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Assessment of advancements in self-healing concrete for high-performance cementitious systems

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Abstract
This study assessed advancements in self-healing cementitious systems, which comprised natural autogenous mechanisms and engineered interventions. Autogenous healing relies on ongoing hydration, calcium carbonate precipitation and the swelling of hydration products to restore microcracks. Engineered systems employ biological agents, polymers, fibres, shape memory materials and expansive additives to enhance repair capacity. Bacteria-based strategies, particularly those using *Bacillus pasteurii*, achieve recovery of mechanical properties through mineral precipitation, with encapsulation methods such as alginate beads and clay microcapsules extending microbial viability. Fungal agents, such as Fusarium oxysporum and Trichoderma reesei, form mycelial networks that promote calcium carbonate deposition across broader crack regions under varying pH and oxygen conditions. Polymeric agents, such as epoxy, polyurethane and PMMA, rely on controlled chemical reactions activated by crack formation, while fibres and expansive additives restrict crack propagation and facilitate mineral-based sealing. Ultra-high-performance fiber-reinforced concrete demonstrates enhanced self-healing through controlled environmental exposure, frost-melt saturation and microcrack management. The study assessed the efficiency of these mechanisms in restoring structural integrity, reducing permeability and limiting reinforcement corrosion. Current limitations comprise of environmental sensitivity, temperature dependence, nutrient delivery challenges and reduced performance in marine or chemically aggressive conditions. The study recommended the development of multi-agent systems capable of sustained activity under diverse conditions, integration of encapsulation technologies and improved compatibility with field-scale applications. These strategies aim to extend service life, reduce maintenance requirements and support the long-term durability of reinforced concrete structures.

Keywords: Self-healing concrete, *Bacillus pasteurii*, Fungal biomineralization, Polymeric healing agents, Fibre-reinforced concrete, Calcium carbonate precipitation

Introduction

Concrete possesses the inherent ability to recover from microcracking through natural processes, often referred to as autogenous healing and this capability arises from hydration of unreacted cement particles, precipitation of calcium carbonate, swelling of hydrated products and entrapment of debris within cracks (De Rooij, Van Tittelboom, De Belie & Schlangen, 2013) [7]. Water presence is essential for these processes, as crack width directly influences healing effectiveness, with microcracks from 50 to 300 µm exhibiting closure depending on material properties and concrete age (Jacobsen & Sellevold, 1995; Aldea *et al*., 2000) [1, 13]. In early-age concrete, unhydrated cement contributes predominantly to closure, while calcium carbonate precipitation dominates in older concrete (Nijland, Larbi, van Hees, Lubelli & de Rooij, 2007) [29] and swelling of the cement matrix together with debris deposition provide additional mechanical closure. Geopolymer systems demonstrate extended autogenous healing, with slag-based geopolymers maintaining compressive strengths above 80 MPa over nearly three decades of service, indicating continued microcrack repair (Glukhovskij, Zaitsev & Pakhomov, 2007) [9], while laboratory experiments on geopolymer mortar beams showed strength recovery from 42% to 166% under controlled thermal curing, attributed to ongoing geopolymerization (Ali *et al*., 2015) [2]. Denser microstructures in these systems promote superior crack closure compared to Portland cement composites (Wu, Johannesson & Geiker, 2012) [56] and fiber incorporation, polymers and supplementary cementitious materials (SCMs) regulate crack width, enhancing precipitation and gap closure (Nguyen *et al*., 2018; Musil & Kriven, 2014) [26, 28]. In Portland cement systems, SCMs such as fly ash or blast-furnace slag leave unhydrated particles, allowing progressive hydration and crack sealing, with cracks below 200 µm achieving full closure (De Rooij *et al*., 2013) [7], while engineered cementitious composites (ECCs) combine hydrophilic fibers to limit crack width, reduce brittleness and mitigate reinforcement corrosion (Sabapathy *et al*., 2020) [39]. Curing conditions and early-age loading influence healing, as water immersion fosters precipitation and compressive stress brings crack faces into contact (Li & Yang, 2007; Schlangen, ter Heide & van Breugel, 2006) [42]. Artificial self-healing or autonomous mechanisms, introduces external chemical or biological agents into concrete to initiate repair upon cracking (Zhu, Yang & Yao, 2012) [58], with delivery systems such as microcapsules, tubular networks or vascular channels that release healing substances when exposed to stimuli such as moisture, heat, air or direct contact with the cement matrix (Nishiwaki, Oohira & Pareek, 2011; Van Tittelboom, De Belie, Van Loo & Jacobs, 2011; Wang, Van Tittelboom, De Belie & Verstraete, 2012) [30]. Standards organizations describe autonomous healing as involuntary crack repair induced by materials absent from the original mix (Wang *et al*., 2012;

Wu, Johannesson & Geiker, 2012) [54, 56]. Capsule-based strategies store chemical or biological agents within spherical or cylindrical carriers, where passive chemical systems use microcapsules or pipettes to retain reactive substances, while active approaches employ vascular networks to supply adhesives directly into cracks (Wu *et al*., 2012) [56]. Biological capsules contain bacteria or fungi capable of precipitating calcium carbonate or polymorphic iron-aluminum-silicates, restoring material continuity upon activation (Al-Thawadi, 2011) [3] and super absorbent polymers, mineral admixtures, microbial induced carbonate precipitation (MICP) and textile-reinforced concrete provide additional autonomous healing pathways (De Rooij *et al*., 2013) [7].

Bacteria-based self-healing exploits spores embedded in the matrix or protective carriers, with alkaliphilic, endospore-forming bacteria germinating upon water ingress, metabolizing supplied substrates and precipitating calcium carbonate within cracks (Jonkers, 2007; Wiktor & Jonkers, 2011) [17, 19, 55]. Initial systems combined spores with organic mineral precursors, enabling closure of microcracks while reducing water permeability and chloride penetration (Jonkers, 2011) [19]. Encapsulation extends viability using clay, diatomaceous earth, melamine or calcium alginate carriers, incorporating nutrients and mineral precursors to sustain bacterial activity under variable environmental conditions, such as low-temperature marine climates (Tziviloglou *et al*., 2016) [48] and the combination of physical obstruction from bead swelling and mineral deposition enhances crack repair longevity. Self-healing agents comprise of fungi, polymers, fibers, shape memory materials and expansive minerals, with filamentous fungi forming mycelial networks that serve as nucleation sites for calcium carbonate deposition, tolerating pH 2–13 and temperatures from 4 °C to 62 °C, depending on species (Van *et al*., 2021). Epoxy, polyurethane and PMMA polymers utilize chemical reactions to form crosslinked networks that fill cracks, with activation controlled by water or thermal stimuli and encapsulation systems ensuring delayed curing (Wang *et al*., 2019). Fibers, such as steel, glass and carbon, mechanically bridge cracks and chemically enhance nucleation of calcium silicate hydrates (Rajput *et al*., 2023) [36], while shape memory alloys and polymers respond to thermal or mechanical triggers to restore geometry and close cracks. Expansive materials such as MgO, CaO, bentonite and calcium sulfoaluminate swell upon hydration, producing brucite, ettringite or hydrotalcite to seal fissures (Rodriguez, Luo & Mather, 2011) [37].

The efficiency of self-healing depends on water availability, curing, environmental exposure and pre-damage strain, as ultra-high-performance fiber-reinforced concrete (UHPFRC) exhibits limited cracking due to micro steel fibers and water re-curing promotes calcium carbonate deposition, restoring stiffness and sealing microcracks (Kim, Qudoos & Ryou, 2018) [21]. Freeze–thaw cycles influence healing, with extended water exposure increasing frost resistance (Jamshidi *et al*., 2016) [15]. Pre-cracked strain-hardening composites recover partially depending on pre-load levels and moisture exposure (Zhu *et al*., 2012) [58] and laboratory and field evaluations indicate that autogenous, autonomous chemical and microbial strategies collectively maintain structural integrity, reduce permeability and enhance long-term performance of cementitious materials under diverse conditions. This study presents a comprehensive discussion on the advancements in self-healing cementitious systems, comprising natural autogenous mechanisms and engineered interventions.

Overview of Self-Healing Concrete

Concrete is the most widely used man-made material after water, valued for its compressive strength, which resists compression unlike steel, whose strength resists tension and when combined with steel reinforcement, concrete resists both compressive and tensile forces. Despite this combination, concrete remains susceptible to shrinkage, cracking and durability challenges over time and several factors influence reinforced concrete performance, such as water and chloride penetration, sulfate attack, carbonation, alkali-aggregate reaction, freeze-thaw cycles and frost action (Basheer, Kropp & Cleland, 2001) [4]. High water content increases porosity, promoting shrinkage and micro-cracking and these micro-cracks provide pathways for gases and liquids, initiating corrosion of steel reinforcement, while micro-cracks can self-repair to some extent, macro-cracks present structural hazards requiring intervention (Hager *et al*., 2010) [11]. Concrete structures experience cracking due to internal stresses from hydration and external stresses, such as dead or live loads, temperature fluctuations and humidity variations. Early micro-cracks may be addressed by autogenous processes, where unhydrated cement reacts with infiltrating water to seal cracks or by autogenic carbonation when calcium hydroxide reacts with carbon dioxide (Van Tittelboom *et al*., 2012). In marine environments, chloride and sulfate ions accelerate concrete deterioration, making repair essential for extending service life (Kim, Qudoos & Ryou, 2018) [21]. Blended slag cements have been used to enhance early-age crack healing by improving autogenous hydration and healing occurs when water or atmospheric CO_2 penetrates cracks, promoting further hydration or forming calcium carbonate from $Ca(OH)_2$ (Van Tittelboom *et al*., 2012).

Self-healing concrete (SHC) emerged from autogenous healing concepts, extending natural crack-repair capacity with engineered strategies and the first autonomous SHC was developed in the 1990s, with Henk Jonkers' work at Delft University of Technology in 2006 introducing Bacillus-based healing agents (Qureshi & Al-Tabbaa, 2020) [33]. SHC imitates biological wound healing, dispersing capsules or fibers containing repair agents within the concrete matrix and when cracks form, these capsules rupture, releasing the healing solution to seal the fissures (Sangadji, 2017) [40]. Crack widths exceeding the limits of autogenous healing require such autonomous interventions, as cracks permit ingress of corrosive agents, emphasizing the need for immediate treatment to protect embedded steel (Han, Yu & Ou, 2014) [12]. Several SHC strategies have been explored, such as capsule-based and vascular systems that release chemical healing agents upon crack formation, electrodeposition that repairs fractured concrete by depositing repair compounds into fissures (Jiang, Xing, Sun & Wang, 2008) [16], microbiological self-healing that employs spores of alkali-resistant bacteria embedded in the concrete to precipitate calcium carbonate when activated by moisture (Wang *et al*., 2014) [52] and shape-memory alloys (SMAs) embedded in the concrete that can restore structural geometry when exposed to temperature, mechanically closing cracks (Li, Liu & Ou, 2006).

Autogenous healing relies on unhydrated cement particles reacting with water, limiting repair to cracks 50–150 μm wide (Li & Yang, 2007) and early-age concrete exhibits higher self-healing efficiency due to the abundance of unhydrated cement, while wet-dry cycles and compressive stress improve hydration and closure of micro-cracks (Yang, Lepech, Yang & Li, 2009). Fibers can restrict crack propagation and lower water-to-cement ratios reduce the likelihood of crack formation, enhancing healing potential (Sabapathy *et al*., 2020) [39] and shrinkable polyethylene terephthalate (PET) tendons activated by heat compress cracks, accelerating autogenous healing in structural elements (Qureshi & Al-Tabbaa, 2016) [35]. Supplemental cementitious materials (SCMs) and smart expanding minerals contribute to improved micro-crack sealing (Jiang, Li & Yuan, 2015; Qureshi, 2018; Qureshi & Al-Tabbaa, 2015) [34].

Autonomous SHC systems involve encapsulation or vascular networks to deliver healing agents, with common encapsulation materials such as glass and polymer matrices, while healing agents range from bacteria to alkali-silica solutions, methyl methacrylate, expansive minerals and hydrogels (Khitab *et al*., 2019; Qureshi & Al-Tabbaa, 2020; Šavija & Schlangen, 2016) [20, 33, 41]. Bacteria-based healing often utilizes spores and nutrients such as calcium lactate, which, upon crack formation and exposure to moisture and oxygen, precipitate calcium carbonate, sealing cracks up to 0.5–0.8 mm wide (Spinks, 2015) [44]. Encapsulation ensures bacterial survival during mixing, protects against hydration-induced pore size reduction and provides controlled release during cracking (Jonkers, 2016). Microcapsule strategies comprise of urea formaldehyde microcapsules filled with epoxy and gelatin microcapsules containing acrylic resin, which release healing agents when cracked (Khitab *et al*., 2019) [20] and electrodeposition and SMA integration provide alternative mechanical and chemical closure methods. Early concrete stages exhibit the highest autogenous healing potential due to unhydrated cement availability and favorable environmental conditions (Šavija & Schlangen, 2016) [41].

Evaluation of SHC performance employs visual crack monitoring, microstructural analyses, strength recovery tests and durability measurements. Visual inspection identifies crack closure, while scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) confirm the precipitation of healing compounds. Compressive strength recovery is limited but can indicate the functional restoration of material properties (Van Tittelboom & De Belie, 2013; Qureshi & Al-Tabbaa, 2020; Šavija & Schlangen, 2016; Lesovik *et al*., 2021) [33, 41]. Durability improvement is assessed by permeability reduction and resistance to environmental degradation. Concrete production exceeds 12 billion tons per year, with repair costs averaging $147 per cubic meter and conventional repair is labor-intensive with typical maintenance intervals covering only a fraction of the intended 50-year service life, generating substantial economic burdens. Autogenous healing reduces these costs by exploiting unhydrated cement hydration, physical clogging and calcium carbonate precipitation, while bacteria-based self-healing enhances repair potential and maintains uniformity within the alkaline matrix. Costs of bio-additives remain high and encapsulation methods are explored for efficiency and reduced environmental impact, particularly avoiding nitrogen oxide generation during urea hydrolysis (Silva *et al*., 2015) [43].

The progression of SHC integrates autogenous mechanisms with engineered autonomous strategies to control early-age micro-cracks and extend the service life of concrete structures and microbial precipitation, encapsulated chemical agents and mechanical interventions collectively mitigate the ingress of harmful substances, maintain reinforcement integrity and reduce maintenance interventions. Early micro-cracks, if untreated, provide pathways for deleterious ions, emphasizing the role of engineered healing agents, while autogenous processes, supplemented by fibers, SCMs and PET tendons, enable closure of micro-cracks and autonomous strategies handle wider cracks, deploying encapsulated healing agents or vascular networks to restore structural continuity.

Classification of Self-Healing Concrete

The classification of self-healing concrete covers autogenous healing, autonomous self-healing, autonomous capsule-based repair and biologically driven strategies, each providing distinct approaches to restoring structural integrity, reducing permeability and enhancing durability through intrinsic, engineered or bio-activated processes.

1. Autogenous Self-Healing Concrete

Autogenous self-healing in concrete refers to the material capacity to repair cracks without external intervention and the phenomenon relies on the intrinsic properties of cementitious materials, primarily the hydration of unhydrated cement particles, precipitation of calcium carbonate, swelling of hydrated cement and blockage by debris present in the mix water or from cracked concrete surfaces (De Rooij, Van Tittelboom, De Belie & Schlangen, 2013) [7]. Water availability is a prerequisite for these mechanisms to proceed and the effectiveness of autogenous healing is limited by crack width, which ranges from 50 to 300 µm depending on the material and age of concrete at the time of cracking (Aldea *et al*., 2000) [1]. Hydration of unhydrated cement particles contributes most significantly to healing in early-age concrete, providing additional crystalline products to seal micro-cracks, while in older concrete, the primary mechanism shifts toward calcium carbonate precipitation, which fills the cracks over time (Nijland, Larbi, van Hees, Lubelli & de Rooij, 2007) [29]. Physical effects arise from the expansion of the cement matrix surrounding cracks upon water absorption, narrowing openings and aiding closure and mechanical effects comprise of the migration of small debris particles into cracks, further promoting sealing (De Rooij *et al*., 2013) [7].

Investigations into autogenous healing in geopolymer systems have demonstrated that slag-based geopolymers achieve long-term strength recovery after initial cracking and an irrigation pipeline constructed with slag-based geopolymer concrete maintained a long-term strength exceeding 80 MPa after nearly 30 years of service, suggesting self-healing capacity (Glukhovskij, Zaitsev & Pakhomov, 2007) [9]. Laboratory studies on geopolymer mortar beams subjected to controlled cracking and subsequent thermal curing observed strength recovery ranging from 42 to 166 percent, depending on curing age, attributed to continuous geopolymerization kinetics (Ali *et al*., 2015) [2]. Microstructural analysis revealed denser matrices in geopolymeric composites than Portland cement-based systems, correlating with superior crack closure and durability (Wu, Johannesson & Geiker, 2012) [56]. Incorporating polyethylene fibers or other additives into slag-based geopolymers can regulate crack width, allowing healing products to precipitate effectively (Nguyen *et al*., 2018) [28], while polymers such as polyethylene vinyl acetate (PVA) and chamotte particles enhance healing by promoting gap closure upon thermal activation, improving compressive strength and reducing void content (Musil & Kriven, 2014) [26]. Bacterial self-healing has also been applied to geopolymers, where spores remain viable within the microstructure and precipitate calcium carbonate when cracks form, contrasting with Portland cement, where bacterial viability declines with age due to pore structure densification (Jadhav *et al*., 2018; Jonkers *et al*., 2010) [14, 18].

Enhancements in Portland cement-based systems comprise of the use of supplementary cementitious materials (SCMs) such as fly ash and blast-furnace slag, which leave residual unhydrated particles, enabling additional hydration and crack filling over time. Cracks smaller than 200 μm exhibit complete closure more readily, while larger cracks may partially heal (De Rooij *et al*., 2013) [7]. Engineering cementitious composites (ECCs) incorporate hydrophilic fibers to limit crack width and provide sites for precipitation, mitigating brittleness and reducing reinforcement corrosion risk. Superplasticizers lower the water-cement ratio, reducing the formation of micro-cracks (Sabapathy *et al*., 2020) [39]. Curing conditions and early-age mechanical loading influence autogenous healing, with water curing encouraging precipitation of healing products, while compressive stress can bring crack faces into contact, facilitating closure and partial strength recovery (Schlangen, ter Heide & van Breugel, 2006) [42]. Early-age cracking in high-heat concrete is managed using low-heat SCMs, which reduce thermal stress and allow controlled crack formation, indirectly supporting healing (Thenbs.com, 2015) [47].

Crystalline admixtures act as internal healing agents, remaining dormant until exposed to moisture and promoting self-healing through controlled crack precipitation (Oliveira, Gomes, Ferrara, Fairbairn & Filho, 2021) [31]. Optimal performance depends on crack width limitation, achievable through fiber-reinforced ECCs, ensuring that the crack is narrow enough for hydration and precipitation processes to occur effectively. Marine and aggressive environmental conditions impact autogenous healing, as ordinary Portland cement (OPC) mortars sealed cracks more efficiently than blast-furnace slag (BFS) mortars under saltwater immersion, whereas BFS mortars performed better in freshwater (Palin, Jonkers & Wiktor, 2016) [32]. In chloride and sulfate solutions, the formation of brucite ($Mg(OH)_2$) and aragonite enhanced crack sealing and the efficiency of healing is influenced by chemical composition, with supplementary pozzolanic materials improving precipitation of hydration products and supporting long-term crack closure (Zhu *et al*., 2012) [58].

The combination of autogenous mechanisms, engineered interventions and environmental conditioning allows concrete to regain mechanical integrity and reduce permeability and for water-retaining structures, the ability to self-heal mitigates leakage and reduces maintenance needs (Rose *et al*., 2018) [38]. Research demonstrates that healing is more effective in narrower cracks, under early-age loading and with controlled moisture exposure. Methods to enhance healing comprise of mineral admixtures, fibers, superplasticizers, engineered cementitious composites and controlled curing conditions (De Rooij *et al*., 2013; Qureshi & Al-Tabbaa, 2020) [7, 33]. Autogenous self-healing remains a critical property for extending the service life of cementitious systems and OPC, slag-based and geopolymer matrices exhibit variable healing behaviors based on chemical composition, curing, mechanical stress and environmental exposure, while incorporating residual unhydrated particles, SCMs, crystalline admixtures and fibers can improve crack closure efficiency. Geopolymer systems offer potential advantages due to denser microstructures, while bacteria-based approaches demonstrate viability for long-term healing and marine environments, solution chemistry and temperature play roles in healing efficiency, indicating the need for material selection and design strategies aligned with service conditions.

2. Autonomous Self-Healing Concrete

Artificially triggering self-healing processes in concrete cementitious matrix, autonomous crack healing refers to self-healing mechanisms introduced into the cementitious matrix through the introduction of chemicals or biological agents and single- or multi-channel tubular networks as well as spherical or cylindrical capsules can be used to deliver these external agents (Zhu, Yang & Yao, 2012) [58]. Autonomous healing is based on the premise that healing substances are released from containers when damage occurs, such as cracks and react to particular stimuli, thereby activating the self-healing process. The healing agent may react when exposed to air, moisture or heat (Nishiwaki, Oohira & Pareek, 2011) [30] or when it comes into contact with the cementitious matrix (Van Tittelboom *et al*., 2011; Wang *et al*., 2012) [50, 54]. JCI defines autonomous healing as "involuntary healing of cracks that are provided by admixtures," whereas RILEM states that the recovery process uses material components that would otherwise not be found in the material and concrete is said to be autonomously healed when this mechanism is artificially induced by external agents such as biological, chemical or mineral substances in various forms (Wang *et al*., 2012; Wu, Johannesson & Geiker, 2012) [54, 56].

Autonomous healing of concrete is named for concrete in which the healing mechanism is artificially stimulated in the matrix using chemical or biological materials externally and these agents can be incorporated in spherical forms. Autonomous crack-healing is associated with artificial healing processes, occurring either biologically or chemically. Biologically, it occurs through precipitation of $CaCO_3$ and polymorphic iron-aluminum-silicates, with reactions catalyzed by fungi and bacteria (Al-Thawadi, 2011) [3]. Chemically, self-healing is achieved via passive and active modes, where passive methods employ capsules or shallow pipettes and active methods utilize vascular networks supplying adhesives directly into cracks (Wu *et al*., 2012) [56]. Super absorbent polymers (SAPs), mineral admixtures, microbial induced carbonate precipitation (MICP) and textile-reinforced concrete provide additional autonomous healing mechanisms (De Rooij *et al*., 2013) [7].

3. Autonomous Capsule-Based Self-Healing Concrete

Autonomous capsule-based self-healing concrete employs engineered systems to release healing agents when cracks form within the cementitious matrix, introducing chemical or biological substances into concrete through encapsulation or tubular networks, which remain dormant until triggered by crack formation (Zhu, Yang & Yao, 2012) [58]. Healing agents are designed to react to specific environmental stimuli, such as moisture, air exposure, heat or direct contact with cementitious components, enabling controlled initiation of the repair process (Wiktor & Jonkers, 2011; Van Tittelboom *et al*., 2011; Wang *et al*., 2012) [19, 50, 54, 55]. Encapsulation techniques use spherical or cylindrical carriers to contain healing substances, isolating them from the cementitious matrix until crack occurrence and in chemical systems, passive methods store reactive materials in microcapsules or pipettes, while active methods employ vascular networks to distribute adhesives or binders directly into damaged zones (Wu, Johannesson & Geiker, 2012) [56]. The selection of capsule material influences both the mechanical stability and release kinetics, thereby determining the efficiency of crack sealing and restoration of structural properties.

Biological mechanisms utilize microbial activity to induce precipitation reactions that fill voids, with bacteria or fungi embedded in capsules precipitating calcium carbonate or polymorphic iron-aluminum-silicates upon activation, contributing to the recovery of material integrity (Al-Thawadi, 2011) [3]. Chemical processes can incorporate super absorbent polymers, mineral admixtures or microbial induced carbonate precipitation (MICP) to enhance autogenous healing within the concrete matrix (De Rooij, Van Tittelboom, De Belie & Schlangen, 2013) [7]. Standards organizations describe autonomous healing as involuntary crack repair induced by admixtures or as recovery facilitated by materials absent from the original concrete composition, with the mechanism becoming operational once cracks expose the encapsulated agents, initiating reactions that restore continuity within the cementitious matrix (Wang *et al*., 2012; Wu, Johannesson & Geiker, 2012; Al-Thawadi, 2011; Chahal *et al*., 2011) [3, 54, 56]. Capsule-based systems thus provide a controlled, repeatable and externally triggered method for integrating self-repairing functionality into high-performance concrete.

4. Autonomous Bacteria-Based Self-Healing Concrete

Autonomic self-healing in cementitious materials relies on the incorporation of specialized additives, such as microcapsules containing bacterial spores, which deposit healing materials into cracks (Da Silva, De Belie, Boon & Verstraete, 2015) [5, 43]. Bacteria-based self-healing presents an alternative approach, employing spherical, thick-walled cells such as alkaliphilic endospore-forming bacteria to achieve crack repair (Wiktor & Jonkers, 2011) [19, 55]. The first bacteria-based self-healing concrete (SHC) agent combined bacterial spores with an organic mineral precursor to facilitate crack closure (Jonkers, 2007) [17]. Within these systems, calcium carbonate formation occurs through bacterial metabolic conversion of organic acids or enzymatic ureolysis and activation requires the presence of an organic substrate that provides both nutrients and water, enabling bacterial activity and subsequent mineral precipitation (Palin, Wiktor & Jonkers, 2016) [32]. Crack formation in concrete permits water ingress, triggering bacterial spores to germinate into active cells capable of converting mineral precursors into calcium carbonate, which fills microcracks, limits water penetration, reduces chloride ion intrusion and mitigates corrosion of steel reinforcement (Jonkers, 2011) [19]. Early implementations demonstrated effective healing in freshwater and controlled room-temperature conditions, while performance decreased under low-temperature marine environments (Wiktor & Jonkers, 2011; Wang *et al*., 2014; Tziviloglou, Wiktor, Jonkers & Schlangen, 2016) [19, 48, 52, 55], highlighting that bacterial agents must remain active under specific environmental conditions for successful integration into marine structures.

Direct injection of microorganisms into freshly mixed concrete has shown limited effectiveness over extended periods due to rapid depletion of nitrates, which are essential for microbial activity (Jonkers *et al*., 2010; Van Tittelboom *et al*., 2011) [18, 50]. Encapsulation techniques were developed to protect bacterial spores and extend their functional lifetime, such as clay microcapsules (Tziviloglou *et al*., 2016; Wiktor & Jonkers, 2011) [19, 48, 55], diatomaceous earth matrices (Wang, De Belie & Verstraete, 2012) and melamine-based microcapsules (Wang *et al*., 2014; Volodchenko *et al*., 2018) [51, 52]. Although these approaches prolonged microbial viability, the improvement in crack-healing efficiency remained modest. Calcium alginate has been introduced as a protective carrier for bacterial spores and for fabricating bacteria-based beads (Wang *et al*., 2015; Palin, Wiktor & Jonkers, 2016) [32, 53], which incorporate bacterial spores, yeast extract as a nutrient source and magnesium acetate as a mineral precursor. When exposed to water in a simulated marine concrete crack at low temperatures (8°C), the beads swell, activating the bacterial spores, which metabolize the acetate, triggering precipitation of calcium-based minerals that bind with the alginate matrix to form a calcite-alginate composite capable of filling cracks (Zhang *et al*., 2020) [57].

During crack propagation, bead swelling physically obstructs the crack while releasing bacterial spores, yeast extract and magnesium acetate (Zhang *et al*., 2020) [57]. Magnesium acetate precipitates as magnesium-based minerals and active bacteria induce calcium carbonate deposition on and around the beads, contributing to crack closure. This dual mechanism, combining physical obstruction and mineral deposition, enhances the longevity and efficiency of bacterial self-healing in cementitious matrices. Research on bacteria-based self-healing highlights environmental sensitivity, particularly regarding temperature and moisture availability, as most marine infrastructures are located in regions with mild annual temperatures averaging 10°C and summer temperatures around 20°C (Fookes, Simm & Barr, 1986) [8]. Conventional bacterial self-healing agents perform optimally in these conditions but require adaptation for colder marine climates (Jonkers, 2011; Wang *et al*., 2012) [19, 54]. Encapsulation in protective matrices, such as alginate and clay, allows bacterial spores to remain viable until crack-induced water ingress initiates metabolic activity, ensuring mineral precipitation occurs where needed.

The incorporation of bacteria-based beads into cementitious composites represents a progression from earlier self-healing strategies by integrating nutrient delivery, protective encapsulation and mineral precursor availability within a single system, thereby extending bacterial activity and enhancing crack repair in low-temperature environments. By coupling bacterial activation with controlled mineral precipitation, this approach addresses limitations of previous microbial self-healing methods, offering improved durability for reinforced concrete structures exposed to water and chloride ingress. Schematic representations depict bead swelling and subsequent bacterial activation within cracks, illustrating the sequential stages of water absorption, bacterial germination, nutrient utilization and calcite deposition (Zhang *et al*., 2020) [57]. This strategy ensures localized repair, prevents further crack propagation, reduces permeability and enhances structural longevity.

Efficiency of Self-Healing for Cementitious Structures

Self-healing in cementitious materials occurs through the intrinsic capacity of concrete to repair microcracks without external intervention, primarily driven by ongoing hydration or calcium carbonate precipitation. Neville (2002) [27] emphasized that water is a necessary factor for the self-healing process, as it facilitates both chemical and physical mechanisms responsible for crack closure. *Bacillus pasteurii* has demonstrated the ability to restore cracked concrete to approximately 90% of its initial strength, highlighting the effectiveness of biological self-healing agents. Zwaag (2014) [59] noted that when concrete is reloaded after healing, it exhibits mechanical properties closely matching the original, with comparable stiffness and strength, suggesting that properly activated self-healing can restore both durability and functional performance. Natural self-healing can proceed through four distinct mechanisms: precipitation of calcium carbonate or calcium hydroxide, obstruction of cracks by waterborne impurities, continued hydration of unreacted cementitious components and expansion of hydration products along crack edges, commonly referred to as C-S-H swelling (Talaiekhozani & Abd Majid, 2014) [46].

Calcium carbonate and calcium hydroxide formation are particularly effective for autogenous crack repair, as they fill microcracks and restore local density within the matrix (Talaiekhozani & Abd Majid, 2014) [46]. de Azevedo *et al*. (2020) [6] observed that healing during freeze-thaw exposure affects concrete durability, while Jamshidi *et al*. (2016) [15] investigated self-healing under these conditions and identified improvements in performance linked to microcrack closure. Jacobsen and Sellevold (1995) [13] performed freeze-thaw cycles in water on frost-damaged beams and recorded full recovery of resonant frequency, attributing the effect to water-assisted healing. The interval between freeze-thaw cycles influences recovery, with a 30-day rest period enhancing autogenous healing efficiency. Sukhotskaya *et al*. (1983) [45] reported that water exposure during freeze-thaw cycles increased frost resistance, while Jamshidi *et al*. (2016) [15] recorded slight performance improvements in soil-cement specimens, linking the outcome to hydration and microcrack closure. Zhu *et al*. (2012) [58] examined pre-cracked strain-hardening cementitious composites using tensile, ultrasonic pulse and sorptivity tests, observing that self-healing response declined with higher pre-loaded strain levels, demonstrating the sensitivity of autogenous healing to pre-damage conditions.

Ultra-high-performance fiber-reinforced concrete (UHPFRC) exhibits restricted cracking due to micro steel fibers, which enhance the material self-healing potential (Kim, Qudoos & Ryou, 2018; Granger *et al*., 2007) [10, 21]. Cryogenic cooling offers a method for activating self-healing in existing UHPFRC structures through frost-melted water saturation, enabling mineral precipitation and microcrack sealing. Granger *et al*. (2007) [10] analyzed pre-cracked ultra-high-performance concrete (UHPC) without steel fibers, using flexural and acoustic emission experiments and observed that water re-curing prompted crystal formation and recovery of initial stiffness, whereas air curing produced no healing effect. Kwon *et al*. (2013) [22] explored micro-crack repair and air permeability recovery in UHPFRC, identifying calcium carbonate deposition during water re-curing as the principal mechanism facilitating crack closure. Research on UHPFRC self-healing remains limited, with Kim, Qudoos and Ryou (2018) [21] investigating the material behavior under cryogenic conditions for liquefied natural gas storage applications. Across these studies, the efficiency of self-healing is closely linked to water availability, pre-damage strain and curing environment, which collectively influence both mechanical performance and durability under cyclic or extreme conditions.

Challenges in High-Performance Self-Healing Cementitious Systems

1. Autogenous healing is effective primarily for microcracks ranging from 50 to 300 µm (Aldea *et al*., 2000) [1]. Larger cracks exceed the precipitation capacity of calcium carbonate and unhydrated cement particles, leading to incomplete closure and compromised durability (Neville, 2002) [27].
2. Water presence is essential for hydration, calcium carbonate precipitation and microbial activation (Talaiekhozani & Abd Majid, 2014) [46]. Variability in curing conditions and environmental exposure can restrict water ingress, limiting healing in field applications (Jamshidi *et al*., 2016) [15].
3. Bacteria-based self-healing relies on alkaliphilic endospore-forming strains and encapsulated nutrients (Wiktor & Jonkers, 2011) [55]. Temperature, moisture and salinity influence metabolic activity and mineral precipitation. Performance declines in low-temperature marine environments (Wiktor & Jonkers, 2011; Wang *et al*., 2014; Tziviloglou *et al*., 2016) [48, 52, 55]. Microbial viability depends on protective encapsulation in clay, diatomaceous earth, melamine or alginate matrices (Wang *et al*., 2015) [53].
4. Direct injection of spores into fresh concrete shows limited long-term effectiveness due to rapid depletion of nitrates and other substrates necessary for microbial activity (Van Tittelboom *et al*., 2011) [50]. Nutrient insufficiency reduces the rate and completeness of crack closure, especially in deeper or inaccessible cracks (Wiktor & Jonkers, 2011) [55].
5. Freeze-thaw cycles can damage concrete and influence healing potential (Jamshidi *et al*., 2016) [15]. Water-saturated conditions facilitate healing, while air curing or insufficient moisture prevents mineral precipitation and crack closure (Kim, Qudoos & Ryou, 2018) [21]. UHPFRC exhibits microcracking control, but extreme thermal or cryogenic conditions require additional water activation for self-repair (Kim, Qudoos & Ryou, 2018; Kwon *et al*., 2013) [21, 22].
6. Microcapsules, vascular networks and beads protect chemical or biological agents but can reduce mechanical strength if incorporated in high volume (Tziviloglou *et al*., 2016) [48]. Capsule rupture or delayed release can prevent uniform healing and some carriers may degrade under alkaline or marine

conditions (Wang *et al*., 2012; Volodchenko *et al*., 2018) [51, 54].

7. Fungal and bacterial agents operate optimally within defined pH ranges: Trichoderma reesei (pH 7-9), Fusarium oxysporum (pH 6-7, tolerates up to 10), Paecilomyces inflatus (pH 3-11), calthemites-derived ureolytic bacteria (pH 12-13) (Jonkers *et al*., 2010). Extreme alkalinity or acidity reduces biomineralization rates, limiting effectiveness in certain cementitious matrices (Jonkers *et al*., 2010).
8. Fungal metabolism operates between 4 °C and 62 °C with optimal activity near 25-30 °C (Jonkers *et al*., 2012). Shape memory polymers recover at 12-50 °C, SMP optimal at 25-70 °C, SMA activation depends on alloy composition (Chen *et al*., 2020). Extreme temperatures affect polymer curing, microbial activity and expansive material reactions, reducing healing efficiency (Wang *et al*., 2019).
9. Seawater ions influence healing differently. NaCl can reduce long-term durability of fiber-induced mineral nucleation, while calcium and magnesium ions support brucite, ettringite or calcite precipitation (Rajput *et al*., 2015). Bacterial and fungal systems require encapsulation or adapted nutrient delivery to remain active in submerged conditions (Jonkers *et al*., 2011; Wang *et al*., 2012) [54].
10. Most microbial and polymeric self-healing systems have been validated in laboratory conditions (TRL 3-4), with few large-scale field applications achieving consistent long-term performance (Wang *et al*., 2019). Vascular networks, capsule integration and fiber-assisted healing require optimization for structural scale, placement and durability without compromising mechanical properties.

Conclusion

Self-healing in cementitious systems describes the capacity of concrete to recover mechanical and durability properties through natural and engineered repair processes. Autogenous healing occurs through ongoing hydration and calcium carbonate precipitation, sealing microcracks when water is available and helping the cement matrix regain strength. Bacteria-based systems, including *Bacillus pasteurii*, achieve recovery through bacterial activity that converts mineral compounds into calcium carbonate deposits. Controlled nutrient delivery and encapsulation methods using alginate beads and clay capsules protect bacterial spores until water enters cracks and activates mineral production at damaged points. The deposits fill openings and reduce water flow and chloride penetration that may lead to reinforcement corrosion. Fungal agents form mycelial networks that support calcium carbonate growth over larger crack areas. Fusarium oxysporum and Trichoderma reesei can survive under varied pH values and oxygen conditions, making them suitable for different moisture environments. Polymeric materials such as epoxy, polyurethane and PMMA produce chemical reactions after crack formation, while fibers and expansive additives limit crack growth and encourage fissure filling through swelling and hydration product formation. Ultra-high-performance fiber-reinforced concrete restricts crack width, improving healing through water curing, frost-melt saturation and controlled exposure. These approaches lower permeability and protect steel reinforcement from harmful agents. Future development of improved encapsulation methods, nutrient supply systems and compatible healing agents may support concrete repair in marine, cold and chemically aggressive environments, extending service life and reducing maintenance needs.

Recommendations

1. Material scientists, microbiologists and concrete engineers should combine autogenous healing with capsules, fibres, vascular networks, resilient microorganisms and slow-release nutrient carriers to improve crack repair beyond the natural healing limit and maintain microbial activity over time.
2. Concrete designers, contractors and material manufacturers should incorporate internal curing agents, superabsorbent polymers, moisture-retaining materials and frost-resistant mixtures to maintain water availability and improve healing under freeze-thaw and harsh environmental conditions.
3. Researchers and material developers should produce durable encapsulation systems, select microorganisms with high alkali tolerance and develop healing agents that remain active under different pH levels, temperatures and environmental conditions.
4. Marine engineers, microbiologists and material developers should design salt-resistant healing systems with protective encapsulation and nutrient delivery methods that maintain healing performance during prolonged seawater exposure.
5. Researchers, industry partners, construction companies and regulatory agencies should conduct long-term field trials, full-scale structural testing and material refinement before large-scale adoption in engineering practice.

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