit depends on service life and design	Medium–low	Harmonised functional units and system boundaries; structure-level LCA
Cost and regulation	Mostly projections; unclear status of living additives	Low	Validated life-cycle cost data; specifications and regulatory pathways

10. Authors' Perspectives

The focus of bio-inspired self-healing concrete has shifted from whether cracks can heal to how reliably and repeatedly healing occurs under realistic exposure conditions. Although laboratory studies have established the underlying mechanisms, evidence sufficient to guide structural designers and infrastructure owners remains limited. This review identifies five critical considerations.

First, bio-inspired self-healing should be regarded as a targeted durability strategy rather than a replacement for conventional concrete. Its greatest potential lies in marine environments, inaccessible structures, crack-prone elements, and water-retaining infrastructure, where extended service life may justify additional costs and environmental impacts [84], [92].

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Second, substantial benefits may arise at the structural-design stage. If reliable healing is demonstrated, crack-control reinforcement could be optimised to offset the additional production burden, provided that safety, serviceability and durability requirements remain satisfied. Healing capacity should therefore be recognised only when verified under representative exposure conditions, reinforcing the need for performance-based specifications.

Third, a single healing event provides limited assurance for structures designed to last 50–100 years. Evidence that previously healed cracks may fail to heal again suggests that hybrid systems combining bacteria with fibres, polymers or replenishable vascular networks deserve greater attention than further optimisation of individual mechanisms.

Fourth, reporting practices require greater transparency. Results obtained under continuous immersion should not be presented as typical field performance. Studies should specify crack geometry, exposure conditions, healing duration, repeatability and assessment methods. Sustainability claims should disclose the additional production burden [44] and include structure-level life-cycle assessments accounting for service-life extension and avoided repairs.

Finally, where inspection and maintenance resources are limited, locally available carriers such as expanded clay [48] and expanded perlite [64] may improve practical feasibility. However, their cost-effectiveness, climatic suitability and long-term healing performance require local validation.

Overall, the field must progress beyond demonstrating crack closure towards establishing reproducible, reliable and economically justified durability performance.

11. Conclusion and Future Perspectives

This review addresses four research questions concerning the capabilities, design requirements, evidence base and sustainability of self-healing concrete.

RQ1: Autogenous healing generally addresses very narrow cracks, approximately 0.1-0.15 mm wide, whereas engineered systems can extend healing capacity to wider cracks, with laboratory studies reporting sealing of cracks up to approximately 0.8-0.97 mm. Bacteria-based systems commonly promote calcium carbonate precipitation, including calcite, which can seal cracks and remain compatible with the cementitious matrix. Vascular systems offer the potential for repeated healing when healing agents can be replenished, whereas enzyme-based and fungal systems remain at an earlier stage of development.

RQ2: Bacterial viability depends on the protection provided by encapsulation or immobilisation, while carrier characteristics and nutrient selection influence healing performance, mechanical properties, cost and environmental impacts. Expanded clay and perlite are promising practical carriers, although their suitability depends on the concrete mixture, intended exposure conditions, and required healing performance.

RQ3: The literature provides substantial but heterogeneous evidence of self-healing performance. Reported outcomes vary with crack width, exposure conditions, healing duration, and test methods. Consequently, laboratory results cannot be directly extrapolated to structural performance under real-world conditions. Field evidence remains limited, with relatively few short-term demonstration projects and insufficient long-term monitoring.

RQ4: Self-healing concrete may incur an initial environmental penalty because healing agents, carriers and associated materials increase embodied impacts. One life-cycle assessment reported a 36% increase in embodied carbon per cubic metre compared with conventional concrete. However, selective application may deliver environmental benefits through extended service life and avoided repairs. Reported benefits vary substantially across studies and depend on system boundaries, service-life

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assumptions and the functional unit; therefore, the reported reductions should not be treated as universally applicable.

Future research should prioritise five areas:

1. Establish harmonised test methods, performance indicators and acceptance criteria for crack sealing, mechanical recovery and durability.
2. Conduct instrumented field trials that monitor healing, durability and structural performance under realistic exposure conditions over extended periods.
3. Combine bacterial precipitation with fibres, polymers or crystalline admixtures to address limitations associated with crack width, healing-product availability and mechanical recovery.
4. Integrate mechanistic models, machine learning and structural-monitoring data to predict healing performance and support condition assessment.
5. Investigate synthetic biology and engineered living materials to improve bacterial robustness and explore carbon-sequestering healing pathways. These developments should be supported by appropriate biosafety assessments and regulatory frameworks.

Progress in these areas will require collaboration among materials scientists, microbiologists, structural engineers, sustainability researchers and infrastructure owners. Such cooperation is essential to establish reliable performance, practical deployment strategies and independently verified environmental benefits.

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