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Perspectives on the incorporation of self-healing in the design practice of reinforced concrete structures

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Abstract

Self-healing concrete, with its ability to autonomously repair damages, holds promise in enhancing its structural durability and resilience. Research on self-healing concrete in the past decade has advanced in understanding the mechanisms behind healing, exploring various healing agents, and assessing their effectiveness in concrete structures. However, the full potential of self-healing concrete remains untapped unless its effects are effectively integrated into the design practices of reinforced concrete structures. Realizing this challenge, this paper synthesizes the current research progress and discusses the possibilities to consider self-healing into design codes. The focus was placed on two specific benefits of applying self-healing concrete: one centered on durability and the other on mechanical performance. Specifically, the effect of self-healing on impeding chloride penetration into cracked reinforced concrete was discussed first. Modifications of parameters in existing predictive models based on different types of healing approaches were recommended. Furthermore, the possible impact of the self-healing capacity in mitigating the stiffness reduction of concrete was also discussed. Equations that can describe the stiffness regained due to healing action are presented. In each part of the case study, limitations and challenges still hindering standardization and wider application in the construction field are discussed.

KEYWORDS
chloride ingress, crack width, self-healing, stiffness reduction, structural design

1 | INTRODUCTION

Structural concretes in service are prone to developing cracks due to various causes. The formation of these cracks accelerates many durability issues, as they create additional pathways for external (aggressive) agents such as water, chlorides, and sulfates to penetrate the cementitious matrix more deeply. For instance, chloride ions can break down the protective oxide layer on steel reinforcement, leading to electrochemical reactions that cause rust formation. This rust expansion induces internal pressure, leading to cracking, spalling, and ultimately compromising the structural integrity of the concrete. Furthermore, the presence of cracks can adversely affect the mechanical properties of a concrete structure. Not only do they result in reduced stiffness, but they also alter the distribution of stresses within the structure. This weakening of mechanical properties may render the structure less capable of withstanding loads and resisting environmental conditions, thereby increasing the risk of structural failure over time.

Self-healing in materials refers to the process where cracks undergo partial or complete self-closure, leading to the restoration of the durability and physical-mechanical properties of the materials. Self-healing in cement-based materials can occur through one or a combination of two mechanisms: autogenous and autonomous healing. The former, autogenous healing, typically involves the continued hydration of residual unreacted cement particles or other reactive binders. The latter, autonomous healing, often refers to the release of adhesives or minerals into the damaged areas. Over the past decades, extensive research has been conducted to enhance the self-healing capabilities of concrete. This includes efforts to stimulate its intrinsic autogenous healing properties (e.g., via the use of mineral additives [1,2], crystalline admixtures [3,4], or superabsorbent polymers [4]), or to develop novel autonomous self-healing mechanisms (e.g., via the application of micro- [5], macro- [6], or vascular-encapsulated polymers [7], minerals, or bacteria [8]). It has been observed in several instances that key durability metrics, including but not limited to gas and water permeability, chloride diffusion, and capillary absorption, exhibit signs of positive influence [9]. Additionally, an evident recovery in various mechanical properties such as strength [10,11], stiffness [12], and ductility [2,13], along with an increase in resistance to fatigue [14] and impact [15] has also been reported.

To explore the benefits of self-healing in real-world applications, efforts have been made to align infrastructure requirements with the self-healing functionality [16–19]. One of the proven examples are concrete structures in wet environments. Waterproof structures typically necessitate the elimination of cracking risks, or at the very least, the restriction of cracks to a width of 0.1 mm or smaller. Achieving such minimal crack formation requires a large amount of steel reinforcement to control crack width, rather than for load bearing. In contrast, EN 1992-3 [20] allows crack widths up to 0.2 mm in concrete structures where minor leakage is acceptable and autogenous self-healing is to be expected within a short amount of time. If autonomous self-healing concrete is used, the design criteria of waterproof construction can be simply altered by allowing larger cracks, since the water tightness of the self-healing concrete can be ensured even when the cracks are 0.2–0.4 mm wide [18]. This transition from crack prevention to crack management not only offers potential material savings and a reduced CO_2 footprint but also streamlines application processes by mitigating reinforcement congestion. Several full-scale demonstrators, such as those in the Netherlands, have been constructed with bacteria-based self-healing concrete for water-proofing purposes [18,21].

The integration of self-healing concrete in water-retaining structures exemplifies a scenario wherein the advantages of incorporating the self-healing properties can be quantified at the design phase. This is possible because the effects of cracking are explicitly described in the standards used for the prediction of water tightness. However, this is not the case for the design of many other properties of concrete. For instance, when estimating the corrosion initiation time, conventional service life models typically assume concrete to be intact and devoid of cracks. Therefore, integrating the advantages of healing requires an extension of the current design models in use. These extensions could involve either adjusting parameters within the established engineering models or alternatively developing new numerical models capable of capturing processes that would otherwise be impossible to be account for.

This paper aims to discuss how self-healing can be accounted for in the design models for durability and mechanical properties of reinforced concrete structures. Specifically, the focus will be placed on exploring the incorporation of healing effects into the prediction of chloride resistance and stiffness reduction in reinforced concrete structures as example cases. Firstly, the extension of models for chloride ion penetration to account for self-healing is discussed. Adjustments of models tailored to specific healing scenarios are proposed. Following this, the discussion will turn towards assessing how self-healing mechanisms can alleviate stiffness reduction caused by microcracking. Analytical and numerical methods able to describe the restoration of stiffness attributed to healing will be outlined. Finally, to incorporate self-healing into design methodologies, the current limitations and challenges hindering the standardization and widespread adoption of self-healing design practices are discussed. Based on these, further research objectives are identified.

2 | EFFECT OF HEALING ON CHLORIDE ION PENETRATION IN CRACKED CONCRETE

2.1 | Chloride ingress process altered by cracking and healing

Chloride-induced corrosion is a major deterioration factor in reinforced concrete structures, particularly affecting marine structures, roads, and parking slabs. In uncracked concrete, chloride penetration is slow, occurring mainly through diffusion. However, cracks in concrete create additional pathways, allowing chloride ions to access deeper areas of concrete members more quickly. Studies have demonstrated that once cracks exceed certain thresholds, notably the critical crack width, the diffusion coefficient of chloride ions in cracked concrete increases linearly with the widening of cracks [22].

Self-healing of cracks in concrete can mitigate this process. Regardless of the chosen healing method, be it autogenous or autonomous, it tends to diminish the crack volume, consequently narrowing the effective pathway for aggressive ion transport. Previous research has proven the effectiveness of crack healing in chloride-rich environments [23]. Furthermore, studies have shown that crack healing not only increases the critical crack width but also decreases the diffusion coefficient of chloride ions in cracked concrete when the cracks exceed the critical crack width [9].

Despite the evident effects of healing on resisting chloride ingress through cracks, it is challenging to calculate the benefits of healing in terms of a service life extension of concrete structures. This is because service life models, such as those in the *fib* Model Code for Service Life Design (hereafter referred to as *fib* chloride model) [24], consider concretes to be homogeneous and crack free when determining the time until corrosion initiation. This assumption poses challenges in directly accounting for the impact of cracking and crack-healing. Hence, in this section, first a review of methods for incorporating pre-existing cracks within chloride ingress models is conducted. This is followed by a discussion on the influence of self-healing on chloride diffusion in cracked reinforced concrete for various healing scenarios. Finally, a proposal is put forth to extend the chloride ingress model for accommodating healing effects in probabilistic service life prediction.

2.2 | Service life design considering the presence of cracks in reinforced concrete structures

Reinforcement corrosion in concrete occurs in two stages: initiation and propagation. During the initiation stage, concrete provides a protective alkaline environment that prevents corrosion by forming a passive oxide layer on the reinforcement surface. Over time, aggressive agents like chlorides or CO_2 penetrate the concrete, eventually breaking down this protective layer. This marks the end of the initiation stage and the beginning of the propagation stage, where the active corrosion of the reinforcement starts. From the design perspective, the end of the corrosion initiation stage is usually considered to be the end of the service life of a reinforced concrete structure.

In the case of chloride ingress, the passivation of reinforcement is lost when a critical concentration of chloride is present at the level of the rebar surface. Under the assumption that concrete is crack-free, chloride ingress can be modeled based on Fick's second law of diffusion, and often Gauss error function (erf)-based models are used to predict the chloride content as a function of concrete depth. An illustrative instance of this is the *fib* chloride model [24] as presented below:

$$C_{crit} = C(a,t) = C_0 + (C_{s,\Delta x} - C_0)\left[1 - erf\left(\frac{a-\Delta x}{2\sqrt{D_{app,c}\cdot t}}\right)\right] \tag{1}$$

where, C_{crit} is the critical chloride content, $C(a,t)$ is the content of chlorides at rebar (a is concrete cover thickness), t is the time, C_0 is the initial chloride content, $C_{s,\Delta x}$ is the chloride content at a depth Δx (depth of convection zone), and $D_{app,c}$ is the apparent coefficient of chloride diffusion coefficient, which is a time-dependent variable that can be calculated based on:

$$D_{app,C} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t) \tag{2}$$

which allows the calculation of the apparent diffusion coefficient $D_{app,C}$ from chloride migration coefficient ($D_{RCM,0}$) determined from performance tests of the concrete under chloride ingress. This calculation also considers the impact of environmental alterations, represented by k_e, and the effects of material aging, represented by A(t). With these equations, the duration t required for the chloride content at the cover depth $C(t,a)$ to reach the critical chloride content C_{crit} can be determined. This calculated time can subsequently serve as an estimate for the predicted service life of the concrete structure.

To consider the effects of cracking in the chloride ingress process, different approaches to account for cracks in the erf-solution can be found in the literature. Since cracks represent spatial discontinuities in which the transport of moisture and chlorides is accelerated, the crack-altered chloride ingress process is usually modeled by diminishing the protecting effect of the concrete cover. Figure 1 provides an overview of various methodologies for addressing cracks. The proposed methods focus on either modifying the overall diffusion coefficient of the concrete or adapting the effective depth of the concrete cover. These approaches all assume pre-existing cracks, which occurred at the beginning of the service life.

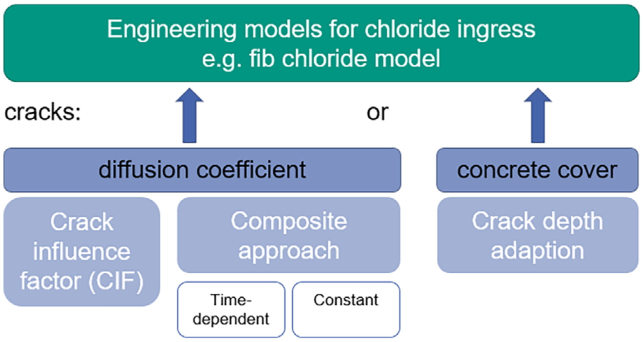


FIGURE 1 Methods to account for cracked concrete in engineering models for chloride ingress [25].

If the diffusion is assumed to be the dominant transport mechanism for chloride ions within cracked concrete, a smeared diffusion coefficient in the erf-solution can account for the increased diffusivity of cracked concrete. The estimation of such a smeared diffusion coefficient can be done by increasing the diffusion coefficient, assuming a composite material characterized by a parallel system of concrete and cracks (composite approach) [25]. Alternatively, a crack influence factor (CIF) can be multiplied by the diffusion coefficient of uncracked concrete D_{uncr} to account for the increased diffusivity due to cracks. CIFs can be experimentally determined by fitting the erf-solution to chloride profiles in cracked and uncracked concrete and using the fitted diffusion coefficients to calculate the ratio between $D_{smeared}$ and D_{uncr} [25,26]. Independent of the method used to account for cracked concrete, the smeared diffusion coefficient is usually described as a function of the crack width [25,27].

For saturated cracks where capillary suction governs, cracks provide direct channels for chlorides and thus render the cover useless up to the tip of the crack, which can be accounted by adapting the convection zone. In the *fib* chloride model, the convection zone describes the surface of the reinforced concrete structure, where the transport mechanisms are not mainly diffusion controlled due to its exposure to frequent cycles of wetting and subsequent drying. To still describe the penetration of chlorides using Fick's second law of diffusion, the resistance of the convection zone is thus neglected, and Fick's second law of diffusion is applied starting at a depth with a substitute surface concentration. Since cracks could provide faster transport pathways for chloride ions, the convection zone could be extended to the crack depth to approximate the reduced effectiveness of the concrete cover [25]. This approach is referred to as 'crack depth adaptation' in Figure 1.

In addition to the engineering models outlined earlier, advanced multi-physics coupled numerical models have been devised to assess the impact of cracking on chloride diffusion in concrete [28–32]. These numerical models consider a wider array of factors, encompassing not only primary parameters like crack width and depth but also secondary influencing factors such as crack tortuosity, the interaction among various ionic species, and the chloride binding capacity of cracked surfaces. However, while numerical models offer a more accurate depiction of the impacts of cracking, estimating the effects of healing on factors beyond the crack width and depth remains challenging. Therefore, subsequent investigations into healing and design strategies focus primarily on key crack parameters, such as width and depth.

2.3 | Role of healing

Since crack healing involves changes in width and depth, proposed models incorporating crack effects can also include healing effects. To gain deeper insights into the impact of various scenarios of healing events on chloride penetration resistance, a literature review was performed to survey studies with relevant results. The findings are presented in Table 1. The table provides details of each study on the employed healing mechanisms, degrees of damage, and their respective scenarios and key findings. In total, 18 research papers were found to have observed healing-induced alterations in chloride resistance properties. Among these publications, 13 studies focused explicitly on investigating the effects of self-healing, while the remaining five reported on observing healing when researching other subjects. Twelve papers reported quantitative data, such as chloride diffusion or migration coefficients, suitable for developing models that account for the healing effect. The remaining studies reported a reduced penetration depth in chloride profiles due to healing but did not provide quantitative data.

One key finding from the literature review is that crack healing may not always completely restore cracked concrete to its original condition. This variability arises from how healing products fill the crack volume. Depending on the healing method selected and the extent of the damage, some cracks may undergo complete restoration, regaining full resistance against aggressive substances, while others experience only partial healing, with healing products dispersed evenly throughout the crack depth or aggregated in specific directions. Various forms of healing are pictured schematically in Figure 2. The forthcoming discussion on the influence of healing on chloride transport in cracked concrete is thus structured according to each specific scenario.

2.3.1 | Scenario 1: Complete healing

Under all healing approaches, complete crack healing is feasible when dealing with sufficiently small cracks. Even

TABLE 1 Summary of studies reporting healing-induced alterations in chloride resistance properties.

	Year	Author	Damage type/ crack width	Healing type/ healing condition	Crack filling scenario	Tests performed/ measured properties	Sample size	Order between healing and chloride ingress	Relevant results
1	1996	Jacobsen et al. [41]	Rapid freeze and thaw/crack width unknown	Autogenous healing/in lime water for 3 months	2	Rapid chloride permeability test AASHTO T 277-89/chloride migration rate	2 specimens per variable investigated	Healing prior to chloride exposure	• Self-healing reduced chloride migration rate as compared to newly cracked specimen. • Chloride migration rate of the healed specimen is still higher than that of undamaged concrete.
2	2007	Şahmaran et al. [69]	Mechanically induced cracks/ crack width = 29–390 microns	Autogenous healing/in NaCl solution for 30 days	1/2	Ponding test AASHTO T259-80/chloride diffusion coefficient	6 specimens with varied crack widths; 2 chloride analyses per crack	Simultaneously	• Self-healing accounted for the marginal effective diffusion coefficient of mortar observed with crack widths below 135 microns. • X-xay diffraction analysis proved the formation of calcite as the main healing products.
3	2008	Ismail et al. [70]	Mechanically induced cracks/ crack width = 6–325 microns	Autogenous healing/in NaCl solution for 14 days	1/2	Modified chloride penetration test/ chloride profile	6–10 specimens with varied crack width per age groups	Simultaneously	• Self-healing can impede chloride diffusion for cracks <55 microns when the specimen is young (at 28 days). • Two-year-old specimens have a smaller healable crack width, indicating diminished healing potential.
4	2014	Yoon et Schlangen [22]	Mechanically induced cracks/ crack width = 25–200 microns	Autogenous healing/in artificial seawater for 472 days	1/2	Chloride migration tests and ponding tests/chloride diffusion and migration coefficient	28 and 18 specimens with varied crack widths for short- and long-term study	Simultaneously	• Critical crack width increased from 0.015 to 0.4 mm after healing. • Crack healing resulted in a slower increase of the chloride migration coefficient with widening cracks, signaling a decelerated chloride penetration process.
5	2014	Maes et al. [36]	Standardized cracks/crack width = 100 & 300 microns	Encapsulated polyurethane	1/4	Standard chloride diffusion test NT Build 443 (7 weeks immersion)/ chloride profiles and diffusion coefficient	9 specimens per variable investigated	Healing prior to chloride exposure	• Across various crack widths, the average diffusion coefficients surrounding a polyurethane • healed crack are lower than those around an unhealed crack. • At a crack width of 100 microns, 50% of the healed specimens exhibit chloride profiles identical to those of uncracked specimens.

(Continues)

TABLE 1 (Continued)

	Year	Author	Damage type/ crack width	Healing type/ healing condition	Crack filling scenario	Tests performed/ measured properties	Sample size	Order between healing and chloride ingress	Relevant results
6	2016	Maes et al. [71]	Standardized cracks/crack width = 100 & 300 microns	Autogenous healing/in artificial seawater for 7 weeks.	1/2	Modified chloride diffusion (immersion for 7 weeks)/chloride profiles	6 specimens per crack width for each tested solution	Simultaneously	• Crack widths lower than 105 microns can heal autogenously. Cracks larger than 105 microns will also heal but not completely. • Samples with autogenously healed cracks have performed an identical chloride profile as uncracked concrete after 7 weeks in a chloride solution.
7	2016	Darquennes et al. [40]	Mechanically induced cracks/ crack width = 126–152 microns	Autogenous healing/ immersion in tap water for 14 and 21 days	1/2	Modified chloride migration tests/ chloride migration coefficients	1 specimen per mixture per curing duration	Healing prior to chloride exposure	• Concrete mixes with blast-furnace slag display potent self-healing. After 21 days in water, their chloride migration coefficient nearly matches uncracked concrete. • A linear behavior is found for the evolution of the chloride migration coefficient of self-healed materials as function of the crack width.
8	2017	Van Belleghem et al. [72]	Standardized cracks/crack width = 300 microns	Encapsulated polyurethane	2/4	Standard chloride migration tests (NT Build 443)/ chloride migration coefficient	6 specimens per variable investigated	Healing prior to chloride exposure	• Healing of cracks largely decreases the chloride content compared to unhealed cracks. • Perfect healing of the crack, so that the concrete would behave as uncracked, was not observed.
9	2018	Van Belleghem et al. [73]	Standardized cracks/crack width = 300 microns	Encapsulated polyurethane	1/4	Electrochemical measurement and modified chloride diffusion test (26 weeks)/ chloride profiles	3 specimens per variable investigated	Healing prior to chloride exposure	• The specimens healed with high viscosity polyurethane exhibited a chloride profile like that of cracked specimens without healing. • Autonomous crack healing with low viscosity polyurethane noticeably reduced chloride content compared to untreated cracked specimens.
10	2019	Van Mullem et al. [42]	Mechanically induced cracks/ crack width = around 150 microns	Stimulated autogenous healing by super absorbent polymers/ wet-dry cycles for 28 days	2	Chloride diffusion test/ chloride profiles	3 specimens per variable investigated	Healing prior to chloride exposure	• SAP stimulated autogenous healing, notably reducing chloride ingress during the initial week of exposure. • Yet, after five weeks in aggressive media, specimens healed with super absorbent polymers exhibited similar chloride ingress levels to reference specimens healed without super absorbent polymers.

TABLE 1 (Continued)

	Year	Author	Damage type/ crack width	Healing type/ healing condition	Crack filling scenario	Tests performed/ measured properties	Sample size	Order between healing and chloride ingress	Relevant results
11	2019	Abro et al. [37]	Mechanically induced cracks/ crack width = 100–500 microns.	Crystalline admixture and expansive admixtures/ immersion in water for 28 and 56 days.	1/2	Modified migration test/ diffusion coefficient	1 specimen per variable investigated	Healing prior to chloride exposure	• After 56 days of healing, specimens with a 0.1 mm crack showed diffusion coefficients nearly identical to uncracked specimens across all mixtures. • For larger crack widths, the reduction in the diffusion coefficients depended on the mixture.
12	2021	Abro et al. [38]	Mechanically induced cracks/ crack width = 200–400 microns.	Crystalline admixture and expansive admixtures/ immersion in water for 28, 56 and 128 days	1/2	Modified migration test/ diffusion coefficient	1 specimen per variable investigated	Healing prior to chloride exposure	• Change of migration coefficient over cracks for different crack widths was reported. • A linear relationship between the migration coefficient and crack width is found. • The concept of equivalent crack width is proposed.
13	2021	Yoo et al. [45]	Mechanically induced cracks/ crack width = 100–300 microns	Autogenous healing/ immersion in water for 28, 56, and 91 days	1/2	Modified migration test/ diffusion coefficient	1 specimen per variable investigated	Healing prior to chloride exposure	• A linear relationship between the migration coefficient and crack width is found. • The slope of the diffusion coefficient to crack width decreases, as the reduction in the diffusion coefficient is larger as the crack width increases.
14	2021	Cuenca et al. [39]	Mechanically induced cracks/ crack width = 200–800 microns	Crystalline admixture/ continuous immersion and wet-dry cycles in NaCl solution for 1, 3, and 6 months.	2	Chloride diffusion test/ chloride profiles	2 specimens per variable investigated	Simultaneously	• When crystalline admixtures are included in the mix, the chloride profile stabilizes at a depth considerably closer to the exposure surface compared to the reference mix. • Crystalline admixture proves more effective in specimens under constant immersion compared to those undergoing wet-dry cycles.

(Continues)

TABLE 1 (Continued)

	Year	Author	Damage type/ crack width	Healing type/ healing condition	Crack filling scenario	Tests performed/ measured properties	Sample size	Order between healing and chloride ingress	Relevant results
15	2022	Rossi et al. [44]	Mechanically induced cracks/ crack width = 100–150 microns	Bacteria-based healing agent/ immersion in water for 28 days	3	Chloride diffusion and migration test/ chloride diffusion and migration coefficients	2–3 specimens per mixture for each test	Healing prior to chloride exposure	• The positive impact of self-healing is evident in chloride diffusion but not in chloride migration. • The healing products formed at the cracked mouth can initially mitigate chloride diffusion, but their blocking effect diminishes in the long term.
16	2023	Cappellesso et al. [74]	Mechanically induced cracks/ crack width = 300 microns	Crystalline admixture and bacteria-based healing agent/ weekly wet-dry cycles for 3 months	2/3	Chloride diffusion test (immersion in a NaCl solution for 3 months)/ chloride profiles	Not mentioned	Healing prior to chloride exposure	Both types of healing agents had improved behavior related to chloride ingress, while reference specimens had an ingress of about 1.5 times more than the self-healing concrete.
17	2024	De Brabandere et al. [48]	Standardized cracks/crack width = 300 microns	Crystalline admixture, expansive, and bacterial healing agents	2/3	Diffusion test (immersion in NaCl solution for 6 and 12 weeks) and migration test/chloride profile and migration coefficient	6 specimens per mixture	Healing prior to chloride exposure	• A higher sealing efficiency does not necessarily mean a higher resistance to chloride ingress. • All healing agents delivered a faster reduction as compared to autogenous healing. However, after 56 days of healing, all test specimens exhibited a chloride migration coefficient similar to the control specimens.
18	2024	Cappellesso et al. [23]	Mechanically induced cracks/ crack width = 100 microns	Manual injection of water-repellent agent, sodium silicate, and polyurethane/ air drying for 2 days	1/2	Diffusion test (immersion in NaCl solution for 140 days)/ chloride profile and diffusion coefficient	At least 3 specimens per variable investigated	Healing prior to chloride exposure	• Selected healing agents can all effectively reduce the rate of chloride ingress. • Polyurethane and water-repellent agents are more effective than sodium silicate. But sodium silicate is more desirable for resisting chloride ingress during freeze–thaw cycles.

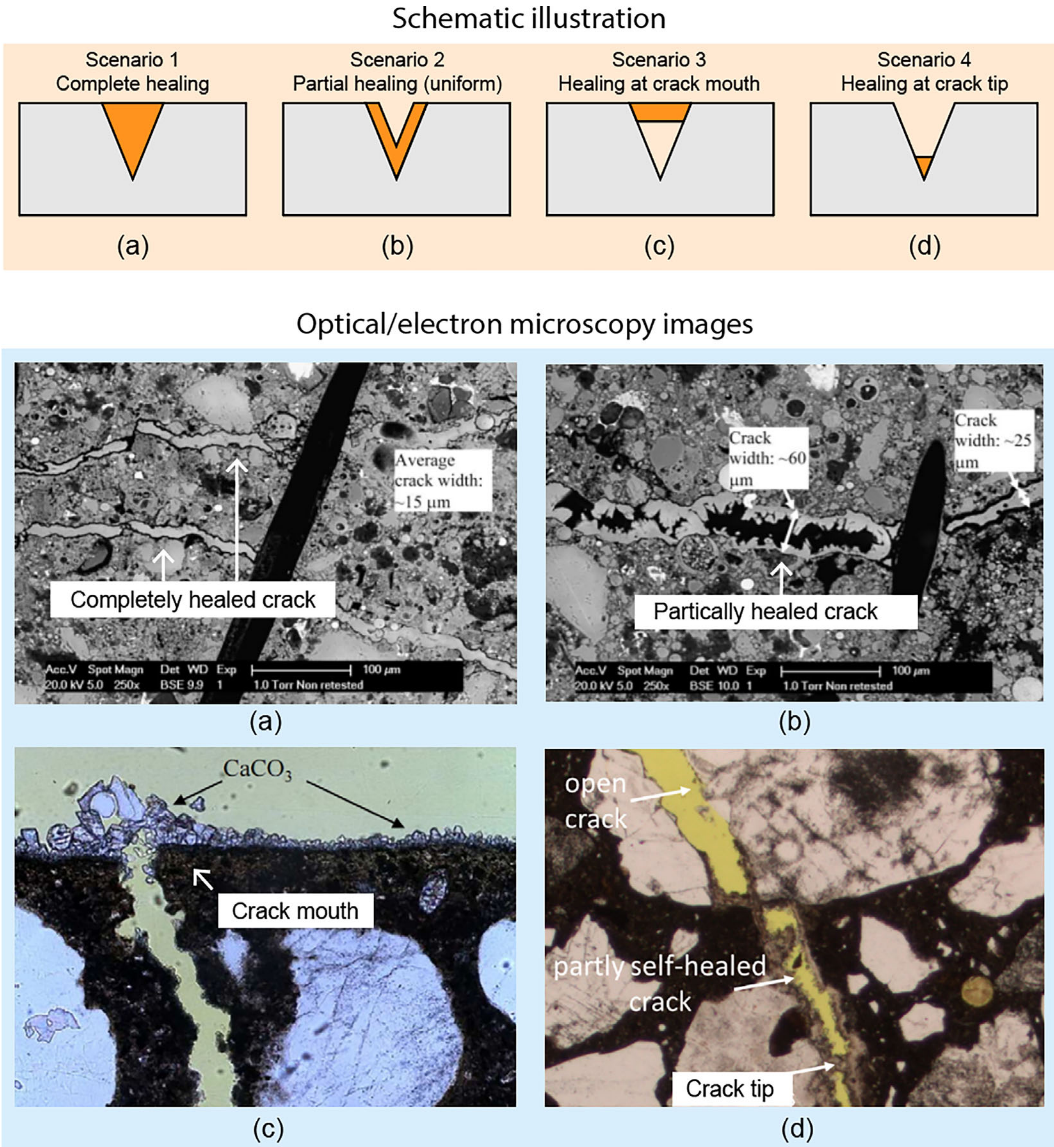


FIGURE 2 Illustration of different healing scenarios: (a) complete healing, (b) uniform partial healing [33], (c) healing at crack mouth [34], and (d) at crack tip [35].

though healing products may be more porous than the matrix, research has shown that a fully healed crack can effectively regain its resistance against chloride ingress. Yoon and Schlangen [22] investigated the impact of microcracking on concrete. They found that the critical crack width for unhealed concrete is 15 μm, whereas prolonged autogenous healing raised this threshold to 40 μm. This establishes that cracks smaller than 40 μm have the potential for complete restoration. Maes et al. [36] studied specimens containing glass capsules filled with polyurethane as a healing agent. The results show that for crack widths of 100 and 300 μm, almost no chloride penetration was measured around the healed crack in 83% and 67% of the cases, respectively. Abro et al. [37,38] and Cuenca et al. [39] both conducted studies investigating the efficiency of crystalline admixture systems. Their research demonstrated that the crystalline system is capable of fully restoring chloride resistance in cracked concrete. Specifically, it was found that specimens with 100 μm cracks, after 56 days of healing, exhibited nearly identical diffusion coefficients to the uncracked specimens, irrespective of the specific mixture used.

2.3.2 | Scenario 2: Partial healing (uniform)

Once a crack surpasses a certain width or encounters adverse conditions, complete healing becomes unfeasible, resulting in only partial recovery. The way partial healing occurs depends on the healing approach. The healing products can form either uniformly along the crack depth or aggregate towards either the crack mouth or tip. In instances of uniform partial healing, the effective crack width uniformly decreases within the crack. Self-healed specimens can be simply seen as specimens characterized by a reduced crack size. This means that if complete healing can happen at a crack width of 100 μm, then any cracks larger than this threshold can have an effective crack width with a 100 μm reduction. Uniform partial healing has been observed across various methods, including autogenous healing through ongoing hydration [22,40,41], stimulated autogenous healing via super-absorbent polymer [42] and autonomous healing utilizing encapsulated polyurethane [36] and crystalline admixture [39].

2.3.3 | Scenario 3: Partial healing (cracked mouth)

Analyzing the healing effects becomes complex in cases of uneven partial healing, where healing products tend to form preferentially either at the crack mouth or tip. For instance, in self-healing bio-concrete, healing typically starts at the crack mouth [43]. This is because the healing in this case relies on the calcium carbonate precipitated by bacteria through aerobic metabolic conversion of organic compounds. Since this microbial activity relies on the availability of oxygen, the rate of precipitation is the highest at the crack mouth. Consequently, even if a crack closure is observed at the surface, the crack might remain largely unhealed along the crack depth. In a recent study by Rossi et al. [44], mortars embedded with bacteria-based healing agents were examined for their chloride penetration resistance. While a surface healing was evident, positive effects of the self-healing on the chloride penetration of cracked specimens were not observed. This was attributed to the thin layer of self-healing products formed at the crack mouth, offering minimal resistance to chloride penetration.

Nevertheless, calcite-precipitating bacteria may prove effective in impeding chloride penetration under specific conditions, particularly when the thickness of the healing product formed at the crack mouth reaches certain thresholds. In a recent study, He et al. [43] explored crack healing in a real-world setting, uncovering noteworthy distinctions from healing under controlled conditions (i.e., moisture curing at constant temperature). Unlike the limited healing restricted to the crack mouth in controlled settings, a substantial healing process was observed throughout the entire crack depth in a realistic environment. However, this study did not measure transport properties.

Therefore, when considering healing specifically at the crack mouth, estimating the transport properties of healed concrete based on the surface crack width is unfeasible. Many existing methods that rely on the surface crack width therefore do not apply to this type of healing. To address this, understanding the healable crack depth within a particular environment over a defined period of time becomes essential for accurate evaluation.

2.3.4 | Scenario 4: Partial healing (crack tip)

Healing only at the crack tip exhibits a contrasting characteristic compared to the previous scenario. In this case, healing might have occurred without any discernible evidence upon surface inspection. This type of healing happens most commonly when the encapsulation technique is used. If the crack volume exceeds the volume of the healing agent released from the carriers, due to capillary forces, only the area proximal to the crack tip can be filled with the healing agent. This circumstance may also manifest in vascular-based self-healing systems if the vessels are not sufficiently ruptured, thus limiting the release of the healing agent. In both instances, the viscosity of the released liquid is a crucial parameter dictating how deep the crack can be healed.

2.4 | Design recommendations

Possible situations where the impact of healing on the chloride penetration resistance can be considered include (1) the determination of maximum allowable crack width for a concrete structure with a known environment and intended service life or (2) the estimation of the remaining service life of a cracked concrete structure. In both cases, the effects of healing will be reflected through the adjustment of a parameter that characterizes a decelerated chloride transport process. Options for adjustment include adapting the crack width, the diffusion coefficient, or the cover depth. The following strategies are suggested depending on the healing scenario:

2.4.1 | For healing scenario 1

In situations where complete crack healing is expected, the cracked concrete can be treated as if it is intact, under the condition that the triggered healing process occurs at a significantly faster rate than the ingress of chloride.

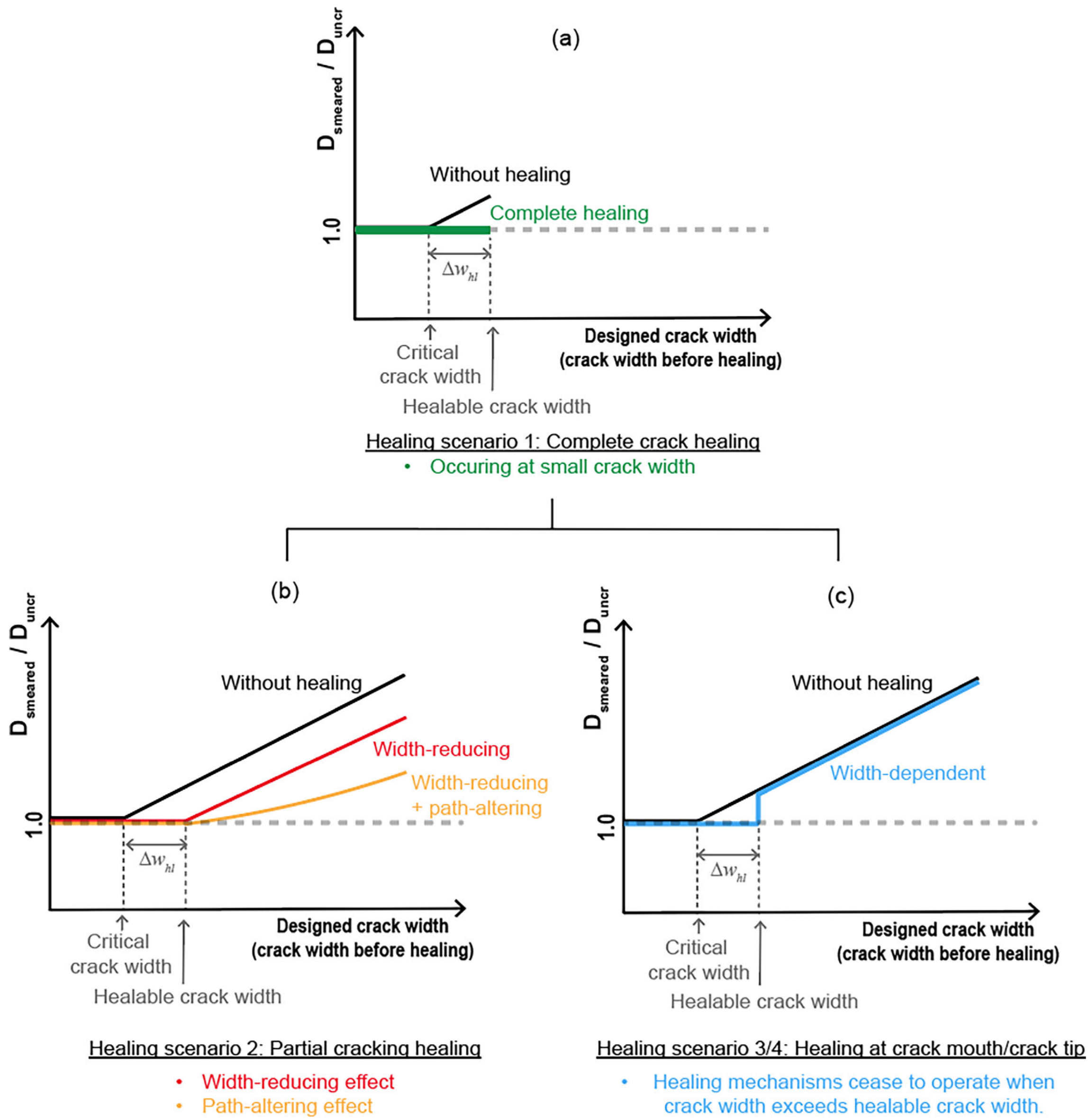


FIGURE 3 Schematic illustration of the relationship between diffusion coefficient and crack width for (a) complete healing, (b) partial healing, and (c) healing methods functioning only at small crack widths for rapid healing.

Prior research indicates that if the width of concrete cracks is below a certain threshold (i.e., the critical crack width), the ion diffusion rate through these cracks aligns with that of uncracked concrete. Consequently, concretes engineered with self-healing capacity can exhibit an increased tolerance for crack widths, hereafter referred to as 'healable crack width' (illustrated in Figure 3a). The difference between the 'critical crack width' and the 'healable crack width' is the net contribution from healing, which is expressed as Δw_{hl}. The healable crack widths, as related to various healing methods, are documented under 'Scenario 1' in Table 1, with specific values of 40, 100, and 300 μm corresponding to the autogenous healing, healing with crystalline admixture, and healing with polyurethane, respectively. It is essential to highlight that accurate determination of the 'healable crack width' requires conducting chloride diffusion/migration tests on healed concretes. The crack width threshold determined by surface observations of crack closure can be misleading, as a visually 'sealed' crack does not guarantee a complete restoration of the chloride resistance.

2.4.2 | For healing scenario 2

If the chosen method of healing aligns with partial healing, two situations emerge. In the first one, partially healed cracks can be simply considered as cracks with reduced openings. This indicates that only the crack width is affected by healing, while other characteristics such as roughness, tortuosity, and path connectivity remain unchanged. In this situation, healing only delays the increase of the diffusion coefficient but does not affect the linear relation between the diffusion coefficient and the crack width, as illustrated schematically as 'width reducing' healing in Figure 3b. Several studies [38,40,45] provide supporting evidence for this situation. In this case, the effective crack width w_{ef} (the width after healing) can be determined by subtracting the healing contribution Δw_{hl} from the designed crack width w_d:

$$w_{ef} = w_d - \Delta w_{hl} \tag{3}$$

If the relationship between crack width and diffusion coefficient is known for a certain type of concrete, the diffusion coefficient of such concrete with healing capacity can be expressed as:

$$D_{cr,hl}(w_d - \Delta w_{hl}) = \begin{cases} D_{uncr}, w_d - \Delta w_{hl} < \mathit{critical\ crack\ width} \\ f(w_d - \Delta w_{hl}), w_d - \Delta w_{hl} \geq \mathit{critical\ crack\ width} \end{cases} \tag{4}$$

The advantage of employing this method is that it eliminates the need to test the diffusion coefficient of healed concrete. Existing databases containing the chloride diffusion coefficients of cracked concrete are sufficient for the analysis.

For certain healing mechanisms, healing does not only reduce the crack width but also change the crack roughness and tortuosity. Depicted schematically as 'path-altering' healing in Figure 3b, can lead to an additional recovery of the diffusion resistance of the partially healed concrete. To describe such effects, it is necessary to experimentally determine the diffusion coefficient of the partially healed concrete by carrying out chloride diffusion tests of healed concrete with different crack widths as reported in several studies [22,45].

2.4.3 | For healing scenarios 3 and 4

If healing is expected to occur preferably at the crack mouth or crack tip, the effects of healing can be better predicted by applying the 'crack depth adaptation' method. Regardless of the healed location along the crack depth, the presence of healing products obstructs the effective diffusion paths for chloride ions to reach the reinforcement, which can be described by a reduced thickness of the convection zone. The depth of the healing can then be estimated by the amount of healing products formed/released. For example, in an encapsulated system, if the theoretical quantity of released healing agent can be estimated using the geometric dimensions of a crack (either measured or anticipated), then the calculated filling ratio could act as a parameter for predicting the extent to which the resistance to chloride diffusion can be restored. In systems employing calcite-precipitating bacteria, the quantity of healing products formed can be deduced from the duration of the healing process and the theoretical rate of formation of the healing agents in its depth direction. It should be noted that healing methods in this category (e.g., bacteria-based and vascular-based) may cease to function when crack widths exceed certain thresholds. In bacteria-based self-healing concrete, small cracks allow nutrients to diffuse effectively throughout the damaged area, supporting bacterial growth and metabolism. However, larger cracks may have areas with limited nutrient availability, reducing healing efficiency. This limitation can result in abrupt changes in the diffusion coefficient, as shown in Figure 3c. It was observed that the bacterial crack healing efficiency is limited when crack width exceeds 0.8 mm [46,47]. References [44, 48] in Table 1 offer relevant data that may serve as guidance.

In previous scenarios, it is assumed that the effect of healing is not time dependent. They are applicable either when healing completes before the start of chloride exposure or when the rate of healing significantly outpaces the rate of the chloride ingress. Thus, alternative strategies must be considered when dealing with a healing process that operates at a slower pace. One way to determine the reduced smeared diffusion coefficient of cracked concrete due to slow-acting healing is by conducting chloride resistance experiments at different stages of the healing process. By repeating the same experiments for concrete with different crack widths, the modified diffusion coefficient can then be expressed as a function of time and crack width. Alternatively, to account for slow healing effects, one might adjust the 'aging' factor in the *fib* chloride model as presented above in Equation (2). This factor is considered in service life prediction models to reflect the increase in diffusion resistance as the concrete matures. This arises from ongoing hydration reactions and the formation of additional calcium silicate hydrate gel, which reduces the pore space for chloride ion penetration and acts similarly to healing.

2.5 | Limitations

While the proposed methods hold theoretical validity, certain limitations persist. The first one is related to the occurrence sequence between the healing action and the chloride exposure. The preceding discussion concerning the design approaches assumes that the healing process initiates concurrently with the beginning of the chloride exposure. In some cases, healing occurs rapidly in relation to the chloride diffusion process, making it suitable for consideration as an almost instantaneous event. In cases of slow-acting healing, it may also be regarded as a time-dependent process, characterized by a gradual reduction in diffusion rate over time. However, experiments in literature usually ensure that healing takes place before exposing the material to chloride. Even for healing processes that require more time, studies often allocated extended periods to allow complete healing, maximizing potential benefits. This approach renders the results from these studies impractical for real-world scenarios. Only four studies adopted simultaneous healing and chloride ingress as listed in Table 1. To date, no publication has provided a direct comparative analysis between the two procedures, that is, simultaneous healing and chloride ingress, and prior healing followed by chloride exposure.

Regarding the determination of the chloride penetration resistance, the method for assessing the chloride penetration resistance must be chosen carefully. Although it falls outside of the scope of this paper to determine the most appropriate test for evaluating self-healing concrete, it is evident from the literature that outcomes differ based on the test employed. Two publications have specifically compared results obtained from various tests [44,48]. Both studies suggested that the effect of healing is more prominent when assessed through diffusion tests. Additionally, studies by Abro et al. [37,38] are directed towards developing a novel testing protocol to measure the chloride migration coefficient in cracked concrete after healing.

The durability of the healing products is another important factor that requires further investigation. If the healing products degrade over time, their effectiveness as barriers diminishes, providing only temporary rather than permanent resistance against chloride penetration. Among the literature found, only the time-dependent efficiency of super absorbent polymer [42] and bacterial healing agents [44] are evaluated. In the case of super absorbent polymer, there was a considerable reduction in chloride ingress in the first week of exposure. However, after exposure to aggressive media for 5 weeks, healed specimens had a similar chloride ingress as healed reference specimens that do not have any super absorbent polymer. A similar initial retarding effect was also observed for bacterial healing [44]. Furthermore, it is important to verify the durability of healing under realistic conditions. Most studies investigate healing under controlled environments, with consistent temperature and moisture. However, reinforced concrete structures are exposed to daily fluctuations in temperature and humidity. This change of environmental conditions could lead to the temporary opening and closing of cracks, which might influence the dynamic of the healing process. A previous study has shown that dynamic cracks are more challenging to heal than static cracks due to their changing nature [49].

Another topic that has received little attention is the reliability of healing, that is, the statistical probability that certain healing mechanisms can deliver the anticipated effect. The probability of healing activation is often investigated for the encapsulation system, where the number of capsules activated is calculated based on the likelihood of a crack intersecting the capsules [50,51]. Beyond assessing activation probability, understanding the success rate of non-failures that produce anticipated effects is also important. Studies from Maes et al. [36] revealed that despite placing a macro-capsule containing polyurethane directly above a notch (ensuring activation), healing was not observed in all specimens. This outcome is reasonable considering that crack healing relies on a sequence of successful events, and the heterogeneous nature of concrete means any reactions within it carry inherent uncertainty. While absolute reliability is not mandatory, having a measurable level of reliability is essential for the application and the incorporation in service life predictions.

To summarize this section, it is evident from the published literature that self-healing processes, whether autogenous or autonomous, can mitigate chloride penetration in cracked concrete, thereby prolonging the service life of infrastructure. By refining models to include the impact of cracks, it becomes possible to predict the healing effects under specific scenarios. However, the process to incorporate self-healing technologies into service life predictions remains in its nascent stages, requiring extensive experimental data and real-world validations before it can be fully realized and effectively implemented.

3 | EFFECT OF HEALING ON STIFFNESS REDUCTION IN CRACKED CONCRETE

Microcracks in concrete can arise from various factors including shrinkage, creep, thermal changes, and external forces. Even for concrete under compression, microcracking can start forming at around 50–70% of the compressive strength of concrete, depending on the composition [52]. If left unmanaged, these microcracks may further develop and reduce the elasticity modulus of concrete, affecting the stiffness of structural elements. Reduced stiffness compromises the ability of a structure to bear loads effectively and alters its response to external forces like wind and seismic activities, potentially leading to increased vibrations and structural instability. Consequently, it becomes necessary to either utilize a higher grade of concrete or to increase the cross-sectional area of structural elements. Both these measures invariably increase the overall cost of the construction projects.

Self-healing of microcracks in concrete has the potential to mitigate stiffness reduction, as the technology can effectively replenish the structural continuity compromised by cracking. This rejuvenation of the concrete matrix can lead to a regain in its original stiffness, enhancing the structure's resilience and performance under stress. The effectiveness of restoration is influenced by various factors, including the chosen healing method, the degree of the initial damage, and the time allotted for the healing process to take effect.

This discussion aims to propose guidelines for capturing the impact of self-healing on concrete stiffness in various situations. Firstly, it will review experimental studies documenting the effects of different healing methods on restoring mechanical properties. From these studies, typical damage-healing response patterns will be extracted and analyzed. Lastly, numerical models that are useful for predicting the outcomes of specific healing effects are explained.

3.1 | Role of healing on stiffness recovery

To quantify the healing effect on mechanical regain, an index called the recovery coefficient or healing efficiency is defined. This coefficient quantifies the relationship between mechanical properties before and after the healing process. Different definitions of the recovery coefficient are reported, including the following:

$$\phi_{h1} = \frac{m_h}{m_0} \tag{5}$$

$$\phi_{h2} = \frac{m_h}{m_d} \tag{6}$$

$$\phi_{h3} = \frac{m_h - m_d}{m_0} \tag{7}$$

$$\phi_{h4} = \frac{m_h - m_d}{m_0 - m_d} \tag{8}$$

where, m_0, m_d, and m_h are mechanical properties (e.g., elastic modulus and compressive strength) of concrete before damaging (o), after damaging (d), and after healing (h), respectively. Each of those coefficients gives different information about the recovery status. ϕ_{h1} explains the level of mechanical regain compared to material initial status, ϕ_{h2} shows the ratio of mechanical parameters after healing to the damaged state. ϕ_{h3} shows the normalized difference in mechanical regain compared to the initial state, and ϕ_{h4} shows relative recovery. Table 2 summarizes results from relevant literature based on their adopted index.

As can be seen from Table 2, the effects of healing depend on the selected mechanical property and on the characteristics of the healing products, that is, the materials formed to fill and repair the cracks or damage. For example, in cases of healing as a result of bacteria-enabled mineral precipitation, while the modulus of the composite may be restored after healing, its tensile properties are often less recoverable due to weak adhesion between the precipitated mineral grains. In situations where healing involves the release of an adhesive polymer, there can be a significant improvement in the tensile properties. However, the modulus may remain unchanged, owing to the relatively lower elasticity of polymeric materials compared to that of the cement-based matrix. Therefore, it is essential to differentiate the discussion of healing effects on mechanical properties based on the selected healing method.

For self-healing concrete using encapsulation techniques, healing verification involved pre-damaging the specimen under compression or flexural loading, followed by retesting after the healing period. For compressive testing, the level of the damage at which healing commenced was between 60% and 80% of ultimate compression strength. This level is selected to ensure that healing occurred when a fair amount of diffused microcracks existed. Factors affecting healing efficiency include the volume fraction of microcapsules, their distribution within the hardened cement matrix, the properties of the capsule shell and core, and the level of damage.

Few experimental studies have verified the effects of crystalline admixture on the recovery of mechanical properties of concrete. These studies often assessed healing after post-peak behavior, showing minimal recovery of strength and stiffness. To better evaluate the efficiency of crystalline admixtures, testing under low-level damage and diffuse cracking conditions is needed, as these admixtures can be distributed throughout the specimen and potentially act similarly to microcapsules.

For the self-healing systems with a vascular network, healing tests were mostly done with beams or prismatic specimens under three- or four-point bending setup. The target is mainly to heal localized cracks rather than diffused damage. Typically, healing is initiated at the crack

TABLE 2 Summary of studies reporting healing-induced mechanical properties recovery.

	Year	Author	Type of test	Sample size	Damage level	System of healing	Recovery indicator	Healing recovery range
1	2013	Wang et al. [75]	Uniaxial compression	3 replicates for each group	$0.6\,f_c$	Encapsulation	ϕ_{h1}	97%–110%
2	2014	Ferrara et al. [4]	Three-point bending test	1–3 specimens per each test condition	CMOD* = 150 and 300 μm/ω = 0.9	Enhanced autogenous	ϕ_{h4}	10%–60%
3	2014	James et al. [76]	Uniaxial compression	3 replicates for each group	$0.6\,f_c$	Encapsulation	ϕ_{h2}	90%–120%
5	2016	Dong et al. [77]	Uniaxial compression	5 replicates	$0.6\,f_c$	Encapsulation	ϕ_{h3}	10%
6	2017	Wang et al. [78]	Uniaxial compression	3 specimens per variable investigated	$0.6\,f_c$	Encapsulation	ϕ_{h1} and ϕ_{h3}	120–320% and 40–230%
7	2020	Selvarajoo et al. [79,80]	Three-point bending test and uniaxial tensile test	4 specimens per variable investigated	CMOD = 100–200 μm	Vascular network	ϕ_{h4}	20%–43%
8	2021	Shields et al. [63]	Three-point bending test	3 replicates for each group	CMOD = 400 μm	Vascular network	ϕ_{h4}	0%–200%
9	2021	Davies et al. [81]	Three-point bending test	3 replicates for each group	CMOD = 300 μm	Vascular network	ϕ_{h4}	15%–69%

*Crack mouth opening displacement (CMOD).

mouth opening displacement (CMOD) within the range of 100–600 μm. Based on the index ϕ_{h4}, the recovery of the mechanical properties ranges from 0.5 to 1.5 (Table 2). It should be noted that in vascular-based self-healing systems, healing does not occur simultaneously with the initiation of damage. Instead, healing happens when the damage reaches a certain level, triggering the breakage of the vessels and the release of the healing agent. The level of damage at which healing can be triggered depends on the type of network (i.e., rigid or flexible), the geometrical design of the vascular system, and the internal pressure applied to transport the healing agents.

3.2 | Methods to consider the effects of healing

In the *fib* Model Code 2010, the effect of micro-cracking is usually considered by using an equivalent secant modulus to represent the effective stiffness of concrete. Where only an elastic analysis of a concrete structure is needed, a simple coefficient α_i can be incorporated to calculate the reduced modulus of elasticity E_c.

$$E_c = \alpha_i \cdot E_{ci} \tag{9}$$

$$a_i = 0.8 + 0.2\frac{f_{cm}}{88} \leq 1.0 \tag{10}$$

where E_{ci} is the tangent modulus of elasticity of concrete in MPa and f_{cm} is the nominal compression strength in MPa. To consider the healing effects on restoring stiffness, the coefficient a_i can be adjusted. Since there is an absence of engineering models for estimating the contribution of healing to stiffness regain, numerical models can be applied to determine the necessary adjustments to the coefficient a_i. This is even more important for scenarios where significant damage is anticipated. Therefore, subsequent discussion will thus center on describing numerical models for predicting influence of healing on stiffness recovery.

3.2.1 | Numerical models for simulating healing behaviors

The challenge in simulating the mechanical properties of self-healing materials lies in the different physical processes interacting together, which also vary across different healing mechanisms. Table 3 summarizes popular numerical models for simulating self-healing materials with various mechanisms. It includes the governing

TABLE 3 Summary of numerical approaches for simulating mechanical regain due to healing.

Models		Description	Application	Inputs: Mechanical parameter	Inputs: Damage/healing parameter	Governing constitutive equations
Continuum methods	Continuum damage mechanics (CDM) approach [56]	CDM is built upon the principles of continuum mechanics. Applied to self-healing concrete, it models material degradation and through damage variables and healing variables.	Distributed crack-healing systems (e.g., self-healing concrete with microcapsules)	• Initial stiffness D • Healing material stiffness D_h • - Strain field ε	• Damage evolution law ω • Healing evolution law h • Activation threshold ω_{th} • - Damage evolution of healed material ω_h	$\sigma=(1-\omega)D\varepsilon+h\omega_{th}D_h(1-\omega_h)(\varepsilon-\varepsilon_h)$ $h=\frac{A_h}{A_\omega}$
	Micro mechanical models (MM) [82]	MM uses homogenization techniques to derive macroscopic properties of self-healing concrete. Damage and healing are considered by the reduction and restoration of stiffness.		• Initial stiffness matrix D • Before/post-healing stiffness ratio B • Transformation matrices N_ε & N	• Damage evolution law ω • Healing efficiency h • Activation threshold ω_{th}	$\sigma=D_{sech}(\varepsilon-\varepsilon_h)D_{sech}=I^{4s}+\frac{D}{2\pi}\cdot\left(\frac{1}{2\pi}\oint_S N_\varepsilon\cdot C_L\cdot N\left(\frac{\omega-h\omega_{th}B}{1-\omega+h\omega_{th}}\right)\right)^{-1}\cdot D$
Discrete methods	2D/3D lattice model [57]	Lattice model simulates materials by a set of beam elements. Damaging and healing mechanisms are considered by removing /recovering elements or by changing element properties.	Discrete crack-healing systems (e.g., self-healing concrete with vascular network)	• Stiffness matrix of damaged elements k_ω • Stiffness matrix of healed elements k_h • Displacement field u	• Updated stiffness matrix at each damage state • Healing evolution function that is going to be used for k_h	$F=k_\omega u+k_h(t)(u-u_h(t))$
	Cohesive zone models (CZM) [83]	CZM analyzes self-healing concrete by using fracture mechanics and traction-separation laws to simulate crack behavior and healing processes.		• Cohesive zone stiffness k • Displacement vector in cohesive zone	• Updated stiffness matrix at each damage state • Healing evolution function that is going to be used for k_h	$\tau=(1-\omega)Ku+rh_\omega(1-\omega_h)Ku$
	Extended finite element models (EFEM) [84]	EFEM assumes healing occurs in a distant two cracked surfaces and allows consideration of transport processes and other mechanisms.		• Element stiffness matrix • Crack opening width	• Updated stiffness matrix at each damage state • Healing evolution function that is going to be used for k_h	$F(t)=(1-\omega(t))ku(t)$ $+h(t)k_h(u(t)-u_h(t))$

equations, required inputs, and the scope of application for each model. The successful application of the models in Table 3 requires a thorough understanding of the physical and chemical processes involved, as well as prior measurement of the input parameters. A comprehensive review of all developed numerical models for simulating the self-healing process can be found in [53].

In the context of distributed self-healing systems, such as the use of embedded microcapsules, the impact of healing on mechanical restoration can be modeled by using the Continuum Damage Mechanics (CDM) approach [54] and the micromechanical models [55]. These methods simulate material degradation as a reduction in stiffness, represented by the damage variable (ω). Since they employ the smeared concept to simulate both damage and healing processes, these methods are particularly well-suited for the simulation of self-healing concrete with embedded microcapsules. To account for the effects of healing, one way is to treat healing as the inverse process of damaging. This can be achieved by either applying a modification factor to the damaged properties or a reduction factor to the damage parameter [56]. For scenarios involving localized damage, discrete models are more suitable. An example is self-healing concrete with embedded vascular networks, where it is crucial to explicitly describe the shapes and locations of cracks. These discrete models use techniques such as cohesive zone elements, 2D/3D lattice models, or extended finite element methods to describe how the healing of localized damages affects the overall response. Among those methods, the 2D/3D lattice models have proven to be particularly helpful, as they can capture the rate dependency of damaging/healing process [57,58].

The selection of appropriate models also depends on the interaction between damage and healing processes as illustrated in Table 4. This interaction is influenced by three key factors: the loading condition during healing, the time dependency of the healing action, and the repeatability of the healing effects. Specifically, healing can occur under loaded or unloaded conditions, which influences the efficiency of healing. In addition, different healing agents operate over different time frames, making the recovery of some material properties time-dependent. Modeling of such behaviors requires transient analysis to account for the varying rates at which healing occurs. Furthermore, from a modeling perspective, the healing mechanism can be implemented as a one-time action or a multiple-cycle process. For instance, encapsulated healing systems provide a one-time healing action for each triggered capsule, whereas vascular networks can facilitate multiple healing cycles. To aid in selecting an appropriate numerical model, Table 4 provides an overview of expected stress–strain responses based on different damaging and healing conditions.

3.2.2 | Simplified numerical models

To further facilitate application, some more streamlined approaches that focus primarily on estimating the overall material stiffness post-healing were also developed. One of the examples is the Hill macrohomogeneity condition [59,60], which originates from plasticity theory can be adapted to describe the behavior of self-healing materials, including concrete. In such cases, healing can be considered an inclusion that fills the cracks, allowing the model to estimate the elastic moduli of the two-phase solid (matrix and healed material). In addition, the CDM and micromechanical model can also be simplified to ignore the effects of damage-healing interaction, healing rate dependency effect, anisotropy behavior due to microcracks orientation. With these simplifications, the models become easy to implement, making them suitable for quick assessments of healing where detail is not essential.

Below is an example where a simplified micromechanical model is applied to estimate the mechanical properties of healed materials. In this example, the level of the damage (ω) concept was adopted from the definition used in the CDM method. For two damage levels, 0.05 and 0.5, Figure 4 illustrates the progression of stiffness recovery over time, using various recovery indicators for different types of healing agents with curing functions presented in [61,62]. Inputs concerning the mechanical properties of healing agents were obtained from [63,64]. Based on the specific healing mechanism employed, the results from Figure 4 can be used to estimate the coefficient a_i at specific intervals following the initiation of the healing process [58,59].

3.3 | Limitations

The preceding discussion underscores the potential of numerical models in assessing the impact of healing on mechanical recovery. However, the successful application of these models necessitates sufficient experimental data for their validation. A thorough review of the current literature reveals a scarcity of experimental results concerning mechanical restoration through healing. Notably, the number of studies exploring mechanical recovery is significantly lower compared to those investigating crack closure or durability enhancement. Relevant studies have predominantly focused on autonomous systems, particularly those incorporating vascular networks and microcapsules. Figure 5 provides an overview of publications related to these two systems, while Table 5 details the specific studies considered.

Furthermore, another challenge is the determination of input parameters. While advanced models can capture complex damage-healing interactions, they also require considerably more inputs related to physical and chemical processes, which can sometimes be difficult to be determine experimentally. For instance, the curing function of the healing agents released from either capsules or vessels is difficult to obtain. Although manufacturers may provide nominal values, the realistic properties are difficult to predict when they are:

1. Embedded in a cement-based matrix: The interaction between the healing agents and the host materials can vary, making it challenging to predict their behavior accurately.
2. Affected by environmental conditions: Factors such as temperature, humidity, and exposure to other chemicals can influence the performance of healing agents, adding complexity to the experimental determination of input parameters.
3. Subject to transport limitations: The rate and extent of healing agent movement within the damaged area can be difficult to quantify, affecting the accuracy of the model inputs.
4. Involving multiple chemical reactions: The healing process often involves a series of chemical reactions, each with its own rate and dependency on various factors, complicating the determination of accurate input data.

These challenges underscore the importance of continued research and development in experimental techniques to better capture the necessary data for accurate model inputs. Enhancing our understanding and measurement capabilities will improve the reliability and applicability of numerical models in predicting mechanical recovery through healing processes.

4 | RECOMMENDATION FOR FURTHER RESEARCH

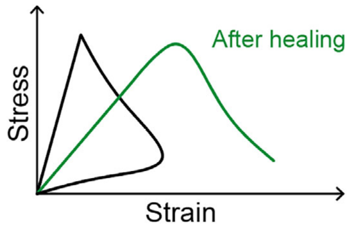
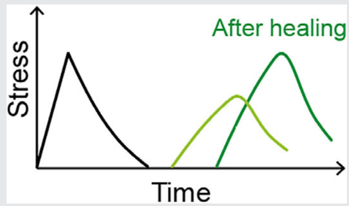
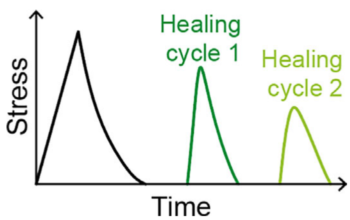
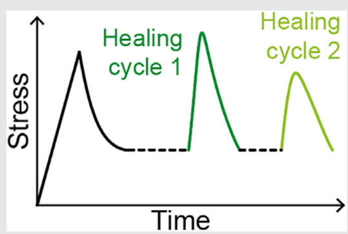
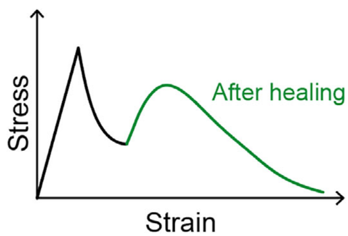
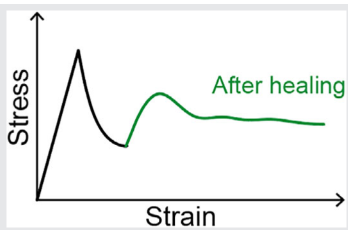
The ability of self-healing concrete to autonomously repair cracks and damage highlights its potential in restoring material properties of the concrete. This versatility, while valuable in a way, also poses a challenge in design, as different structural requirements demand different healing outcomes. For instance, microbial mineral precipitation effectively reduces chloride ingress but may have limited impact on restoring stiffness. This discrepancy highlights the importance of prioritizing certain properties in the healing process. Research is thus needed to determine which concrete characteristics stand to gain the most from self-healing, considering practicality, economic viability, and sustainability. Focused enhancements will ensure more robust and efficient healing performance, providing a greater motivation for the industrial use of this technology.

Selecting the desired effects is critical for designing pilot projects that demonstrate the effectiveness of self-healing concrete at an industrial scale. While these projects have the potential to provide valuable performance data, many primarily rely on qualitative methods, such as visual inspections of crack closure. A key consideration when setting up a monitoring program is determining the specific evidence needed to verify the selected functionality. Self-healing concrete can fulfill various purposes, such as mitigating leakage through cracks to improve watertightness (monitored via water flow measurements), reducing steel rebar corrosion through crack healing and decreased chloride ingress (evaluated using electrochemical techniques), or restoring the mechanical properties of reinforced concrete structures (measured with piezoelectric-based smart aggregates). A robust, evidence-driven approach ensures that the claimed benefits of self-healing concrete are sufficiently validated.

After identifying the key properties, it is essential to evaluate how specific self-healing effects can be accounted for in structural design. Many have proposed the notion of a 'healable crack width', suggesting the relaxation of current crack width requirements for different exposure classes to allow for larger cracks to some extent [16]. This approach offers potential benefits, including a reduction in the reinforcement needed for crack width control, resulting in cost and environmental footprint savings. However, it is crucial to note that the healable crack width should be established by conducting performance tests, such as chloride diffusion/migration tests, on concretes before and after healing. Relying solely on surface observations of crack closure to establish the crack width threshold can be misleading, as visual closure does not always guarantee complete restoration of the chloride resistance.

Still, challenges persist in the availability of input data. Approaches to the design of reinforced concrete structures can be divided into two categories: prescriptive approaches and performance-based approaches. The former consists of simple rules usually presented as threshold values for different parameters, often derived from experience, that should be fulfilled to guarantee an expected service life, using ordinary materials and technologies. The latter consists of design procedures aimed at determining (or verifying) the service life as a function of the desired performance of the structure, allowing the quantification of the effect of all the parameters involved, including the use of innovative materials (e.g., self-

TABLE 4 Illustration of different damage-healing responses and their application.

Damage-healing interaction					
Loading condition	**Repeatability**	**Time dependency**	**Mechanical response**	**Applicability**	**Suitable models**
Fully unloaded	Healing only occurs once.	Time-dependency of the healing is not relevant.		Applicable to self-healing systems where the healing action occurs rapidly, or adequate time is allotted for the healing process to be completed.	Simplified CDM and MM [82,85]
Fully unloaded	Healing only occurs once.	Yes, longer curing time before reloading can deliver a more effective healing.		Applicable to self-healing systems where the effect of healing depends on the amount of curing time given to the healing agent.	Rate-dependent CDM [57,85] or rate-dependent discrete models [86–88]
Fully unloaded	Multiple cycles	No, the healing action occurs rapidly or is provided with enough time for completion before reloading.		Applicable to self-healing systems with multiple healing cycle potential, such as with bacteria.	Rate-dependent CDM suggested by [57,89]
Under sustained loads	Multiple cycles	No, the healing action occurs rapidly or is provided with enough time for completion before reloading.		Applicable to self-healing systems with multiple healing cycle potential, such as with bacteria.	The extended version of CDHM, cohesive zone model, is used to develop this model.
Under active loads (simultaneous damaging and healing)	Healing only occurs once.	Yes, the effects of healing depend on the loading rate.		Applicable to self-healing systems that activate healing at a certain damage level and provide healing material only once (i.e., microcapsule-based self-healing materials)	Systems in which loading is resumed during the healing process, such as vascular networks and encapsulation
Under active loads (simultaneous damaging and healing)	Healing occurs continuously	Yes, the effects of healing depend on the loading rate.		Applicable to self-healing systems that activate healing at a certain damage level and provide continuous supplement of healing material (i.e., vascular-based self-healing materials)	Rate-dependent discrete models considering overlapping healing [57,84,90]

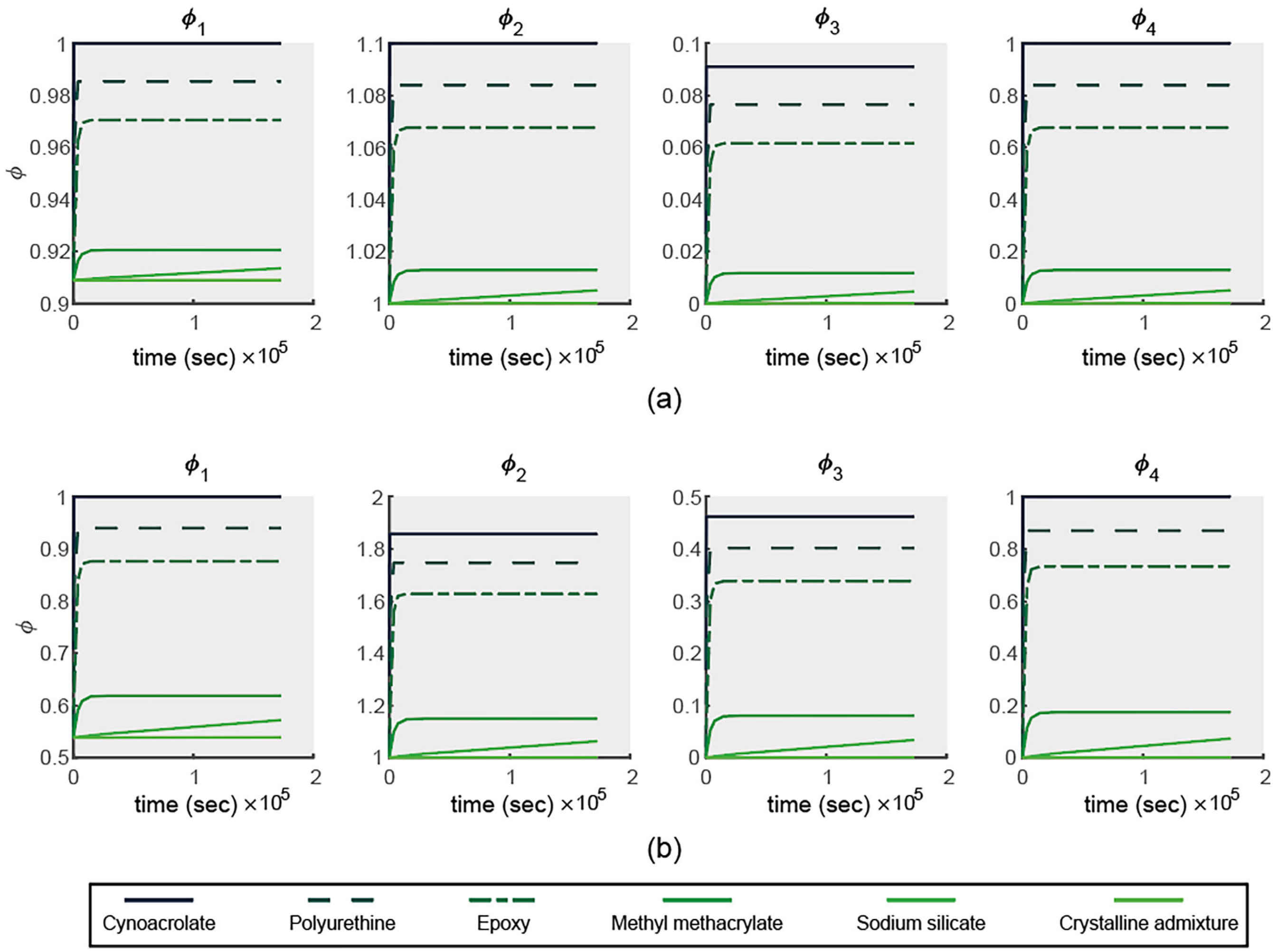


FIGURE 4 Recovery of material stiffness for different damage levels: (a) $\omega = 0.1$ and (b) $\omega = 0.5$.

healing concrete). Obviously, for self-healing concrete, a performance-based approach is essential. However, a critical aspect of this approach is the need for data on all input parameters, especially concerning their variability. This requirement presents a significant challenge in incorporating the effects of healing into the modeling of either mechanical performance or degradation mechanisms. As highlighted in both Section 2.5 and 3.4, despite the abundance of studies showing the positive impact of self-healing on the durability and mechanical related properties of concretes, there is a notable lack of probabilistic assessments evaluating these effects. Future research focusing on investigating the reliability of self-healing concrete over a large sample size would be beneficial.

As mentioned earlier, real-scale demonstration projects offer opportunities to generate substantial performance data for self-healing concrete. However, such projects are currently scarce, and their absence is considered a major barrier to their commercialization [65].

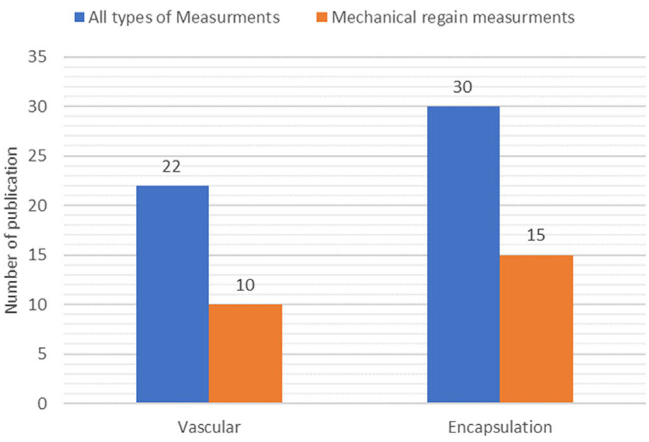


FIGURE 5 Available experimental data related to self-healing.

Additionally, among the limited number of pilot projects, it has been repeatedly noted that cracks were not observed, let alone any evidence of crack healing [18,66,67]. Due to the risk-averse nature of stakeholders, self-healing in pilot projects is often treated as an

TABLE 5 Number of reviewed studies with quantitative data.

	System of healing	Type of measurement	Number of studies found	References
1	Vascular network-based self-healing materials	Recovery of mechanical properties	10	[63,79–81,91–96]
2		Recovery of durability properties and crack closure	12	[7,97–107]
3	Microcapsule-based self-healing cementitious materials	Recovery of mechanical properties	15	[19,75–78,108–117]
4		Recovery of durability properties and crack closure	15	[118–132]

additional precautionary measure to ensure specific functions, such as water tightness, rather than fully leveraging its potential benefits, such as reducing reinforcement requirements by allowing crack formation in a controlled way. Introducing new demonstrators that adopt more ambitious design approaches could position self-healing concrete as a viable crack management solution, complementing or even replacing current crack prevention strategies.

Future research should also aim to enhance the robustness of the shortlisted self-healing mechanisms. Perhaps the absence of probabilistic-based reliability assessments for self-healing concrete might be that the technology, in its current form, is not yet sufficiently reliable. Current research on self-healing concrete typically demonstrates its effectiveness under controlled and ideal conditions. Yet, even in these favorable environments, the effectiveness of these systems has exhibited inconsistencies. For practical application in real-world structures, it is crucial that self-healing processes can reliably maintain their effectiveness under typical operational conditions of infrastructure. Practical examples [68] show that failure to achieve the expected self-healing, particularly in water-bearing separating cracks, can lead to major structural damage. To this end, further research should focus on enhancing the robustness of self-healing mechanisms in concrete. This could include developing new self-healing materials or refining existing ones to make them more effective and reliable.

5 | CONCLUSIONS

The paper offered insights into incorporating the impacts of self-healing when designing the durability and mechanical characteristics of reinforced concrete structures. The study centered around two particular advantages of adopting self-healing concrete: its effectiveness in resisting chloride ingress within cracked concrete, and its ability to mitigate stiffness reduction caused by micro-cracking. In both cases, modifications to existing engineering models and numerical models were proposed such that the effects of healing can be quantified. The main findings of the current study are:

- Incorporating the influence of healing into the calculation of corrosion initiation time poses a challenge, as current service life models typically assume concrete to remain crack-free. Nevertheless, by appropriately adjusting parameters such as the diffusion coefficient and aging factor in these models, it becomes feasible to incorporate the effect of the healing process.
- While the integration of healing mechanisms into service life predictions holds theoretical promise, it remains at an early developmental stage, requiring significant experimental data which is currently insufficient. Despite the abundance of studies in this field, data reflecting real-world conditions are scarce, emphasizing the crucial need for validation of healing processes in practical settings.
- The typical approach to address stiffness reduction from micro-cracking involves applying a reduction factor, which can be adjusted to account for the specific contribution of healing. Numerical models offer a means to quantify this contribution, with varying levels of complexity enabling the description of both initial damage and the interplay between loading and healing processes.
- In both scenarios, it is crucial to emphasize that determining the 'healable crack width' necessitates conducting performance tests, such as chloride ingress or mechanical loading, on concrete before and after healing. Relying solely on surface observations of crack closure to establish the crack width threshold can be deceptive, as visual closure does not always ensure complete restoration of the desired properties.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

1. Huang H, Ye G, Damidot D. Effect of blast furnace slag on self-healing of microcracks in cementitious materials. Cem Concr Res. 2014;60:68–82. https://doi.org/10.1016/J.CEMCONRES.2014.03.010
2. Yang Y, Lepech MD, Yang EH, Li VC. Autogenous healing of engineered cementitious composites under wet-dry cycles. Cem Concr Res. 2009;39:382–90. https://doi.org/10.1016/J.CEMCONRES.2009.01.013
3. de Nardi C, Bullo S, Ferrara L, Ronchin L, Vavasori A. Effectiveness of crystalline admixtures and lime/cement coated granules in engineered self-healing capacity of lime mortars. Mater Struct. 2017;50:1–12. https://doi.org/10.1617/S11527-017-1053-3
4. Ferrara L, Krelani V, Carsana M. A "fracture testing" based approach to assess crack healing of concrete with and without crystalline admixtures. Constr Build Mater. 2014;68:535–51. https://doi.org/10.1016/J.CONBUILDMAT.2014.07.008
5. Wang JY, Soens H, Verstraete W, de Belie N. Self-healing concrete by use of microencapsulated bacterial spores. Cem Concr Res. 2014;56:139–52. https://doi.org/10.1016/J.CEMCONRES.2013.11.009
6. van Mullem T, Anglani G, Dudek M, Vanoutrive H, Bumanis G, Litina C, et al. Addressing the need for standardization of test methods for self-healing concrete: an inter-laboratory study on concrete with macrocapsules. Sci Technol Adv Mater. 2020;21(1):661–682. https://doi.org/10.1080/14686996.2020.1814117
7. Shields Y, de Belie N, Jefferson A, van Tittelboom K. A review of vascular networks for self-healing applications. Smart Mater Struct. 2021;30:063001. https://doi.org/10.1088/1361-665X/ABF41D
8. Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E. Application of bacteria as self-healing agent for the development of sustainable concrete. Ecol Eng. 2010;36:230–5. https://doi.org/10.1016/J.ECOLENG.2008.12.036
9. Cappellesso V, di Summa D, Pourhaji P, Prabhu Kannikachalam N, Dabral K, Ferrara L, et al. A review of the efficiency of self-healing concrete technologies for durable and sustainable concrete under realistic conditions. Int Mater Rev. 2023;68:556–603. https://doi.org/10.1080/09506608.2022.2145747
10. Al-Obaidi S, He S, Schlangen E, Ferrara L. Effect of matrix self-healing on the bond-slip behavior of micro steel fibers in ultra-high-performance concrete. Mater Struct. 2023;56(9):161. https://doi.org/10.1617/S11527-023-02250-5
11. Qiu J, He S, Yang E-H. Autogenous healing and its enhancement of interface between micro polymeric fiber and hydraulic cement matrix. Cem Concr Res. 2019;124:105830. https://doi.org/10.1016/j.cemconres.2019.105830.
12. Cuenca E, Ferrara L. Self-healing capacity of fiber reinforced cementitious composites. State of the art and perspectives. KSCE J Civ Eng. 2017;21:2777–89. https://doi.org/10.1007/S12205-017-0939-5
13. Yang Y, Yang EH, Li VC. Autogenous healing of engineered cementitious composites at early age. Cem Concr Res. 2011;41:176–83. https://doi.org/10.1016/J.CEMCONRES.2010.11.002
14. Qiu J, Aw-Yong WL, Yang EH. Effect of self-healing on fatigue of engineered cementitious composites (ECCs). Cem Concr Compos. 2018;94:145–52. https://doi.org/10.1016/J.CEMCONCOMP.2018.09.007
15. Kannikachalam NP, Marin Peralta PS, Snoeck D, de Belie N, Ferrara L. Assessment of impact resistance recovery in ultra high-performance concrete through stimulated autogenous self-healing in various healing environments. Cem Concr Compos. 2023;143:105239. https://doi.org/10.1016/J.CEMCONCOMP.2023.105239
16. Huang Z, Cuenca E, Ferrara L. Incorporation of self-healing of UHPC in structural design approaches through healable crack width threshold and kinetics: the case study of H2020 project ReSHEALience database. Dev Built Environ. 2024;18:100388. https://doi.org/10.1016/J.DIBE.2024.100388
17. Roig-Flores M, Formagini S, Serna P. Self-healing concrete-what is it good for? Mater Constr. 2021;71:e237. https://doi.org/10.3989/MC.2021.07320
18. Mors RM, Jonkers HM. Bacteria-based self-healing concrete: evaluation of full scale demonstrator projects. RILEM Tech Lett. 2019;4:138–44. https://doi.org/10.21809/RILEMTECHLETT.2019.93
19. Al-Tabbaa A, Litina C, Giannaros P, Kanellopoulos A, Souza L. First UK field application and performance of microcapsule-based self-healing concrete. Constr Build Mater. 2019;208:669–85. https://doi.org/10.1016/J.CONBUILDMAT.2019.02.178
20. EN 1992–3:2006. Eurocode 2: Design of concrete structures - Part 3: Liquid retaining and containment structures. 2006.
21. Mors R, Jonkers H. Bacteria-based self-healing concrete: towards standardization. Res Dev Mater Sci. 2019;10(2):RDMS.000732.2019. https://doi.org/10.31031/rdms.2019.10.000732
22. Yoon IS, Schlangen E. Experimental examination on chloride penetration through micro-crack in concrete. KSCE J Civ Eng. 2014;18:188–98. https://doi.org/10.1007/s12205-014-0196-9

23. Cappellesso V, Van Mullem T, Gruyaert E, Van Tittelboom K, De Belie N. Enhancing concrete durability in chloride-rich environments through manual application of healing agents. J Build Eng. 2024;90:109380. https://doi.org/10.1016/J.JOBE.2024.109380
24. Schiessl P, Helland S, Gehlen C, Nilsson LO, Rostam S. fib bulletin 34: Model code for service life design. 2006.
25. Schultheiß AL, Patel RA, Vogel M, Dehn F. Comparative study of probabilistic modeling approaches for chloride ingress in concrete structures with macro-cracks. Struct Concr. 2023;24:345–58. https://doi.org/10.1002/suco.202200069
26. Pacheco Farias J. Corrosion of steel in cracked concrete: Chloride microanalysis and service life predictions. 2015 https://doi.org/10.4233/UUID:BC726EAD-0999-4FE4-BAD1-5C26C0E50405
27. Djerbi A, Bonnet S, Khelidj A, Baroghel-bouny V. Influence of traversing crack on chloride diffusion into concrete. Cem Concr Res. 2008;38:877–83. https://doi.org/10.1016/j.cemconres.2007.10.007
28. Schultheiß AL, Patel RA, Dehn F. Probabilistic service life prediction of cracked concrete using numerical and engineering models. Ce/Papers. 2023;6:1524–33. https://doi.org/10.1002/CEPA.2958
29. Bentz DP, Garboczi EJ, Lu Y, Martys N, Sakulich AR, Weiss WJ. Modeling of the influence of transverse cracking on chloride penetration into concrete. Cem Concr Compos. 2013;38:65–74. https://doi.org/10.1016/J.CEMCONCOMP.2013.03.003
30. Ishida T, Iqbal PON, Anh HTL. Modeling of chloride diffusivity coupled with non-linear binding capacity in sound and cracked concrete. Cem Concr Res. 2009;39:913–23. https://doi.org/10.1016/J.CEMCONRES.2009.07.014
31. Liu QF, Yang J, Xia J, Easterbrook D, Li LY, Lu XY. A numerical study on chloride migration in cracked concrete using multi-component ionic transport models. Comput Mater Sci. 2015;99:396–416. https://doi.org/10.1016/J.COMMATSCI.2015.01.013
32. Marsavina L, Audenaert K, De Schutter G, Faur N, Marsavina D. Experimental and numerical determination of the chloride penetration in cracked concrete. Constr Build Mater. 2009;23:264–74. https://doi.org/10.1016/J.CONBUILDMAT.2007.12.015
33. Qian S, Zhou J, de Rooij MR, Schlangen E, Ye G, van Breugel K. Self-healing behavior of strain hardening cementitious composites incorporating local waste materials. Cem Concr Compos. 2009;31:613–21. https://doi.org/10.1016/J.CEMCONCOMP.2009.03.003
34. Sisomphon K, Copuroglu O, Koenders EAB. Self-healing of surface cracks in mortars with expansive additive and crystalline additive. Cem Concr Compos. 2012;34:566–74. https://doi.org/10.1016/J.CEMCONCOMP.2012.01.005
35. Danner T, Jakobsen UH, Geiker MR. Mineralogical sequence of self-healing products in cracked marine concrete. Minerals. 2019;9:284. https://doi.org/10.3390/MIN9050284
36. Maes M, Van Tittelboom K, De Belie N. The efficiency of self-healing cementitious materials by means of encapsulated polyurethane in chloride containing environments. Constr Build Mater. 2014;71:528–37. https://doi.org/10.1016/j.conbuildmat.2014.08.053
37. Abro F u R, Buller AS, Lee K-M, Jang SY. Using the steady-state chloride migration test to evaluate the self-healing capacity of cracked mortars containing crystalline, expansive, and swelling admixtures. Materials. 2019;12:1865.
38. Abro FUR, Buller AS, Ali T, Ul-Abdin Z, Ahmed Z, Memon NA, et al. Autogenous healing of cracked mortar using modified steady-state migration test against chloride penetration. Sustainability. 2021;13(17):9519. https://doi.org/10.3390/su13179519
39. Cuenca E, Lo Monte F, Moro M, Schiona A, Ferrara L. Effects of autogenous and stimulated self-healing on durability and mechanical performance of UHPFRC: validation of tailored test method through multi-performance healing-induced recovery indices. Sustainability. 2021;13:11386.
40. Darquennes A, Olivier K, Benboudjema F, Gagné R. Self-healing at early-age, a way to improve the chloride resistance of blast-furnace slag cementitious materials. Constr Build Mater. 2016;113:1017–28. https://doi.org/10.1016/j.conbuildmat.2016.03.087
41. Jacobsen S, Marchand J, Boisvert L. Effect of cracking and healing on chloride transport in OPC concrete. Cem Concr Res. 1996;26:869–81. https://doi.org/10.1016/0008-8846(96)00072-5
42. van Mullem T, Caspeele R, De Belie N. The influence of SAPs on chloride ingress in cracked concrete. MATEC Web of Conferences, Cluj Napoca, Romania. Volume 289. EDP Sciences; 2019. 08007. https://doi.org/10.1051/matecconf/201928908007
43. He S, Wan Z, Chen Y, Jonkers HM, Schlangen E. Microstructural characterization of crack-healing enabled by bacteria-embedded polylactic acid (PLA) capsules. Cem Concr Compos. 2023;143:105271. https://doi.org/10.1016/j.cemconcomp.2023.105271
44. Rossi E, Roy R, Copuroglu O, Jonkers HM. Influence of self-healing induced by polylactic-acid and alkanoates-derivates precursors on transport properties and chloride penetration resistance of sound and cracked mortar specimens. Constr Build Mater. 2022;319:126081. https://doi.org/10.1016/j.conbuildmat.2021.126081
45. Yoo KS, Jang SY, Lee KM. Recovery of chloride penetration resistance of cement-based composites due to self-healing of cracks. Materials. 2021;14(10):2501. https://doi.org/10.3390/ma14102501
46. Javeed Y, Goh Y, Mo KH, Yap SP, Leo BF. Microbial self-healing in concrete: A comprehensive exploration of bacterial viability, implementation techniques, and mechanical properties. J Mater Res Technol. 2024;29:2376–95. https://doi.org/10.1016/J.JMRT.2024.01.261
47. Luo M, Qian CX, Li RY. Factors affecting crack repairing capacity of bacteria-based self-healing concrete. Constr Build Mater. 2015;87:1–7. https://doi.org/10.1016/J.CONBUILDMAT.2015.03.117
48. De Brabandere L, Van Mullem T, Lee JH, Suh J-I, Lee K-M, De Belie N. Comparative analysis of three different types of self-healing concrete via permeability testing and a quasi-steady-state chloride migration test. Constr Build Mater. 2024;411:134288. https://doi.org/10.1016/j.conbuildmat.2023.134288

49. Feiteira J, Gruyaert E, de Belie N, Grantham M, Basheer PAM, Magee B, et al. Self-healing of dynamic concrete cracks using polymer precursors as encapsulated healing agents. Concrete Solutions: Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair. Boca Raton, FL: CRC Press; 2014. p. 65–9.
50. Wan Z, Chang Z, Xu Y, Šavija B. Optimization of vascular structure of self-healing concrete using deep neural network (DNN). Constr Build Mater. 2023;364:129955. https://doi.org/10.1016/J.CONBUILDMAT.2022.129955
51. Sayadi S, Ricketts E, Schlangen E, Cleall P, Mihai I, Jefferson A. Effect of microstructure heterogeneity shapes on constitutive behaviour of encapsulated self-healing cementitious materials. MATEC Web Conf. 2023;378:09004. https://doi.org/10.1051/MATECCONF/202337809004
52. van Mier JGM. Fracture processes of concrete. Boca Raton, FL: CRC Press; 2017. https://doi.org/10.1201/b22384
53. Freeman BL, Jefferson AD. Numerical simulation of self-healing cementitious materials BT – self-healing construction materials: fundamentals, monitoring and large scale applications. In: Kanellopoulos A, Norambuena-Contreras J, editors. Cham: Springer International Publishing; 2022. p. 151–85. https://doi.org/10.1007/978-3-030-86880-2_6
54. Kachanov M. On the effective elastic properties of cracked solids – Editor's comments. Int J Fract. 2007;146(4):295–9. https://doi.org/10.1007/s10704-007-9170-6
55. Jefferson A, Bennett T. Micro-mechanical damage and rough crack closure in cementitious composite materials. Int J Numer Anal Methods Geomech. 2007;31:133–46. https://doi.org/10.1002/nag.551
56. Abu Al-Rub RK, Darabi MK. A thermodynamic framework for constitutive modeling of time- and rate-dependent materials. Part I: theory. Int J Plast. 2012;34:61–92. https://doi.org/10.1016/j.ijplas.2012.01.002
57. Sayadi S, Chang Z, He S, Schlangen E, Mihai IC, Jefferson A. An enhanced lattice beam element model for the numerical simulation of rate-dependent self-healing in cementitious materials. Eng Fract Mech. 2023;292:109632. https://doi.org/10.1016/j.engfracmech.2023.109632
58. Jiang N, Ge Z, Wang Z, Gao T, Zhang H, Ling Y, et al. Size effect on compressive strength of foamed concrete: experimental and numerical studies. Mater Des. 2024;240:112841. https://doi.org/10.1016/J.MATDES.2024.112841
59. Hill R. A self-consistent mechanics of composite materials. J Mech Phys Solids. 1965;13:213–22. https://doi.org/10.1016/0022-5096(65)90010-4
60. Ahmed A, Sanada K. Micromechanical modeling and experimental verification of self-healing microcapsules-based composites. Mech Mater. 2019;131:84–92. https://doi.org/10.1016/J.MECHMAT.2019.01.020
61. Mergheim J, Steinmann P. Phenomenological modelling of self-healing polymers based on integrated healing agents. Comput Mech. 2013;52(3):681–92. https://doi.org/10.1007/s00466-013-0840-0
62. Freeman BL, Jefferson A. A 3D coupled finite-element model for simulating mechanical regain in self-healing cementitious materials. J Eng Mech. 2023;149:04023038.
63. Shields Y, Van Mullem T, De Belie N, Van Tittelboom K. An investigation of suitable healing agents for vascular-based self-healing in cementitious materials. Sustainability. 2021;13(23):12948. https://doi.org/10.3390/su132312948
64. Ferrara L, Van Mullem T, Alonso MC, Antonaci P, Borg RP, Cuenca E, et al. Experimental characterization of the self-healing capacity of cement based materials and its effects on the material performance: A state of the art report by COST action SARCOS WG2. Constr Build Mater. 2018;167:115–42. https://doi.org/10.1016/j.conbuildmat.2018.01.143
65. Bandeira Barros L, Knockaert M, Tenório Filho JR. Towards a more sustainable construction industry: bridging the gap between technical progress and commercialization of self-healing concrete. Constr Build Mater. 2023;403:133094. https://doi.org/10.1016/J.CONBUILDMAT.2023.133094
66. van Mullem T, Gruyaert E, Caspeele R, de Belie N. First large scale application with self-healing concrete in Belgium: analysis of the laboratory control tests. Materials. 2020;13:997. https://doi.org/10.3390/MA13040997
67. Tenório Filho JR, Mannekens E, Van Tittelboom K, Van Vlierberghe S, De Belie N, Snoeck D. Innovative SuperAbsorbent polymers (iSAPs) to construct crack-free reinforced concrete walls: an in-field large-scale testing campaign. J Build Eng. 2021;43:102639. https://doi.org/10.1016/J.JOBE.2021.102639
68. Edvardsen C. Selbstheilung von Rissen in Beton- Kann man sich auf die Selbstheilung verlassen? Ce/Papers. 2023;6:1376–81. https://doi.org/10.1002/CEPA.3009
69. Şahmaran M. Effect of flexure induced transverse crack and self-healing on chloride diffusivity of reinforced mortar. J Mater Sci. 2007;42:9131–6. https://doi.org/10.1007/s10853-007-1932-z
70. Ismail M, Toumi A, François R, Gagné R. Effect of crack opening on the local diffusion of chloride in cracked mortar samples. Cem Concr Res. 2008;38:1106–11. https://doi.org/10.1016/j.cemconres.2008.03.009
71. Maes M, Snoeck D, De Belie N. Chloride penetration in cracked mortar and the influence of autogenous crack healing. Constr Build Mater. 2016;115:114–24. https://doi.org/10.1016/j.conbuildmat.2016.03.180
72. Van Belleghem B, Van den Heede P, Van Tittelboom K, De Belie N. Quantification of the service life extension and environmental benefit of chloride exposed self-healing concrete. Materials. 2016;10:5. https://doi.org/10.3390/ma10010005
73. Van Belleghem B, Kessler S, Van den Heede P, Van Tittelboom K, De Belie N. Chloride induced reinforcement corrosion behavior in self-healing concrete with encapsulated polyurethane. Cem Concr Res. 2018;113:130–9. https://doi.org/10.1016/j.cemconres.2018.07.009
74. Cappellesso VG, Van Mullem T, Gruyaert E, Van Tittelboom K, De Belie N. Comparison of different types of self-healing concrete under extreme conditions. MATEC Web of Conferences, Ghent, Belgium. Volume 378. EDP Sciences; 2023. 08005. https://doi.org/10.1051/matecconf/202337808005
75. Wang X, Xing F, Zhang M, Han N, Qian Z. Experimental study on cementitious composites embedded with organic microcapsules. Materials. 2013;6(9):4064–81. https://doi.org/10.3390/ma6094064
76. Gilford J III, Hassan MM, Rupnow T, Barbato M, Okeil A, Asadi S. Dicyclopentadiene and sodium silicate microencapsulation for self-healing of concrete. J Mater Civ Eng. 2014;26:

886–96. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000892
77. Dong B, Fang G, Ding W, Liu Y, Zhang J, Han N, et al. Self-healing features in cementitious material with urea-formaldehyde/epoxy microcapsules. Constr Build Mater. 2016;106:608–17. https://doi.org/10.1016/j.conbuildmat.2015.12.140
78. Wang X, Sun P, Han N, Xing F. Experimental study on mechanical properties and porosity of organic microcapsules based self-healing cementitious composite. Materials. 2017;10(1):20. https://doi.org/10.3390/ma10010020
79. Selvarajoo T, Davies RE, Freeman BL, Jefferson AD. Mechanical response of a vascular self-healing cementitious material system under varying loading conditions. Constr Build Mater. 2020;254:119245. https://doi.org/10.1016/j.conbuildmat.2020.119245
80. Selvarajoo T, Davies RE, Gardner DR, Freeman BL, Jefferson AD. Characterisation of a vascular self-healing cementitious material system: flow and curing properties. Constr Build Mater. 2020;245:118332. https://doi.org/10.1016/j.conbuildmat.2020.118332
81. Davies R, Jefferson T, Gardner D. Development and testing of vascular networks for self-healing cementitious materials. J Mater Civ Eng. 2021;33(7):04021164. https://doi.org/10.1061/(asce)mt.1943-5533.0003802
82. Davies R, Jefferson A. Micromechanical modelling of self-healing cementitious materials. Int J Solids Struct. 2017;113:180–91. https://doi.org/10.1016/j.ijsolstr.2017.02.008
83. Ponnusami SA, Krishnasamy J, Turteltaub S, van der Zwaag S. A cohesive-zone crack healing model for self-healing materials. Int J Solids Struct. 2018;134:249–63. https://doi.org/10.1016/j.ijsolstr.2017.11.004
84. Jefferson AD, Freeman BL. A crack-opening-dependent numerical model for self-healing cementitious materials. Int J Solids Struct. 2022;244–245:111601. https://doi.org/10.1016/j.ijsolstr.2022.111601
85. Darabi MK, Abu Al-Rub RK, Little DN. A continuum damage mechanics framework for modeling micro-damage healing. Int J Solids Struct. 2012;49(3–4):492–513. https://doi.org/10.1016/j.ijsolstr.2011.10.017
86. Freeman BL, Bonilla-Villalba P, Mihai IC, Alnaas WF, Jefferson AD. A specialised finite element for simulating self-healing quasi-brittle materials. Adv Model Simul Eng Sci. 2020;7:32. https://doi.org/10.1186/s40323-020-00171-4
87. Cibelli A, Pathirage M, Cusatis G, Ferrara L, Di Luzio G. A discrete numerical model for the effects of crack healing on the behaviour of ordinary plain concrete: implementation, calibration, and validation. Eng Fract Mech. 2022;263:108266. https://doi.org/10.1016/j.engfracmech.2022.108266
88. Di Luzio G, Ferrara L, Krelani V. Numerical modeling of mechanical regain due to self-healing in cement based composites. Cem Concr Compos. 2018;86:190–205. https://doi.org/10.1016/j.cemconcomp.2017.11.006
89. Ponnusami SA, Krishnasamy J, Turteltaub S, van der Zwaag S. A micromechanical fracture analysis to investigate the effect of healing particles on the overall mechanical response of a self-healing particulate composite. Fatigue Fract Eng Mater Struct. 2018;42(2):533–45. https://doi.org/10.1111/ffe.12929
90. Freeman BL, Jefferson AD. A 3D coupled chemo-mechanical model for simulating transient damage-healing processes in self-healing cementitious materials. Computational modelling of concrete and concrete structures, Vienna, Austria. Boca Raton, FL: CRC Press; 2022. https://doi.org/10.1201/9781003316404-14
91. Freeman BL, Jefferson T. The simulation of transport processes in cementitious materials with embedded healing systems. Int J Numer Anal Methods Geomech. 2020;44:293–326. https://doi.org/10.1002/nag.3017
92. Joseph C, Gardner D, Jefferson T, Isaacs B, Lark B. Self-healing cementitious materials: A review of recent work. Proc Inst Civ Eng. 2011;164(1):29–41. https://doi.org/10.1680/coma.900051
93. de Nardi C, Gardner D, Cristofori D, Ronchin L, Vavasori A, Jefferson T. Advanced 3D printed mini-vascular network for self-healing concrete. Mater Des. 2023;230:111939. https://doi.org/10.1016/j.matdes.2023.111939
94. de Nardi C, Freeman BL, Gardner D, Jefferson T. Mechanical response and predictive modelling of vascular self-healing cementitious materials using novel healing agents. Cem Concr Compos. 2023;142:105143. https://doi.org/10.1016/j.cemconcomp.2023.105143
95. Jefferson A, Selvarajoo T, Freeman B, Davies R. An experimental and numerical study on vascular self-healing cementitious materials. MATEC Web Conf. 2019;289:01004. https://doi.org/10.1051/matecconf/201928901004
96. Minnebo P, Thierens G, de Valck G, van Tittelboom K, de Belie N, van Hemelrijck D, et al. A novel design of autonomously healed concrete: towards a vascular healing network. Materials. 2017;10(1):49. https://doi.org/10.3390/ma10010049
97. Davies R, Jefferson A, Lark R, Gardner D. A novel 2D vascular network in cementitious materials. Fib Symposium 2015: Concrete - Innovation and Design, Copenhagen, Denmark; 2015.
98. Huang H, Ye G, Shui Z. Feasibility of self-healing in cementitious materials - by using capsules or a vascular system? Constr Build Mater. 2014;63:108–18. https://doi.org/10.1016/j.conbuildmat.2014.04.028
99. Li Z, de Souza LR, Litina C, Markaki AE, Al-Tabbaa A. Feasibility of using 3D printed polyvinyl alcohol (PVA) for creating self-healing vascular tunnels in cement system. Materials. 2019;12(23):3872. https://doi.org/10.3390/ma12233872
100. Van Tittelboom K, De Belie N. Self-healing in cementitious materials-a review. Materials. 2013;6(6):2182–217. https://doi.org/10.3390/ma6062182
101. Van Tittelboom K, De Belie N, Van Loo D, Jacobs P. Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. Cem Concr Compos. 2011;33(4):497–505. https://doi.org/10.1016/j.cemconcomp.2011.01.004
102. Van Tittelboom K, Tsangouri E, Van Hemelrijck D, De Belie N. The efficiency of self-healing concrete using alternative manufacturing procedures and more realistic crack patterns. Cem Concr Compos. 2015;57:142–52. https://doi.org/10.1016/j.cemconcomp.2014.12.002

103. De Rooij M, Van Tittelboom K, De Belie N, Schlangen E. Self-Healing Phenomena in Cement-Based Materials. 2013.
104. Snoeck D, Malm F, Cnudde V, Grosse CU, Van Tittelboom K. Validation of self-healing properties of construction materials through nondestructive and minimal invasive testing. Adv Mater Interfaces. 2018;5(17):1800179. https://doi.org/10.1002/admi.201800179
105. Snoeck D, Van Tittelboom K, Steuperaert S, Dubruel P, De Belie N. Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers. J Intell Mater Syst Struct. 2012;25(1):13–24. https://doi.org/10.1177/1045389X12438623
106. Šavija B, Feiteira J, Araújo M, Chatrabhuti S, Raquez J-M, Van Tittelboom K, et al. Simulation-aided Design of Tubular Polymeric Capsules for self-healing concrete. Materials (Basel). 2016;10:10. https://doi.org/10.3390/ma10010010
107. Van Tittelboom K, Wang J, Araújo M, Snoeck D, Gruyaert E, Debbaut B, et al. Comparison of different approaches for self-healing concrete in a large-scale lab test. Constr Build Mater. 2016;107:107–37. https://doi.org/10.1016/j.conbuildmat.2015.12.186
108. Cao S, Liu T. Compressive response of self-healing polymer foams containing bilayered capsules: coupled healing agents diffusion and stress simulations. J Mech Phys Solids. 2021;149:104314. https://doi.org/10.1016/j.jmps.2021.104314
109. Ma Y, Liu J, Zhang Y, Ge Y, Wu R, Song X, et al. Mechanical behavior and self-healing mechanism of polyurea-based double-walled microcapsule/epoxy composite films. Prog Org Coat. 2021;157:106283. https://doi.org/10.1016/j.porgcoat.2021.106283
110. Li W, Jiang Z, Yang Z, Zhao N, Yuan W. Self-healing efficiency of cementitious materials containing microcapsules filled with healing adhesive: mechanical restoration and healing process monitored by water absorption. PLoS One. 2013;8(11):e81616. https://doi.org/10.1371/journal.pone.0081616
111. Xue C, Li W, Li J, Tam VWY, Ye G. A review study on encapsulation-based self-healing for cementitious materials. Struct Concr. 2019;20(1):198–212. https://doi.org/10.1002/suco.201800177
112. Mostavi E, Asadi S, Hassan MM, Alansari M. Evaluation of self-healing mechanisms in concrete with double-walled sodium silicate microcapsules. J Mater Civ Eng. 2015;27(12):04015035. https://doi.org/10.1061/(asce)mt.1943-5533.0001314
113. Li W, Zhu X, Zhao N, Jiang Z. Preparation and properties of melamine urea-formaldehyde microcapsules for self-healing of cementitious materials. Materials. 2016;9(3):152. https://doi.org/10.3390/ma9030152
114. Hassan MM, Milla J, Rupnow T, Al-Ansari M, Daly WH. Microencapsulation of calcium nitrate for concrete applications. Transp Res Rec. 2016;2577(1):8–16. https://doi.org/10.3141/2577-02
115. Milla J, Hassan MM, Rupnow T, Al-Ansari M, Arce G. Effect of self-healing calcium nitrate microcapsules on concrete properties. Transp Res Rec. 2016;2577(1):69–77. https://doi.org/10.3141/2577-09
116. Dong B, Wang Y, Fang G, Han N, Xing F, Lu Y. Smart releasing behavior of a chemical self-healing microcapsule in the stimulated concrete pore solution. Cem Concr Compos. 2015;56:46–50. https://doi.org/10.1016/j.cemconcomp.2014.10.006
117. Dong B, Wang Y, Ding W, Li S, Han N, Xing F, et al. Electrochemical impedance study on steel corrosion in the simulated concrete system with a novel self-healing microcapsule. Constr Build Mater. 2014;56:1–6. https://doi.org/10.1016/j.conbuildmat.2014.01.070
118. Xiong W, Tang J, Zhu G, Han N, Schlangen E, Dong B, et al. A novel capsule-based self-recovery system with a chloride ion trigger. Sci Rep. 2015;5:10866. https://doi.org/10.1038/srep10866
119. Lv LY, Zhang H, Schlangen E, Yang Z, Xing F. Experimental and numerical study of crack behaviour for capsule-based self-healing cementitious materials. Constr Build Mater. 2017;156:219–29. https://doi.org/10.1016/j.conbuildmat.2017.08.157
120. Kim YJ, Choi YW, Oh S-R. A study on the healing performance of solid capsules for crack self-healing of cementitious composites. Crystals. 2022;12(7):993. https://doi.org/10.3390/cryst12070993
121. Rodríguez CR, de Mendonça Filho FF, Mercuri L, Gan Y, Rossi E, Anglani G, et al. Chemo-physico-mechanical properties of the interface zone between bacterial PLA self-healing capsules and cement paste. Cem Concr Res. 2020;138:106228. https://doi.org/10.1016/j.cemconres.2020.106228
122. Litina C, Al-Tabbaa A. First generation microcapsule-based self-healing cementitious construction repair materials. Constr Build Mater. 2020;255:119389. https://doi.org/10.1016/j.conbuildmat.2020.119389
123. Jiang S, Lin Z, Tang C, Hao W. Preparation and mechanical properties of microcapsule-based self-healing cementitious composites. Materials. 2021;14(17):4866. https://doi.org/10.3390/ma14174866
124. Lv L, Schlangen E, Yang Z, Xing F. Micromechanical properties of a new polymeric microcapsule for self-healing cementitious materials. Materials. 2016;9(12):1025. https://doi.org/10.3390/ma9121025
125. Souza L, Al-Tabbaa A. Microfluidic fabrication of microcapsules tailored for self-healing in cementitious materials. Constr Build Mater. 2018;184:713–22. https://doi.org/10.1016/j.conbuildmat.2018.07.005
126. Tan NPB, Keung LH, Choi WH, Lam WC, Leung HN. Silica-based self-healing microcapsules for self-repair in concrete. J Appl Polym Sci. 2016;133. https://doi.org/10.1002/app.43090
127. Wang Y, Fang G, Ding W, Han N, Xing F, Dong B. Self-immunity microcapsules for corrosion protection of steel bar in reinforced concrete. Sci Rep. 2015;5(1):18484. https://doi.org/10.1038/srep18484
128. Arce GA, Hassan MM, Mohammad LN, Rupnow T. Characterization of self-healing processes induced by calcium nitrate microcapsules in cement mortar. J Mater Civ Eng. 2017;29(1):04016189. https://doi.org/10.1061/(asce)mt.1943-5533.0001717
129. Dong B, Ding W, Qin S, Han N, Fang G, Liu Y, et al. Chemical self-healing system with novel microcapsules for corrosion inhibition of rebar in concrete. Cem Concr Compos. 2018;85:83–91. https://doi.org/10.1016/j.cemconcomp.2017.09.012

130. Kanellopoulos A, Giannaros P, Palmer D, Kerr A, Al-Tabbaa A. Polymeric microcapsules with switchable mechanical properties for self-healing concrete: synthesis, characterisation and proof of concept. Smart Mater Struct. 2017;26(4):045025. https://doi.org/10.1088/1361-665X/aa516c
131. Kanellopoulos A, Giannaros P, Al-Tabbaa A. The effect of varying volume fraction of microcapsules on fresh, mechanical and self-healing properties of mortars. Constr Build Mater. 2016;122:577–93. https://doi.org/10.1016/j.conbuildmat.2016.06.119
132. Perez G, Erkizia E, Gaitero JJ, Kaltzakorta I, Jiménez I, Guerrero A. Synthesis and characterization of epoxy encapsulating silica microcapsules and amine functionalized silica nanoparticles for development of an innovative self-healing concrete. Mater Chem Phys. 2015;165:39–48. https://doi.org/10.1016/j.matchemphys.2015.08.047

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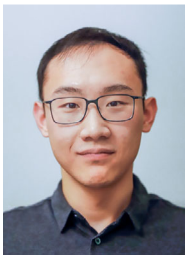

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