



Self-healing concrete: state of the art and relationship with sustainability

Concretos autocicatrizantes: estado da arte e relação com a sustentabilidade

Hormigones autocurativos: estado del arte y relación con la sostenibilidad

Bruno Brandão Rodrigues¹

Almir Barros da Silva Santos Neto²

Ana Paula Maran³

André Lübeck¹

Rogério Cattelan Antochaves de Lima²

¹ PPGE CAM - Programa de Pós-graduação em Engenharia Civil e Ambiental, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brasil

² PPGAUP - Programa de Pós-Graduação em Arquitetura, Urbanismo e Paisagismo, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brasil

³ UFFS - Universidade Federal da Fronteira Sul, Cerro Largo, Rio Grande do Sul, Brasil

Correspondence to: bruno.b.rodrigues8@gmail.com

Abstract: This article presents the state of the art of the self-healing concrete process, outlining different methods of carrying out the process in order to understand the advances made so far and to observe the environmental impacts associated with the use of these materials—such as increased structural durability and the reduction in the need for cementitious materials used in maintenance pro-

ORIGINAL ARTICLE - SCIENTIFIC SECTION

Responsible editors: Liane Ilha Librelotto, Dr. Eng., Paulo Cesar Machado Ferroli, Dr. Eng.

Submitted on

21/03/2025

Accepted on

07/12/2025

Published on

19/03/2026

PID

10.29183/2447-
3073.MIX2026.v12.n1.19-
46



Standard License Text

This work is licensed under a Creative Commons Attribution 4.0 International License.

Copyright Statement

Authors retain the copyright and grant the journal the right of first publication, with the work simultaneously licensed under a Creative Commons Attribution

cesses related to cracking. Furthermore, the development stages of research on the two main types of self-healing were assessed: autogenous healing, which was the origin of studies in the field, and autonomous healing, which involves enhancing healing properties through the use of additives. The studies included in the article were selected by filtering practical works focused on the healing process available in two databases (Scopus and Web of Science). The evaluated data shows that self-healing concrete demonstrates the potential to increase the durability of buildings and consequently reduce the environmental impacts caused by the construction industry. It was also notable that concretes using biological agents as healing additives are more advanced than others; this advancement is also reflected in the preference for autonomous healing among researchers.

Keywords: Sustainability; Self-healing; Concrete; Durability; Cracks.

Resumo: Este artigo apresenta o estado da arte do processo de autocicatrização do concreto, apresentando diferentes formas de realização do processo de modo a compreender os avanços realizados até o presente momento, e observar os impactos ambientais gerados pela utilização desses materiais, tais como o aumento da durabilidade das estruturas e da redução da necessidade do uso de materiais cimentantes empregados nos processos de manutenções relacionados à fissuração, ademais, foram avaliados os estados de avanço das pesquisas dos dois principais tipos de autocicatrização, a cicatrização autógena que foi a origem dos estudos na área e a autônoma que consiste no incremento das propriedades de cicatrização através do uso de aditivo. os estudos utilizados no artigo foram selecionados através da filtragem de trabalhos práticos focados no processo de cicatrização disponíveis em duas bases de dados (scopus e web of science). a base de dados avaliada demonstra que os concretos autocicatrizantes demonstram um potencial de aumento da durabilidade de edificações e conseqüentemente uma redução dos impactos ambientais gerados pela construção civil, também foi notável que os concretos que fazem uso de agentes biológicos como aditivos cicatrizantes estão mais avançados que os demais, esse avanço também reflete na escolha da cicatrização autônoma pelos pesquisadores.

Palavras-chave: Sustentabilidade; Autocicatrizante; Concreto; Durabilidade; Fissuras.

Resumen: Este artículo presenta el estado del arte del proceso de autocuración del concreto, exponiendo diferentes formas de llevar a cabo el proceso con el fin de comprender los avances realizados hasta el momento y observar los impactos

tion license, which permits sharing of the work with proper acknowledgment of authorship and initial publication in this journal.

Author Contributions according to the CRediT Taxonomy

Conflict declaration

Nothing to declare.

Funding source

Our most sincere thanks to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for their financial support.

ambientales generados por el uso de estos materiales, tales como el aumento de la durabilidad de las estructuras y la reducción de la necesidad de emplear materiales cementantes en los procesos de mantenimiento relacionados con la fisuración. Además, se evaluaron los niveles de avance de las investigaciones sobre los dos principales tipos de autocuración: la autocuración autógena, que dio origen a los estudios en el área, y la autónoma, que consiste en el incremento de las propiedades de curación mediante el uso de aditivos. Los estudios utilizados en el artículo fueron seleccionados mediante la filtración de trabajos prácticos enfocados en el proceso de curación disponibles en dos bases de datos (Scopus y Web of Science). La base de datos analizada demuestra que los concretos autocurativos presentan un potencial para aumentar la durabilidad de las edificaciones y, en consecuencia, reducir los impactos ambientales generados por la construcción civil. También se observó que los concretos que utilizan agentes biológicos como aditivos curativos se encuentran más avanzados que los demás; este avance también se refleja en la preferencia de los investigadores por la autocuración autónoma.

Palabras clave: Sostenibilidad; Autocuración; Concreto; Durabilidad; Fisuras.

How to cite: RODRIGUES, Bruno Brandão; SANTOS NETO, Almir Barros da Silva; MARAN, Ana Paula; LÜBECK, André; LIMA, Rogério Cattelan Antochaves de. Self-healing concrete: state of the art and relationship with sustainability. **Mix Sustentável**, Florianópolis, v. 12, n. 1, p. 19-46, 2026. DOI: <https://doi.org/10.29183/2447-3073.MIX2026.v12.n1.19-46>.

1 INTRODUCTION

Cracking is a recurring problem in reinforced concrete structures. Although it does not necessarily indicate a structural risk, this manifestation, largely due to concrete's low tensile strength, can accelerate the degradation process. The presence of cracks can act as an entry point for aggressive agents, leading to deterioration reactions such as reinforcement corrosion or the disintegration of the concrete itself (Snoeck; Belie, 2015).

Based on this principle, it is evident that there is a need to address these cracks, which in some cases can be quite costly or even infeasible due to accessibility challenges. In this regard, self-healing concrete has enormous potential to revolutionize the construction industry, as its ability to recover without human intervention can resolve issues in areas that are difficult to maintain, while also providing environmental and economic benefits related to reduced maintenance processes for the structure.

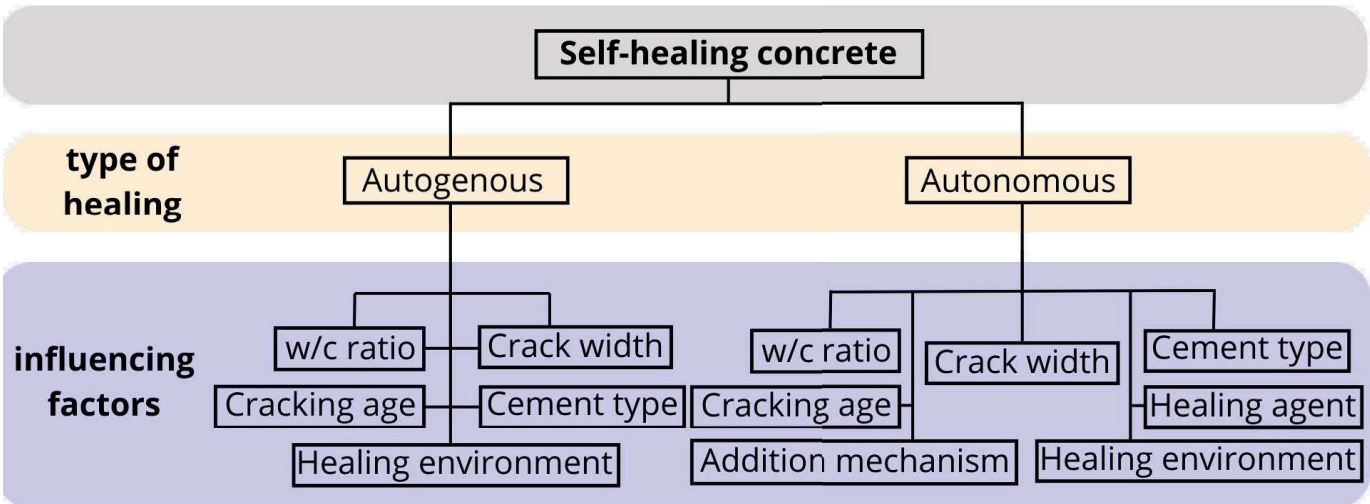
Although self-healing has been a hot topic in the last century, the knowledge about the phenomenon in concrete is ancient, initially through autogenous healing. However, this phenomenon is difficult to control, limited to small cracks, and occurs only in the presence of water. Therefore, there is an increasing search for materials capable of enhancing this healing property, resulting in autonomous self-healing concretes (Tittelboom; Belie, 2013).

Using self-healing concrete can generate environmental and economic benefits by increasing the lifespan of concrete elements and reducing maintenance costs, making it a sustainable alternative. This reduction in maintenance also leads to decreased use of materials like cement, whose production has a significant environmental impact (Andrew, 2019). However, the initial cost of producing self-healing concrete is one of the challenges that needs to be addressed to enable widespread use (Silva *et al.*, 2015).

As highlighted, healing in concrete can occur in two ways: autogenous and autonomous, the main difference between the two lines is how the healing processes are generated. In autogenous healing, the process is caused by materials present in the concrete that are not intended for self-healing, it is generated by the concrete's components (coarse aggregate, fine aggregate, and cement) or by additives added for other purposes that inadvertently benefit the healing process. In contrast, autonomous healing is generated through healing agents deliberately added to the cement matrix with the specific aim of self-healing (Rooij *et al.*, 2013). In addition to these differences, several factors affect both types of healing or only one, as shown in Figure 1.

Self-healing concrete emerges as a sustainable potential for the construction industry, título de seção ou subseção deverá ser seguido de texto. Para as seções textuais utilizar numeração progressiva self-healing concrete and to produce sustainable, high-performance materials. The performance of different healing agents is evaluated in various studies. These include the incorporation of bacteria (Krishnapriya; Babu; G., 2015; Metwally; Mahdy; El-raheem, 2020; Tan *et al.*, 2023), the use of fungi (Luo *et al.*, 2018; Zhang *et al.*, 2021; Jin; Yu; Shui, 2018), the use of crystallizing additives (Geraldo; Guadagnini; Camarini, 2021; Gojević *et al.*, 2021; Wang *et al.*, 2021) and the addition of superabsorbent polymers (Chindasiriphan *et al.*, 2022; Mousavi *et al.*, 2021; Wu *et al.*, 2020), among others.

Figure 1 – Flowchart highlighting the types of healing and their influencing factors



Source: Authors.

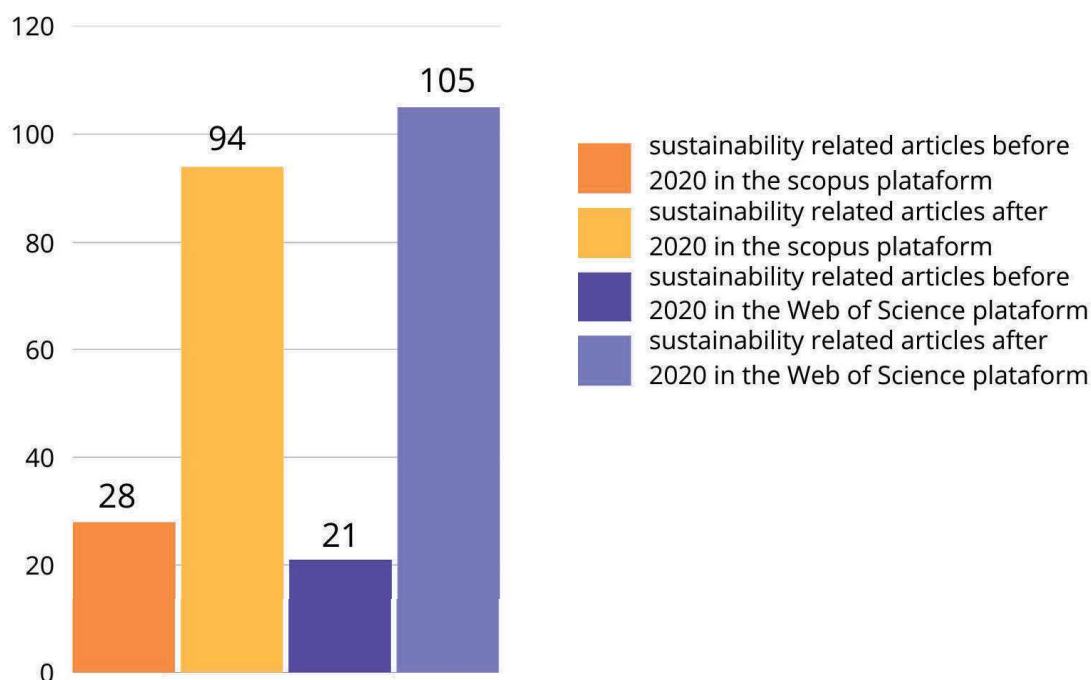
In addition to comparative studies between reference concretes and healing agents, it is essential to evaluate different application systems for these elements in the concrete mix, such as the use of internal vascular networks, the encapsulation of healing agents, or even their immobilization within aggregates or recyclable materials, to find an effective, sustainable, and economically viable combination.

Sustainability is strongly linked to self-healing concrete, which has the potential to positively impact the environmental effects of the construction industry, whether by reducing the materials used in maintenance processes or by utilizing sustainable materials in their production. This relationship between sustainability and self-healing concrete has only recently been recognized, since then, its growth has been remarkable. This can be seen in the graph in Figure 2, which shows the relationship between the number of studies highlighting the connection between self-healing concrete and sustainability before and after 2020.

The research landscape for self-healing concretes is positive, as the number of studies on the topic has grown over the past few years (Cappellesso *et al.*, 2023). However, there is a challenge in connecting these research efforts, as each laboratory employs different strategies for executing and evaluating results. In light of this situation, and aiming to facilitate the interconnection between research and consequently the development of these sustainable materials, the present article’s objective is to assess the current state of the art in self-healing concrete research. This includes encompassing the different perspectives presented in the field and evaluating the positive environmental impacts that these materials can generate.

1.1 Autogenous self-healing

As previously highlighted, autogenous healing is an intrinsic property of concrete, generated by the material’s constituents without additions specifically aimed at the healing process. However, it is a phenomenon

Figure 2 – Number of published articles relating self-healing concretes to sustainability

Source: Authors.

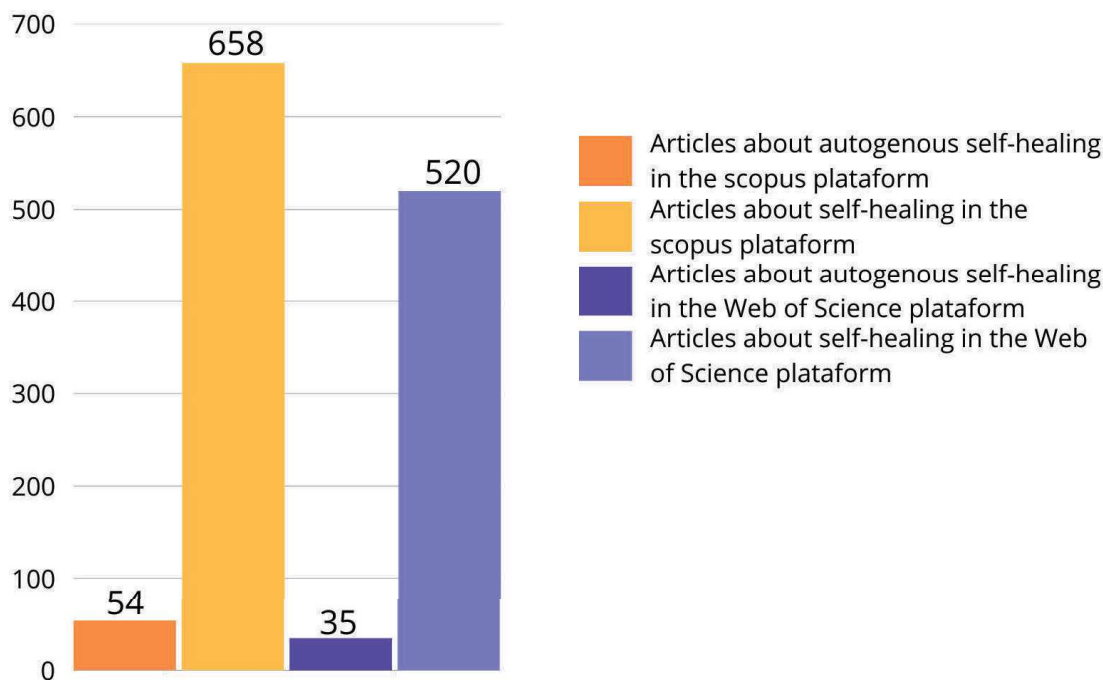
that is difficult to control and has more restrictive limitations when compared to autonomous healing. As suggested by Van Tittelboom and De Belie (2013), research that was predominantly focused on the development of autogenous healing concrete should shift its focus to autonomous healing, as the latter has fewer restrictions and is not as directly influenced by various factors, such as the age of the crack. This shift in focus can be observed in the graph in Figure 3.

Even with the shift in focus, research on autogenous healing is still being conducted. For example, the study by Hana Žáková, Jirí Pazderka, and Pavel Reiterman (2020) uses crystallizing additives to enhance the capacity for autogenous healing, while the research by Huang et al. (2021) employs machine learning techniques to predict the behavior of autogenous healing in concrete. Thus, it is evident that understanding the mechanisms involved in the autogenous healing process is important.

1.2 Autonomous self-healing

Research on autonomous healing has been growing over the years, especially since 2014, as predicted in previous studies (Tittelboom; Belie, 2013), where the greatest potential for the evolution of self-healing concretes was expected to come from research into autonomous healing technologies. This increase in the number of studies can be seen in the graph in Figure 4.

Despite representing a large sample of research on self-healing, studies focused on autonomous healing exhibit significant variability due to the lack of standardization in the tests, as highlighted by Litina et al.

Figure 3 – Publications on self-healing concrete in general and autogenous healing after 2014

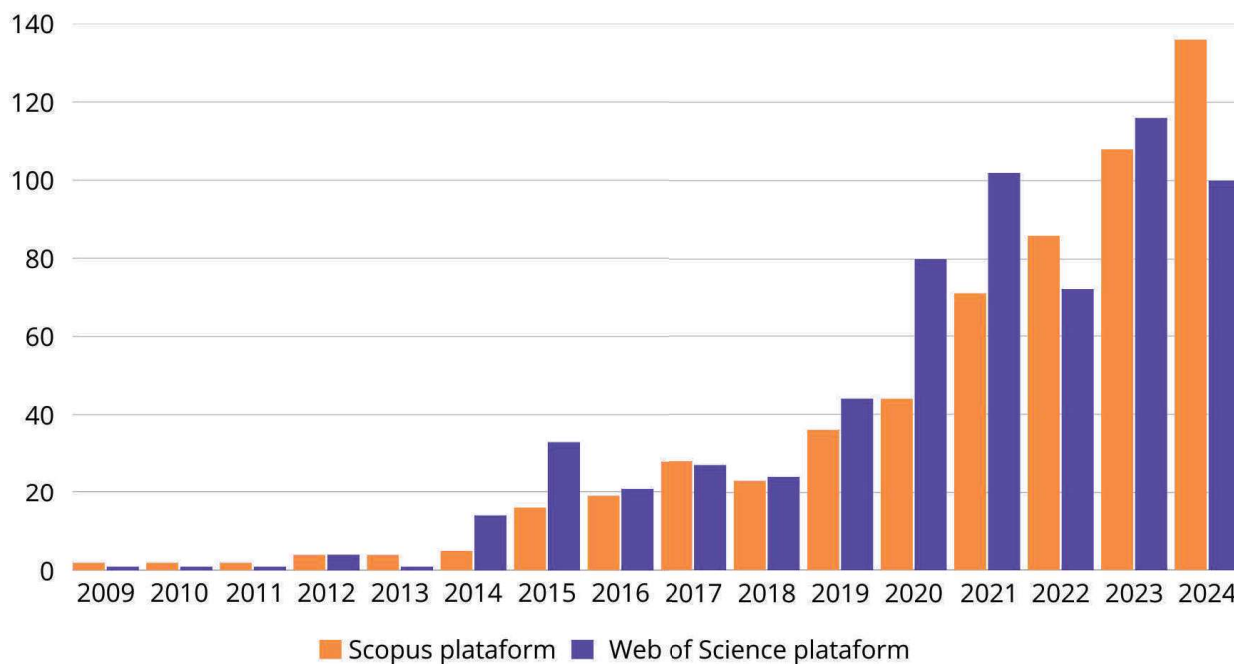
Source: Authors.

(Litina *et al.*, 2021). Moreover, in addition to the tests, the studies also differ based on the various approaches to adding materials to the cementitious matrix, as well as the wide range of materials evaluated as healing agents. Therefore, there is still an evolutionary path to be taken through research to find the combinations of addition methods and agents that yield the best sustainability results, structural performance, and financial viability.

2 STUDY METHODOLOGY

In order to carry out a comprehensive state-of-the-art review, it is essential to encompass the most relevant research within the field, incorporating the most robust and reliable findings available. This necessitates a preliminary screening process to identify and select the studies to be included in the review. Accordingly, the methodology was structured in two sequential stages: the first aimed at filtering the articles, and the second dedicated to their detailed evaluation, thereby ensuring the inclusion of studies with direct relevance to the topic under investigation.

To prioritize high-quality and relevant sources, the Scopus and Web of Science databases were employed, as these platforms provide reliable and peer-reviewed publications, are internationally recognized by academic and scientific institutions, and offer extensive global coverage, incorporating research from a wide range of geographical and institutional origins.

Figure 4 – Articles published on autonomous self-healing and studies on potential healing agents

2.1 Systematic literature review

To retrieve the articles from the selected databases, a broad and general search string was developed in order to encompass the largest possible number of studies related to the topic. While this approach increases the workload during the screening process, it minimizes the risk of excluding relevant articles due to discrepancies with a more restrictive search string. The search string employed is presented in Figure 5.

Figure 5 – Search string used for article retrieval

"Concreto autocicatrizante" or "Argamassa autocicatrizante" or "Self-healing concrete" or "Self-sealing concrete" or "Self-healing mortar" or "Self-healing paste" or "Self-healing cimentitious materials" or "Autogenous self-healing" or "Autonomous self-healing"

Source: Authors.

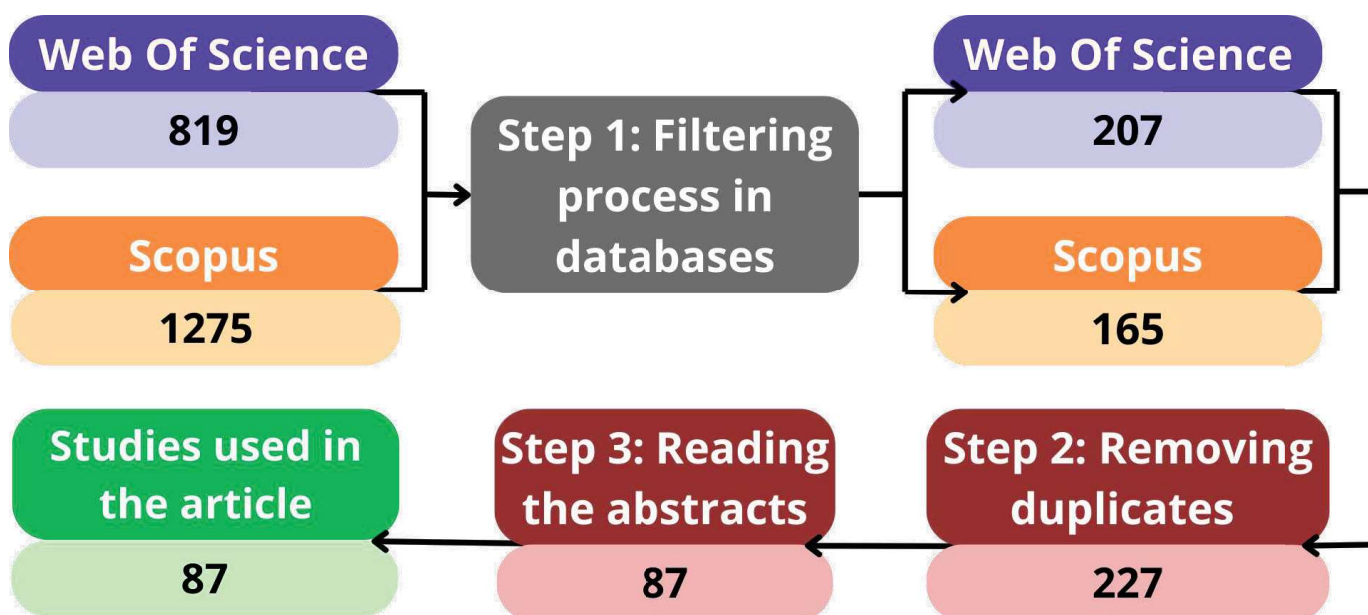
By applying the search string presented in Figure 5 to both databases mentioned earlier, a total of 2,094 studies related to self-healing concrete were retrieved. The first screening process was carried out within the databases themselves by applying filters for document type, primary language, and subject area. This step reduced the selection to 372 articles published in English or Portuguese within the fields of engineering and

materials science, considering the combined results from both databases.

Subsequently, the articles remaining after the first screening stage were imported into Mendeley, a reference management software, where the second screening process was conducted. This step consisted of removing duplicate records, that is, articles indexed in both databases, which reduced the total number of articles to 227.

Finally, still within Mendeley, the abstracts of the 227 remaining articles were reviewed to verify whether they addressed the practical effects on the healing process of different self-healing concrete compositions. This step eliminated, for instance, studies focused on the production of healing agents rather than on the healing process generated by the material itself, thereby reducing the total to 87 articles. These were subsequently organized into reference sheets and used as the basis for the present study. Figure 6 illustrates the article screening process.

Figure 6 – Filtering process for selecting the articles used in the present study



Source: Authors.

2.2 Reading and summarizing of the studies used

In the second stage of the methodology, summary sheets were prepared for the 87 articles approved in the initial evaluation, with the aim of identifying their objectives, the methodologies employed, and the conclusions reached. This process was carried out to enable the grouping of similar studies into the thematic topics to be presented later in this article.

3 FACTORS THAT INFLUENCE BOTH TYPES OF SELF-HEALING

Various factors make autogenous healing difficult to control, as they interact with different concrete mechanisms, such as the cement type, exposure environment, and age of crack formation, among others. These factors also influence autonomous healing; however, in this case, the use of additions facilitates the control of the desired properties and helps reduce the constraints present in autogenous healing.

3.1 Type of cement and additions

The production of Portland cement is one of the largest contributors to greenhouse gas emissions in the atmosphere, generating significant interest in the search for more sustainable options that can replace this material. The possibility of substituting cement with ecologically less impactful materials and its relation to the phenomenon of autogenous healing was the focus of research (Tittelboom *et al.*, 2012), which evaluated the effect of replacing cement with supplementary cementitious materials, such as fly ash and blast furnace slag. The study observed that from the perspective of autogenous healing, these materials are more effective, as they exhibit greater susceptibility to the occurrence of continuous hydration since even after long periods, they still contain a significant portion of particles capable of hydrating.

Research is also being conducted on variations in cement type, such as the study by Cappellesso (2018), which evaluated the performance of autogenous healing for three different types of cement (CPII-F, CPIV, and CPV ARI). The study concluded that, regarding internal matrix healing, concrete produced with CPIV exhibited superior performance. In terms of surface healing, observed through optical microscopy, CPV ARI outperformed the other types.

3.2 Concrete curing and exposure environments

Another property that affects autogenous self-healing is the type of concrete curing, as this stage is related to the amount of water available in the material and the duration for which self-healing can occur; without water, there is no self-healing. Shahid, Jaafar, and Yahaya (2014) evaluated the substitution of cement with palm oil ash under the influence of different curing types, concluding that the kind of curing affects the behavior of the materials regarding healing. Moreover, it was observed that the curing process with the highest effectiveness for healing was submerged curing in water; additionally, regardless of the curing type, the longer the curing period, the greater the self-healing.

Research has been conducted, such as that by Cappellesso *et al.* (2022), which observed that concrete using active silica performs better than concrete with crystallizing additives in environments with limited water availability; however, the performance of concrete with crystallizing additive was superior to the reference

concrete that had no additions. Exposure environments can affect the properties of materials, as demonstrated in the study by Esaker et al. (2021), which concluded that aggressive soils can inhibit the healing properties of concrete. Additionally, observing the effect of curing in concrete exposed to soil, the research by Hamza et al. (2024) yielded results indicating that natural soils provide a more favorable environment for healing than sterilized soils.

3.3 Cracking age

The age of crack formation is directly related to the occurrence of the self-healing phenomenon, as different times of crack formation may indicate the presence of anhydrous grains and water within the material, which is an extremely relevant factor for the occurrence of autogenous healing (Tittelboom; Belie, 2013).

In addition to the direct influence on the healing process, the factors can also affect the performance of other aspects, as evidenced in the study by Arndt (2019), which used test specimens with different ages of crack opening (3 and 28 days) while evaluating the influence of the water-to-cement ratio on the healing properties of the material. It became clear that the water-to-cement ratio has much greater significance for cracks opened at 28 days than for those opened at 3 days.

3.4 Cracking width

The thickness of the crack is a relevant factor when it comes to the structural safety of concrete elements and also when addressing the efficiency of the self-healing process, as the phenomenon of autogenous healing is limited to small cracks. Al-Tabbaa et al. (2019) highlight that autogenous healing is generally effective for cracks with a thickness of less than 0.15 mm.

The thickness of the crack can be the main focus of studies, such as the one conducted by Medeiros and Di Sarno (2024), where the effects on the self-healing process resulting from cracks generated by different cracking methods were evaluated. They observed that the nylon string method showed a more positive influence on cylindrical and cubic test specimens and is a method that is easy to replicate. In the study by Yuan et al. (2023), the authors utilized different approaches applying Machine Learning to predict the thickness of cracks in self-healing concrete, both before and after the healing process, finding that the random forest method and SHAP analysis performed best for predicting the post- and pre-healing thickness, respectively.

4 HEALING AGENTS AND ENHANCEMENT OF HEALING

As previously discussed, autogenous and autonomous healing share some influencing factors. However, due to the use of additions aimed at healing, which occurs in self-healing concretes, autonomous healing must

also take into account the influence generated by healing agents, in addition to the concomitant influencing factors of both types of healing. This includes their effects on healing properties as well as their impact on mechanical properties and durability.

The range of healing agents studied is quite broad, and even the healing mechanism generated by each healing agent differs from the others so the entire healing process varies according to the healing agent used. The healing mechanisms can be seen in Table 1.

Table 1 – Different healing mechanisms of healing agents

Healing agent	Healing mechanism	References
Crystallizing additives	Formation of crystals with different compositions that are responsible for filling the cracks	(Shetiya <i>et al.</i> , 2024; Park; Choi, 2021)
Superabsorbent polymers	Providing the availability of water for the hydration reactions responsible for healing the cracksreinforced	(Lefever; Okude; Shiotani, 2023; Mignon <i>et al.</i> , 2019; Gruyaert <i>et al.</i> , 2016)
Bacteria	Inducing the precipitation of calcite, which seals the cracks	(Chuo <i>et al.</i> , 2020; Hu <i>et al.</i> , 2022; Reeksting <i>et al.</i> , 2020)
Fungi	Inducing the precipitation of calcite or other minerals that seal the cracks	(Chiadighikaobi <i>et al.</i> , 2024; Luo <i>et al.</i> , 2018; Menon <i>et al.</i> , 2019)
Substitution of cement with supplementary materials	Greater availability of materials for late hydration reactions	(Tittelboom <i>et al.</i> , 2012; Medeiros; Sarno, 2022)

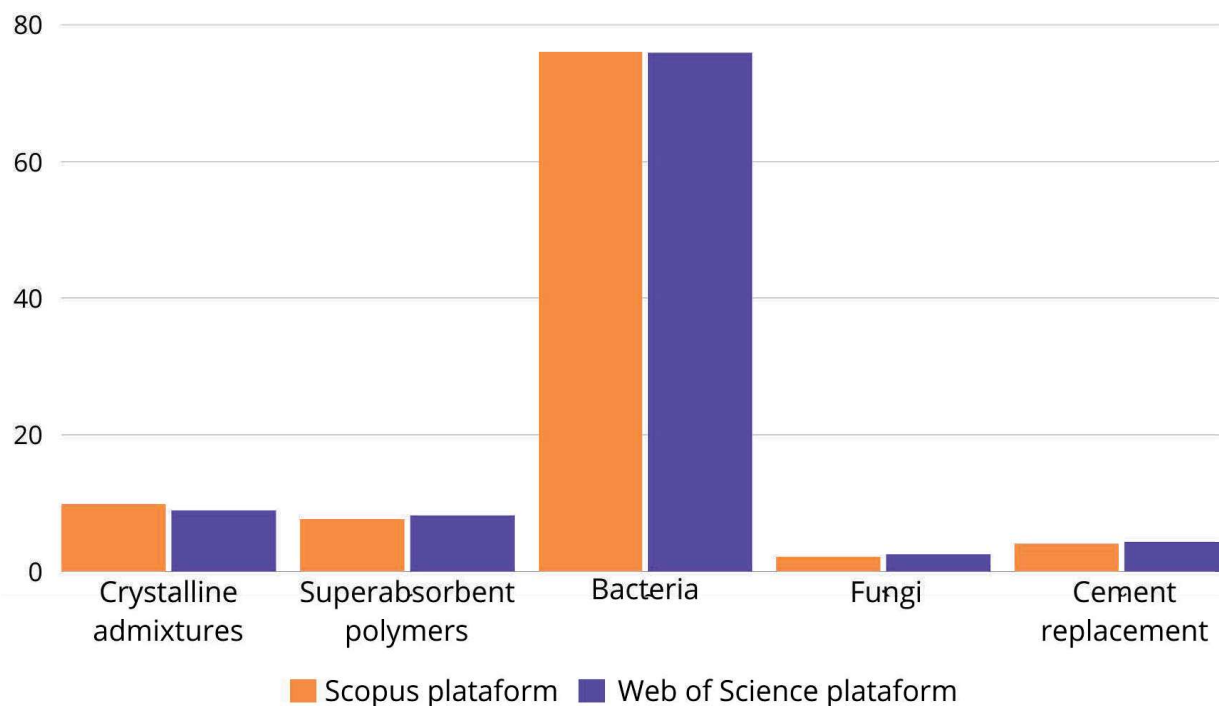
Source: Authors.

Among the healing agents, there is a clear trend towards the use of biological agents, with the use of bacteria being the most common in studies, accounting for more than 75% of the articles on healing agents, as can be seen in the graph in Figure 7.

Some materials can be used to enhance autogenous healing, as their properties are not exclusively healing. Moreover, these materials are often combined with other healing agents to improve autonomous healing, as is commonly the case with crystallizing additives and superabsorbent polymers.

4.1 Crystallizing additives

Studies on crystallizing additives have different approaches, some more direct, such as the case of Ziegler *et al.* (2020), where various methods were used to assess the efficiency of internal and external healing of concrete with crystallizing additives under the effect of wetting (2 days) and drying (12 days) cycles. For the evaluation of external healing, visual analysis was conducted using a scanning electron microscope, revealing that the wetting and drying cycles were not effective in activating hydration reactions on the surface of the concrete. For the internal healing of cracks, assessing chloride diffusion, it was observed that after the wetting and drying cycles, concretes with crystallizing additives exhibited superior performance compared to the reference

Figure 7 – Published articles on healing agents in percentage

Source: Authors.

samples.

Lo Monte and Ferrara (2021) tested the healing properties of ultra-high-performance concrete reinforced with fibers alongside the use of crystallizing additives, utilizing optical microscopy and permeability measurements to assess specimens in terms of maintaining crack openings. The samples approached 100% healing after 6 months; however, after reopening the cracks, the recovery rates only reached 40%. Park and Choi (2021) evaluated the performance of different supplementary cementitious materials, such as ground granulated blast furnace slag, active silica, and fly ash in combination with ordinary Portland cement, along with crystallizing additives and calcium sulfoaluminate. Their aim was to assess the different self-healing products generated by the various combinations using X-ray diffraction, thermogravimetry, and optical microscopy. The authors highlighted that the generation of healing products from the mixture with crystallizing additives was superior to those from the mixtures with calcium sulfoaluminate.

Shetiya et al. (2024) evaluated the performance of self-healing concrete using crystallizing additives and conducted various comparative tests with reference concretes without additions. They observed that the concrete utilizing crystallizing additives exhibited very satisfactory healing performance, which was verified through thickness and depth tests of the cracks. Additionally, they showed superior performance in mechanical characterization tests, such as compressive strength, especially in concretes with a higher dosage of additive. Furthermore, the additives also positively affected the durability of the material compared to the reference samples.

4.2 Superabsorbent polymers

Superabsorbent polymers can be used in various ways. Numerous articles (Chindasiriphan *et al.*, 2022; Snoeck *et al.*, 2014; Snoeck; Debo; Belie, 2020; Lefever *et al.*, 2020; Lefever *et al.*, 2020; Wu *et al.*, 2020; Zhang; Ma; Liu, 2023) combine superabsorbent polymers with other materials to induce healing in concrete. Additionally, there are many studies (Summa *et al.*, 2022; Snoeck; Belie, 2015; Snoeck; Belie, 2019; Snoeck, 2018; Mousavi *et al.*, 2021; Lefever; Okude; Shiotani, 2023) that use them independently to enhance the autogenous healing capacity of the cement matrix. Beyond these two application possibilities, research is also being conducted (Heede *et al.*, 2018; Gruyaert *et al.*, 2016; Nielsen *et al.*, 2019) to develop new polymers or assess the capabilities of different polymers as healing agents.

The combination of superabsorbent polymers (SAPs) with other materials aims to improve the healing performance of the materials, but it is also important for mitigating the negative effect of superabsorbent polymers on the mechanical properties of concrete. As explained by Zhang, Ma, and Liu (2023), the addition of SAPs makes the material more porous, consequently reducing its mechanical capabilities. Table 2 presents a summary of the materials mixed with superabsorbent polymers by different authors and the effects of these mixtures on the mechanical properties and healing capacity of the studied concretes.

Table 2 – Different mixtures and their performances

Material mixed with superabsorbent polymers	The behavior of mechanical properties	Influence on the self-healing performance	Reference
Rice husk ash	Lower than the reference concrete	Significant improvement	(Chindasiriphan <i>et al.</i> , 2022)
Magnesium oxide	Are better than the reference concrete	50% reduction in healing time	(Wu <i>et al.</i> , 2020)
Crystalline admixture	Are better than the reference concrete	Complete crack repair in 90 days	(Zhang; Ma; Liu, 2023)
Nanosilica	Are close to the reference concrete	100% healing in 75% of the cracks evaluated	(Lefever <i>et al.</i> , 2020)
Microfibres	Are close to the reference concrete	Great performance when exposed to wet-dry cycles	(Snoeck <i>et al.</i> , 2014)
Glass fibers	Are close to the reference concrete	Translucent material with good healing capacity	(Snoeck; Debo; Belie, 2020)

Source: Authors.

The application of superabsorbent polymers (SAPs) to enhance autogenous healing can be evaluated from different perspectives, which is essential for the development of the material as a healing agent. The study conducted by Snoeck and De Belie (2015) assessed the repetitive autogenous healing capacity provided by SAPs and showed that, despite a decrease from 75% in the first recovery to 66% in the second, the studied concrete exhibited over 50% recovery in mechanical properties even after the second occurrence of the same crack. Di Summa *et al.* (2022) evaluated the environmental and economic impacts of using SAPs in self-healing

concrete and concluded that the produced concrete yielded positive results, resulting in cost reduction and lower environmental impacts. Another approach used in the study by Pelto et al. (2017) was the encapsulation of superabsorbent polymers, which partially compensated for the reduction in the mechanical properties of the concrete due to decreased swelling of the SAPs during mixing, without compromising the healing capacity.

Overall, the application of superabsorbent polymers (SAPs) has a significant advantage in storing water, which will later be used for autogenous healing (Lefever; Okude; Shiotani, 2023; Snoeck, 2018). Due to their water retention capacity, a long-term study (8 years) was conducted by Snoeck and De Belie (2019) to assess the healing capacity of concrete containing SAP compared to a reference concrete. The results showed that the concrete with SAP exhibited better ductility after 8 years, with no degradation of the matrix during this period. In terms of healing, although the value observed after 8 years represented only one-third of the healing capacity demonstrated at 7 days, it was noteworthy that the concrete with the addition of SAP continued to show healing after 8 years, albeit at reduced rates compared to its performance at younger ages, with this capacity likely stemming from the crystallization of calcium carbonate.

There are different application possibilities for absorbent polymers, as well as various types of polymers, making the evaluation of the use of different polymers in self-healing concrete relevant. The study conducted by Arn Mignon et al. (2017) aimed to assess the characteristics of methacrylate alginate and acrylic monomers as superabsorbent polymers (SAPs). Another application for SAPs is their use as a material for capsules to transport bacteria, which was tested by Nielsen et al. (2019), where the authors inserted endospores of *Bacillus alkalinitrilicus* into SAP capsules to verify bacterial activity within the concrete through optical detection of pH.

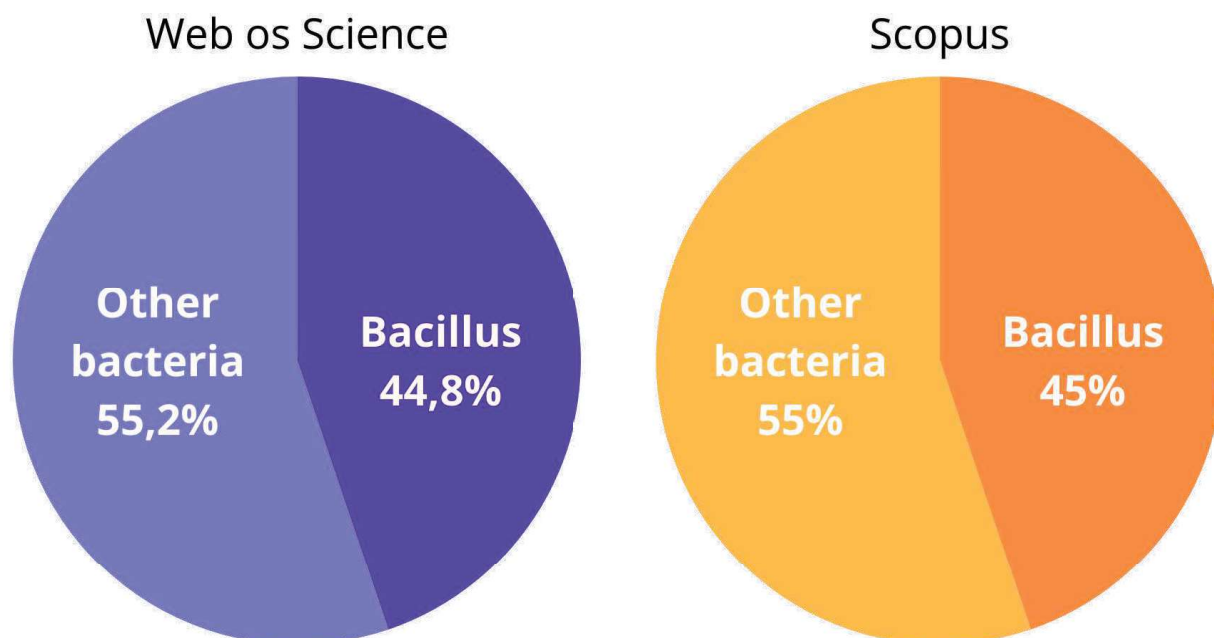
Regarding the creation of new polymers, the study by Van Den Heede et al. (2018) evaluates the life cycle of structures made with self-healing concrete containing fibers and three different semi-synthetic superabsorbent polymers (SAPs) developed by combining acrylic acid with acrylamide-based SAPs and modified sodium alginate-based SAPs. The evaluation results were positive, as although the results indicated that the reference concrete with fly ash had a greater impact on the life cycle, the concrete with the combination of SAPs and microfibers was also able to produce a positive effect. Another study focused on new materials was made by Gruyaert et al. (2016), which assessed the use of pH-sensitive SAPs through water flow tests to verify crack sealing capability. While conventional SAPs performed better in immediate crack sealing, the performance of SAPs made with particles between 400 and 600 μm was superior in sealing and producing CaCO_3 after 28 wetting and drying cycles.

4.3 Bacteria

As demonstrated earlier, bacteria are more frequently addressed in studies than other healing agents, and their main healing mechanism, as outlined in Table 1, is through the induction of calcite precipitation. Despite showing good performance in autogenous healing, evaluations of the performance of different bacteria are still being conducted, along with assessments of various protection techniques for the bacteria to increase

their survival rate in the alkaline environment of concrete. Additionally, there is a need to achieve better cost-effectiveness for biological concrete by finding cheaper methods for producing bacterial colonies. Among the different types of bacteria, studies are more focused on *Bacillus* bacteria, as shown in Figure 8.

Figure 8 – Percentage of studies on *Bacillus* bacteria compared to other bacteria



Source: Authors.

Although *Bacillus* bacteria stand out among the various types of bacteria used, this does not result in less variability among healing agents, as there is a wide range of *Bacillus* bacteria that can be utilized, as shown in Table 3.

Although *Bacillus* bacteria are the focus of various studies, they are not the only ones evaluated as healing agents; other bacterial species have also been assessed, such as *Sporosarcina* bacteria. *Sporosarcina pasteurii* has been the subject of several studies that evaluated its ability to produce self-healing and its effect on mechanical properties (Zaerkabeh *et al.*, 2022; Yan *et al.*, 2023; Xu *et al.*, 2019; Chen; Chen; Tang, 2020), its capacity to regenerate mechanical properties after cracking (Chen *et al.*, 2022) and the variations in its properties when exposed to moisture cycling. Additionally, *Sporosarcina aquimarina* was encapsulated in expanded perlite and assessed for its healing production capability (Amjad *et al.*, 2023), yielding positive results that enhance its potential use in self-healing concrete.

In general, one of the main concerns regarding the use of bacteria is their survival and subsequent development within concrete. As demonstrated by Hind and Ali (2023), the survival rates of bacteria are significantly higher when they are surrounded by some form of protection rather than being added directly to the concrete. By examining Table 3, it is also possible to see that the concern for bacterial protection has indeed stood out among research topics, and this protection is not limited to encapsulation, as the development of vascular networks is also a possibility for transporting these bacteria within the concrete.

One of the challenges of implementing self-healing concrete is its economic viability. Thus, vari-

Table 3 – Different healing mechanisms of healing agents

Healing agent	Healing mechanism	References
Bacillus Subtilis	Evaluation of adverse effects between the direct addition of bacteria and their encapsulation	(Hind; Ali, 2023)
Bacillus Cibi	Evaluation of different encapsulation techniques and the various benefits regarding bacterial survival	(Orozco; Urbino, 2022)
Bacillus Sphaericus	Encapsulation in a new alkali-activated aggregate to assess survival gains	(Risdanareni <i>et al.</i> , 2023)
Bacillus Cereus	Bacterial immobilization in wood ashes to evaluate survival benefits	(Reyad; Mokhtar, 2023)
Bacillus Cohnii	Incorporation with mineral salts to improve growth and encapsulation in polylactic acid for protection	(Rodríguez <i>et al.</i> , 2020)
Bacillus Pseudofirmus	Coating of bacteria with expansive clay for protection	(Veliyev; V, 2023)
Bacillus Megaterium	Influence on the performance of high-strength concretes	(Mauludin <i>et al.</i> , 2024)
Bacillus Pasteurii	Coating with epoxy resin for the protection of bacterial spores	(Hu <i>et al.</i> , 2021)
Bacillus Halodurans	Assessment of the mechanical performance of bacteria-based concrete	(Durga <i>et al.</i> , 2019)
Bacillus Licheniformis	Durability of self-healing concrete	(Durga <i>et al.</i> , 2023)

Source: Authors.

ous studies have been conducted to assess the financial feasibility of biological concrete. As highlighted by Stanaszek-Tomal (2020), the high cost of the bacterial substrates currently used results in their non-applicability at an industrial level. To address or improve viability by reducing the costs of bacterial substrates, research by Hong, Kim, and Park (2019) was conducted. Another approach to this problem was employed by Uguz-zoni *et al.* (2023), who utilized life cycle forecasting for structures based on self-healing concrete and found that, in addition to increased durability, maintenance costs are reduced. These savings could offset higher expenses resulting from the use of healing concrete, along with a reduction in environmental impacts generated by decreased maintenance processes and consequently a reduction in the use of materials that have negative environmental effects, such as cement.

4.4 Fungi

Although the use of bacteria is predominant in research on self-healing concrete based on biological healing agents, fungi possess significant potential (Jin; Yu; Shui, 2018). Fungi are gradually gaining attention as possible healing agents for concrete. However, since this research is still in its early stages, studies like

that of Luo *et al.* (2018) focus on screening different types of fungi, carefully selecting only eco-friendly and non-pathogenic species. The purpose of Luo *et al.*'s research was to evaluate which of the screened fungi would have the greatest capacity to generate calcium precipitation to seal cracks, with *Trichoderma Reesei* showing the most potential for use as a healing agent. Meanwhile, the study conducted by Menon *et al.* (2019) aimed to evaluate different mutations of the fungus *Aspergillus nidulans*, as the authors noted that this fungal filament has the best gene adaptation to environmental pH. They concluded that *Aspergillus nidulans* (MAD1445) could develop in concrete but emphasized that further studies are needed to assess any potential negative effects of the material on the environment and human health before field application.

Among fungi, *Trichoderma Reesei* has gained prominence in research, being the subject of various studies (Chiadighikaobi *et al.*, 2024; Wylick *et al.*, 2024; Wylick *et al.*, 2024-2). These studies evaluate the necessary conditions for the biomineralization of CaCO_3 and the prospects for developing self-healing concrete based on fungi (Wylick *et al.*, 2024), as well as the use of machine learning to predict the mechanical behaviors of concrete produced with fungi (Chiadighikaobi *et al.*, 2024). They also explore adaptations of techniques commonly used in bacteria-based concrete, such as the encapsulation of the material (Wylick *et al.*, 2024-2), in order to improve the survival rates of fungi in concrete.

Although *Trichoderma reesei* has stood out among fungi, research is also being conducted on other species, such as the study led by Zhang *et al.* (2021), which used the fungus *Fusarium oxysporum* as a healing agent. This study evaluated the effects of the concrete environment on the fungus's growth capacity and observed that the alkaline environment increases the time required for fungal growth.

Regarding advances in research on fungi, Jin, Yu, and Shui (2018) emphasize that studies conducted on bacteria continue to face limitations. Therefore, the continuation of research on fungi is essential, as they demonstrate excellent adaptation to deleterious environments, which may favor their development in settings like that provided by concrete.

4.5 Partial substitution of concrete constituents

Low CO₂ emission concrete is increasingly sought after, as the concrete industry is responsible for about 8% of global CO₂ emissions (Andrew, 2019), largely due to the cement production process. As a primary material in construction, concrete is used extensively; moreover, the need for maintenance directly affects the demand for material production and, consequently, the carbon footprint of the industry (Albuhairi; Sarno, 2022). In this context, self-healing concrete emerges as a possibility to reduce concrete consumption in maintenance, as their healing capacity decreases the need for repairs. Another possibility for reducing the carbon footprint comes from replacing cement with low-carbon emission industrial by-products (Albuhairi; Sarno, 2022).

Based on the principle of reducing carbon footprint and producing eco-friendly concretes, the combination of self-healing concretes with the partial replacement of cement by industrial by-products has gained focus in various studies (Wang *et al.*, 2021; Chindasiriphan *et al.*, 2022; Medeiros; Sarno, 2022). In the research

conducted by Medeiros and Di Sarno (2022), the authors evaluated the influence of replacing 50% of cement with ground granulated blast furnace slag in a bacteria-based self-healing concrete. They observed that the only drawback of the substitution was the reduction in the material's initial compressive strength, while the healing properties were maintained, making its use viable for structures that do not require high strength in the early stages of curing. Wang et al. (2021) found that crystalline additives provide good healing properties but may have negative effects when replacing cement with fly ash in percentages greater than 20%. In the case studied by Chindasiriphan et al. (2022), the authors found that replacing cement with rice husk ash resulted in inferior healing properties compared to the replacement of cement with fly ash. However, the combination of rice husk ash with superabsorbent polymers effectively improved the healing properties of the material.

Studies are also being conducted on the healing capacity generated by the replacement of cement with industrial by-products, without the addition of a complementary healing agent. The research by Shahid, Jaafar, and Yahaya (2014) used ash from burning palm kernel shells as a cement substitute and concluded that, for mechanical strength purposes, the ideal replacement proportion is 20%, but for self-healing purposes, the optimal replacement is only 10%.

A study somewhat different from the others was conducted by Asrat and Ghebrab (2020), where the authors did not replace cement with industrial by-products but instead replaced fine aggregates with rejected granular cement grains from milling. This was done to enhance the autogenous healing of concrete, which proved effective, as good values of strength recovery and reduced permeability after cracking were observed, indicating the occurrence of healing.

5 EFFECTS ON MECHANICAL PROPERTIES AND DURABILITY

Although the focus of studies is mostly on evaluating properties related to concrete healing, assessing the effects of healing agents on the mechanical properties of uncracked concrete is also highly relevant from an environmental standpoint. Any reduction in mechanical performance may require increased material consumption or structural oversizing, which directly raises embodied carbon and resource use. Therefore, understanding the adverse effects caused by different additions or by voids resulting from the presence of capsules or internal vascular networks within the matrix is essential not only for structural performance but also for ensuring that self-healing solutions do not offset their own sustainability benefits.

The main focus of these studies is on bacteria, as healing agents like superabsorbent polymers and crystalline additives already have more consolidated performance data. However, it is not only the chemical or biological reactions generated by healing agents that can affect the mechanical properties of the material, geometric modifications, such as pores formed by vascular networks, may significantly influence strength and stiffness. For instance, Wan et al. (2023) demonstrated that optimized vascular network arrangements can limit mechanical strength reductions to acceptable levels when up to three channels are introduced. This finding is particularly relevant because it shows that durability gains do not necessarily require substantial mechanical penalties, meaning that environmental benefits associated with extended service life can be achieved without

increasing structural material demand.

The evaluation of bacterial concentration is also critical. Onyelowe *et al.* (2024), through machine learning modeling, showed that variations in bacterial content did not cause significant reductions in compressive strength, indicating that biological healing agents can be incorporated without compromising structural requirements. Similarly, Zaki and Zeyad (2024) reported not only the absence of relevant mechanical losses but also a considerable reduction in reinforcement corrosion rates. This corrosion mitigation has direct environmental implications, as reinforcement corrosion is one of the main causes of premature structural degradation, often leading to repair or demolition. By reducing corrosion rates, self-healing systems contribute to service-life extension, which in life-cycle terms represents a substantial reduction in emissions associated with repair materials, transportation, and reconstruction processes.

Mechanical recovery after cracking is another key indicator. Studies such as those by Davies, Jefferson and Gardner (2021), Anglani, Tulliani and Antonaci (2020), Asrat and Ghebrab (2020), Chen *et al.* (2022), and Ferrara *et al.* (2017) demonstrate measurable recovery of mechanical properties after healing cycles. This partial or significant recovery reduces the need for external repair interventions. In parallel, the recovery of impermeability, reported by Alghamri, Kanellopoulos and Al-Tabbaa (2016), Al-Tabbaa *et al.* (2019), Vermeer *et al.* (2021), and Wan *et al.* (2022, 2023), directly limits the ingress of aggressive agents. This reduction in permeability delays deterioration mechanisms, particularly reinforcement corrosion and freeze-thaw damage, both of which are strongly associated with high maintenance-related carbon emissions.

Therefore, the improvement in durability observed in works such as Fahimizadeh *et al.* (2022), Belmonte *et al.* (2022), and Cuenca *et al.* (2021) should not be interpreted merely as a technical advantage but as an environmental one. Increased durability translates into longer service life and fewer repair cycles, which, from a life-cycle assessment perspective, represents a reduction in cumulative energy demand and greenhouse gas emissions.

Finally, the study by Kandasamy *et al.* (2024) reinforces this relationship by demonstrating that bacterial concrete can simultaneously enhance durability indicators and maintain satisfactory mechanical performance. These findings suggest that environmental gains are not achieved at the expense of structural safety. Instead, when properly designed, self-healing concrete can reconcile mechanical reliability with sustainability objectives, strengthening its potential as a low-impact construction material.

6 CONCLUSION

After reviewing a wide range of studies, it becomes clear that the environmental relevance of self-healing concrete is strongly linked to measurable durability improvements and their consequences over the service life of structures. The literature consistently indicates reductions in permeability, mitigation of reinforcement corrosion, and partial to significant recovery of mechanical properties. These factors directly contribute to extending service life, which is one of the most effective strategies for reducing the environmental burden of concrete structures.

From a life-cycle perspective, durability gains represent avoided impacts. Each postponed repair intervention implies savings in cement production, steel replacement, transportation, and construction activities, all of which are carbon-intensive processes. Therefore, the environmental advantage of self-healing concrete does not lie merely in the material innovation itself, but in its capacity to reduce the frequency and intensity of future maintenance actions. However, the environmental balance depends on maintaining adequate mechanical performance. The reviewed studies indicate that, when properly designed, self-healing systems, particularly those based on biological agents, do not produce significant mechanical losses and may even enhance resistance to deterioration mechanisms such as corrosion. This compatibility between mechanical integrity and durability enhancement is fundamental to ensuring that sustainability gains are not offset by increased material consumption.

Although economic factors may currently limit large-scale adoption due to higher initial costs, the long-term environmental benefits associated with service-life extension and reduced maintenance frequency position self-healing concrete as a promising strategy for decarbonizing the construction sector.

Regarding healing mechanisms, autonomous systems demonstrate greater environmental potential than autogenous healing, primarily due to their higher controllability and broader applicability. Among healing agents, biological approaches stand out due to their demonstrated capacity to improve durability indicators without compromising structural performance. Nevertheless, challenges related to encapsulation integrity and large-scale implementation remain critical barriers that must be addressed before widespread application becomes feasible.

Overall, the evidence suggests that self-healing concrete represents not only a technological advancement but also a strategically relevant solution for reducing life-cycle environmental impacts in construction.

REFERENCES

- Al-tabbaa, A. *et al.* First uk field application and performance of microcapsule-based self-healing concrete. **CONSTRUCTION AND BUILDING MATERIALS**, v. 208, p. 669–685, 2019. ISSN 0950-0618.
- Albuhairi, D.; Sarno, L. D. Low-carbon self-healing concrete: State-of-the-art, challenges and opportunities. **BUILDINGS**, v. 12, 2022. ISSN 2075-5309.
- Alghamri, R.; Kanellopoulos, A.; Al-tabbaa, A. Impregnation and encapsulation of lightweight aggregates for self-healing concrete. **Construction and Building Materials**, Elsevier Ltd, v. 124, p. 910–921, 2016. ISSN 09500618 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-84981180068&doi=10.1016%2fj.conbuildmat.2016.07.143&partnerID=40&md5=a60aad14cf6e26876236364fb2a51b6a>>.
- Amjad, U. B. *et al.* A study on microbial self-healing concrete using expanded perlite. **Bulletin of the Polish Academy of Sciences: Technical Sciences**, Polska Akademia Nauk, v. 71, 2023. ISSN 02397528 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85175537484&doi=10.24425%2fbpasts.2023.146475&partnerID=40&md5=31acdae25f51eae10b27b4e7b6789f82>>.
- Andrew, R. M. Global co ₂ emissions from cement production, 1928–2018. **Earth System Science Data**, v. 11, p. 1675–1710, 11 2019. ISSN 1866-3516. Disponível em: <<https://essd.copernicus.org/articles/11/1675/2019/>>.
- Anglani, G.; Tulliani, J.-M.; Antonaci, P. Behaviour of pre-cracked self-healing cementitious materials under static and cyclic loading. **Materials**, v. 13, 2020.
- Arndt, J. A.; Alegre, P. **AVALIAÇÃO DE ADITIVOS CRISTALIZANTES NA AUTOCICATRIZAÇÃO DE CONCRETOS DE CIMENTO PORTLAND**. 2019. Tese (Doutorado) — Universidade Federal do Rio Grande do Sul, 2019.
- Asrat, F.; Ghebrab, T. Effect of mill-rejected granular cement grains on healing concrete cracks. **Materials**, v. 13, p. 1–15, 2020.
- Belmonte, I. M. *et al.* Mineralization reaction of calcium nitrate and sodium silicate in cement-based materials. **CRYSTALS**, v. 12, 2022. ISSN 2073-4352.
- Cappellesso, V. *et al.* A review of the efficiency of self-healing concrete technologies for durable and sustainable concrete under realistic conditions. **INTERNATIONAL MATERIALS REVIEWS**, v. 68, p. 556–603, 2023. ISSN 0950-6608.
- Cappellesso, V. G. **AVALIAÇÃO DA AUTOCICATRIZAÇÃO DE FISSURAS EM CONCRETOS COM DIFERENTES CIMENTOS**. 9 2018. Tese (Doutorado) — Universidade Federal Do Rio Grande Do Sul, 9 2018.
- Cappellesso, V. G. *et al.* Reduction of concrete permeability using admixtures or surface treatments. **Journal of Building Pathology and Rehabilitation**, Springer Nature, v. 7, 12 2022. ISSN 23653167.
- Chen, B. C. *et al.* A experimental study on engineered cementitious composites (ecc) incorporated with *sporosarcina pasteurii*. **BUILDINGS**, v. 12, 2022. ISSN 2075-5309.
- Chen, H.-J.; Chen, M.-C.; Tang, C.-W. Research on improving concrete durability by biomineralization technology. **SUSTAINABILITY**, MDPI, v. 12, 2 2020.

Chiadighikaobi, P. C. *et al.* Predicting mechanical properties of self-healing concrete with trichoderma reesei fungus using machine learning. **Cogent Engineering**, Cogent OA, v. 11, 2024. ISSN 23311916 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85183833678&doi=10.1080%2f23311916.2024.2307193&partnerID=40&md5=4c788fef012694b8964b0f6cb4f35534>>.

Chindasiriphan, P. *et al.* Combined effect of rice husk ash and superabsorbent polymer on self-healing capability of mortar. **Construction and Building Materials**, Elsevier Ltd, v. 338, 2022. ISSN 09500618 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129458657&doi=10.1016%2fj.conbuildmat.2022.127588&partnerID=40&md5=66397bdb470f864685fde64b77aa6338>>.

Chuo, S. C. *et al.* Insights into the current trends in the utilization of bacteria for microbially induced calcium carbonate precipitation. **MATERIALS**, v. 13, 2020. ISSN 1996-1944.

Cuenca, E. *et al.* Mechanical properties and self-healing capacity of ultra high performance fibre reinforced concrete with alumina nano-fibres: Tailoring ultra high durability concrete for aggressive exposure scenarios. **Cement and Concrete Composites**, Elsevier Ltd, v. 118, 2021. ISSN 09589465 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85100626740&doi=10.1016%2fj.cemconcomp.2021.103956&partnerID=40&md5=ecac26733b4ef5f9b55309c29730b97b>>.

Davies, R.; Jefferson, T.; Gardner, D. Development and testing of vascular networks for self-healing cementitious materials. **Journal of Materials in Civil Engineering**, American Society of Civil Engineers (ASCE), v. 33, 2021. ISSN 08991561 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85105414584&doi=10.1061%2f%28ASCE%29MT.1943-5533.0003802&partnerID=40&md5=cbbec063c75b3497a671ff477b4d7929>>.

Durga, C. S. S. *et al.* Evaluation of mechanical parameters of bacterial concrete. **ANNALES DE CHIMIE-SCIENCE DES MATERIAUX**, LAVOISIER, v. 43, p. 395–399, 12 2019. ISSN 0151-9107.

Durga, C. S. S. *et al.* Estimation of durability properties of self-healing concrete influenced by different bacillus species. **Research on Engineering Structures and Materials**, MIM RESEARCH GROUP, v. 9, p. 1489–1505, 2023. ISSN 21489807 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85184809766&doi=10.17515%2fresm2023.745st0423&partnerID=40&md5=70b26af2ff90d2905693ebe09fd606bb>>.

Esaker, M. *et al.* Self-healing of bio-cementitious mortar incubated within neutral and acidic soil. **Materials and Structures/Materiaux et Constructions**, Springer Science and Business Media B.V., v. 54, 2021. ISSN 13595997 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85104379465&doi=10.1617%2fs11527-021-01690-1&partnerID=40&md5=a0dbbed450394fe06801ad9540574ee2>>.

Fahimizadeh, M. *et al.* **Multifunctional, Sustainable, and Biological Non-Ureolytic Self-Healing Systems for Cement-Based Materials**. [S.l.]: Elsevier Ltd, 2022. 217-237 p.

Ferrara, L. *et al.* Effects of autogenous healing on the recovery of mechanical performance of high performance fibre reinforced cementitious composites (hprccs): Part 1. **Cement and Concrete Composites**, Elsevier Ltd, v. 83, p. 76–100, 2017. ISSN 09589465 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85025095771&doi=10.1016%2fj.cemconcomp.2017.07.010&partnerID=40&md5=104dc9159c8a260d33c58882a83d0861>>.

Geraldo, R.; Guadagnini, A.; Camarini, G. Self-healing concrete with crystalline admixture made with different cement content. **Ceramica**, v. 67, p. 370–377, 2021.

Gojević, A. *et al.* The effect of crystalline waterproofing admixtures on the self-healing and permeability of concrete. **Materials**, v. 14, 2021.

Gruyaert, E. *et al.* Self-healing mortar with ph-sensitive superabsorbent polymers: testing of the sealing efficiency by water flow tests. **SMART MATERIALS AND STRUCTURES**, v. 25, 2016. ISSN 0964-1726.

Hamza, O. *et al.* Bio-protection of cementitious materials below ground: The significance of natural soil environments. **Developments in the Built Environment**, Elsevier Ltd, v. 17, 2024. ISSN 26661659 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85182730803&doi=10.1016%2fdibe.2024.100331&partnerID=40&md5=afe5b1729c1ab56e2a4f47f448cf6cd9>>.

Heede, P. van den *et al.* Cradle-to-gate life cycle assessment of self-healing engineered cementitious composite with in-house developed (semi-)synthetic superabsorbent polymers. **CEMENT & CONCRETE COMPOSITES**, v. 94, p. 166–180, 2018. ISSN 0958-9465.

Hind, M. T.; Ali, A. S. Investigation of the flexural behavior of bacterial concrete beams. **Civil and Environmental Engineering**, Sciendo, v. 19, p. 474–492, 2023. ISSN 13365835 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85180586002&doi=10.2478%2fcee-2023-0043&partnerID=40&md5=1a7c237f1ed98e21b1625357afd7cfdb>>.

Hong, M.; Kim, W.; Park, W. Low-cost cultivation and sporulation of *alkaliphilic bacillus* sp. strain ak13 for self-healing concrete. **JOURNAL OF MICROBIOLOGY AND BIOTECHNOLOGY**, KOREAN SOC MICROBIOLOGY & BIOTECHNOLOGY, v. 29, p. 1982–1992, 12 2019. ISSN 1017-7825.

Hu, Y. *et al.* Research on the preparation of microbial capsules by epoxy resin-coated *bacillus pasteurii*. **SHOCK AND VIBRATION**, HINDAWI LTD, v. 2021, 11 2021. ISSN 1070-9622.

Hu, Y. Y. *et al.* Investigation on mineralization performance and spore germination conditions of calcium carbonate mineralizing bacteria. **MATERIALS RESEARCH EXPRESS**, v. 9, 2022. ISSN 2053-1591.

Huang, X. *et al.* Prediction of healing performance of autogenous healing concrete using machine learning. **MATERIALS**, v. 14, 2021. ISSN 1996-1944.

Jin, C.; Yu, R.; Shui, Z. Fungi: A neglected candidate for the application of self-healing concrete. **Frontiers in Built Environment**, Frontiers Media S.A., v. 4, 2018. ISSN 22973362 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85064631238&doi=10.3389%2ffbuil.2018.00062&partnerID=40&md5=d73f75b067318ce915f8554e8ca0f34f>>.

Kandaswamy, S. *et al.* A comprehensive study on microbial self-healing concrete for sustainable construction. **MATERIA-RIO DE JANEIRO**, v. 29, 2024. ISSN 1517-7076.

Krishnapriya, S.; Babu, D. V.; G., P. Isolation and identification of bacteria to improve the strength of concrete. **Microbiological Research**, v. 174, p. 48–55, 2015.

Lefever, G. *et al.* The influence of superabsorbent polymers and nanosilica on the hydration process and microstructure of cementitious mixtures. **Materials**, MDPI AG, v. 13, p. 1–16, 11 2020. ISSN 19961944.

Lefever, G.; Okude, N.; Shiotani, T. Evaluation of self-healing by a combination of ultrasonic measurements and 3d numerical simulations. **Developments in the Built Environment**, Elsevier Ltd, v. 16, 2023. ISSN 26661659 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85178919083&doi=10.1016%2fdibe.2023.100268&partnerID=40&md5=a9d399a4bcdcf2992df81b87fc201953>>.

Lefever, G. *et al.* Evaluation of the self-healing ability of mortar mixtures containing superabsorbent polymers and nanosilica. **MATERIALS**, v. 13, 2020. ISSN 1996-1944.

Litina, C. *et al.* Evaluation of methodologies for assessing self-healing performance of concrete with mineral expansive agents: An interlaboratory study. **MATERIALS**, v. 14, 2021. ISSN 1996-1944.

Luo, J. *et al.* Interactions of fungi with concrete: Significant importance for bio-based self-healing concrete. **CONSTRUCTION AND BUILDING MATERIALS**, v. 164, p. 275–285, 2018. ISSN 0950-0618.

Mauludin, L. M. *et al.* Enhancing performance of high-strength concrete using bacillus megaterium as self-healing agent. **International Journal of GEOMATE**, GEOMATE International Society, v. 26, p. 68–75, 2024. ISSN 21862982 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85189675392&doi=10.21660%2f2024.114.4290&partnerID=40&md5=a820c4596968d1ad6e7dd0c853d2abef>>.

Medeiros, J. M. P.; Sarno, L. D. Low carbon bacterial self-healing concrete. **BUILDINGS**, v. 12, 2022. ISSN 2075-5309.

Medeiros, J. M. P.; Sarno, L. D. Cracking methods for testing of self-healing concrete: An experimental approach. **Buildings**, Multidisciplinary Digital Publishing Institute (MDPI), v. 14, 2024. ISSN 20755309 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85197280568&doi=10.3390%2fbuildings14061744&partnerID=40&md5=0d55e63089f9ac24f5871eab0858a151>>.

Menon, R. R. *et al.* Screening of fungi for potential application of self-healing concrete. **SCIENTIFIC REPORTS**, NATURE PORTFOLIO, v. 9, 2 2019. ISSN 2045-2322.

Metwally, G. A. M.; Mahdy, M.; El-raheem, A. H. A. Performance of bio concrete by using bacillus pasteurii bacteria. **CIVIL ENGINEERING JOURNAL-TEHRAN**, v. 6, p. 1443–1456, 2020. ISSN 2676-6957.

Mignon, A. *et al.* Superabsorbent polymers: A review on the characteristics and applications of synthetic, polysaccharide-based, semi-synthetic and ‘smart’ derivatives. **EUROPEAN POLYMER JOURNAL**, PERGAMON-ELSEVIER SCIENCE LTD, v. 117, p. 165–178, 8 2019. ISSN 0014-3057.

Mignon, A. *et al.* Characterization of methacrylated alginate and acrylic monomers as versatile saps. **Carbohydrate Polymers**, Elsevier Ltd, v. 168, p. 44–51, 7 2017. ISSN 01448617.

Monte, F. L.; Ferrara, L. Self-healing characterization of uhpfrcc with crystalline admixture: Experimental assessment via multi-test/multi-parameter approach. **Construction and Building Materials**, Elsevier Ltd, v. 283, 2021. ISSN 09500618 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85101828615&doi=10.1016%2fj.conbuildmat.2021.122579&partnerID=40&md5=521a6d5b94617da30548d210f22d3c93>>.

Mousavi, S. S. *et al.* Application of superabsorbent polymer as self-healing agent in self-consolidating concrete for mitigating precracking phenomenon at the rebar-concrete interface. **Journal of Materials in Civil Engineering**, American Society of Civil Engineers (ASCE), v. 33, 2021. ISSN 08991561 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85111269897&doi=10.1061%2f%28ASCE%29MT.1943-5533.0003881&partnerID=40&md5=e010926c3ea2fee12af4925f017ee488>>.

Nielsen, S. *et al.* Optical sensing of ph and o₂ in the evaluation of bioactive self-healing cement. **ACS Omega**, v. 4, p. 20237–20243, 2019.

Nindhita, K. W.; Zaki, A.; Zeyad, A. M. Effect of bacillus subtilis bacteria on the mechanical properties of corroded self-healing concrete. **FRATTURA ED INTEGRITÀ STRUTTURALE-FRACTURE AND STRUCTURAL INTEGRITY**, p. 140–158, 2024. ISSN 1971-8993.

Onyelowe, K. C. *et al.* Modeling the influence of bacteria concentration on the mechanical properties of self-healing concrete (shc) for sustainable bio-concrete structures. **SCIENTIFIC REPORTS, NATURE PORTFOLIO**, v. 14, 4 2024. ISSN 2045-2322.

Orozco, C. R.; Urbino, I. J. A. Self-healing of cracks in concrete using bacillus cibi with different encapsulation techniques. **Journal of Engineering and Technological Sciences**, Institute for Research and Community Services, Institut Teknologi Bandung, v. 54, 2022. ISSN 23375779 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85132575513&doi=10.5614%2fj.eng.technol.sci.2022.54.3.5&partnerID=40&md5=fd480f1cf6726257643d4044c631c61d>>.

Park, B.; Choi, Y. C. Self-healing products of cement pastes with supplementary cementitious materials, calcium sulfoaluminate and crystalline admixtures. **MATERIALS**, v. 14, 2021. ISSN 1996-1944.

Pelto, J. *et al.* Application of encapsulated superabsorbent polymers in cementitious materials for stimulated autogenous healing. **Smart Materials and Structures**, Institute of Physics Publishing, v. 26, 9 2017. ISSN 1361665X.

Reeksting, B. J. *et al.* In-depth profiling of calcite precipitation by environmental bacteria reveals fundamental mechanistic differences with relevance to application. **APPLIED AND ENVIRONMENTAL MICROBIOLOGY**, AMER SOC MICROBIOLOGY, v. 86, 4 2020. ISSN 0099-2240.

Reyad, A. M.; Mokhtar, G. Impact of the immobilized *bacillus cereus* mg708176 on the characteristics of the bio-based self-healing concrete. **SCIENTIFIC REPORTS, NATURE PORTFOLIO**, v. 13, 1 2023. ISSN 2045-2322.

Risdanareni, P. *et al.* Alkali activated lightweight aggregate as bacterial carrier in manufacturing self-healing mortar. **Construction and Building Materials**, Elsevier Ltd, v. 368, 2023. ISSN 09500618 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85146297476&doi=10.1016%2fj.conbuildmat.2023.130375&partnerID=40&md5=556504abf67eb80385355e96d879951e>>.

Rodríguez, C. R. *et al.* Chemo-physico-mechanical properties of the interface zone between bacterial pla self-healing capsules and cement paste. **CEMENT AND CONCRETE RESEARCH**, v. 138, 2020. ISSN 0008-8846.

Rooij, M. R. *et al.* **Self-Healing Phenomena in Cement-Based Materials**. [S.l.]: Springer Netherlands, 2013. v. 11. ISBN 978-94-007-6623-5.

Shahid, K. A.; Jaafar, M. F. M.; Yahaya, F. M. Self-healing behaviour of pre-cracked pofa-concretes in different curing conditions. **Journal of Mechanical Engineering and Sciences**, Universiti Malaysia Pahang, v. 7, p. 1227–1235, 2014. ISSN 22894659 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-84937002361&doi=10.15282%2fjmes.7.2014.22.0120&partnerID=40&md5=b1bd283e264849f6541b5ba71a798b22>>.

Shetiya, R. K. *et al.* Investigation into the effects of crystalline admixtures and coatings on the properties of self-healing concrete. **MATERIALS**, v. 17, 2024. ISSN 1996-1944.

Silva, F. *et al.* Industrial application of biological self-healing concrete: Challenges and economical feasibility. **Journal of Commercial Biotechnology**, v. 21, p. 31–38, 2015.

Snoeck, D. Superabsorbent polymers to seal and heal cracks in cementitious materials. **RILEM Technical Letters**, RILEM Publications SARL, v. 3, p. 32–38, 7 2018. ISSN 25180231.

Snoeck, D.; Belie, N. D. Repeated autogenous healing in strain-hardening cementitious composites by using superabsorbent polymers. 2015.

Snoeck, D.; Belie, N. D. Autogenous healing in strain-hardening cementitious materials with and without superabsorbent polymers: An 8-year study. **Frontiers in Materials**, Frontiers Media S.A., v. 6, 3 2019. ISSN 22968016.

Snoeck, D.; Debo, J.; Belie, N. D. Translucent self-healing cementitious materials using glass fibers and superabsorbent polymers. **Developments in the Built Environment**, Elsevier Ltd, v. 3, 8 2020. ISSN 26661659.

Snoeck, D. *et al.* Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers. **Journal of Intelligent Material Systems and Structures**, v. 25, p. 13–24, 1 2014. ISSN 1045389X.

Stanaszek-tomal, E. Bacterial concrete as a sustainable building material? **SUSTAINABILITY**, MDPI, v. 12, 1 2020.

Summa, D. D. *et al.* Environmental and economic sustainability of crack mitigation in reinforced concrete with superabsorbent polymers (saps). **Journal of Cleaner Production**, v. 358, 2022.

Tan, L. *et al.* Aerobic non-ureolytic bacteria-based self-healing cementitious composites: a novel approach without added calcium precursor. **Engineering Research Express**, Institute of Physics, v. 5, 2023. ISSN 26318695 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85165215869&doi=10.1088%2f2631-8695%2face298&partnerID=40&md5=d9c6c4584a7af62e2e717728f060dc3f>>.

Tittelboom, K. V.; Belie, N. D. Self-healing in cementitious materials-a review. **Materials**, v. 6, p. 2182–2217, 2013. ISSN 19961944.

Tittelboom, K. V. *et al.* Influence of mix composition on the extent of autogenous crack healing by continued hydration or calcium carbonate formation. **Construction and Building Materials**, Elsevier, v. 37, p. 349–359, 12 2012. ISSN 09500618. Disponível em: <<https://www.sciencedirect.com/science/article/abs/pii/S0950061812004953>>.

Uguzzoni, A. M. P. *et al.* Concrete self-healing for sustainable buildings: A focus on the economic evaluation from a life-cycle perspective. **SUSTAINABILITY**, MDPI, v. 15, 9 2023.

Veliyev, E. F.; V, G. A. Laboratory analysis of self-healing cement composition based on calcium lactate and bacteria. **SOCAR PROCEEDINGS**, STATE OIL CO AZERBAIJAN REPUBLIC, OIL GAS SCIENTIFIC RESEARCH PROJECT INST, p. 102–107, 2023. ISSN 2218-6867.

Vermeer, C. M. *et al.* From waste to self-healing concrete: A proof-of-concept of a new application for polyhydroxyalkanoate. **Resources, Conservation and Recycling**, Elsevier B.V., v. 164, 1 2021. ISSN 18790658.

Wan, Z. *et al.* Mechanical properties and healing efficiency of 3d-printed abs vascular based self-healing cementitious composite: Experiments and modelling. **Engineering Fracture Mechanics**, Elsevier Ltd, v. 267, 2022. ISSN 00137944 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85128302609&doi=10.1016%2fj.engfracmech.2022.108471&partnerID=40&md5=4204ca796aa463cbe06c0ce0bea02390>>.

Wan, Z. *et al.* Direct ink writing of vascularized self-healing cementitious composites. **CEMENT & CONCRETE COMPOSITES**, v. 144, 2023. ISSN 0958-9465.

Wang, X. *et al.* Effect of fly ash on the self-healing capability of cementitious materials with crystalline admixture under different conditions. **AIP Advances**, v. 11, 2021.

Wu, S. *et al.* Sustainable high-ductility concrete with rapid self-healing characteristic by adding magnesium oxide and superabsorbent polymer. **Advances in Materials Science and Engineering**, Hindawi Limited, v. 2020, 2020. ISSN 16878434 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85079212334&doi=10.1155%2f2020%2f5395602&partnerID=40&md5=757a502f16c26f26257a78a783d7b289>>.

Wylick, A. V. *et al.* Encapsulation of *trichoderma reesei* and *neurospora crassa* in calcium alginate capsules for fungi-mediated self-healing concrete: An explorative study on the protocol, survival of the organisms and CaCO_3 biomineralization. **DEVELOPMENTS IN THE BUILT ENVIRONMENT**, v. 18, 2024–2. ISSN 2666-1659.

Wylick, A. V. *et al.* Conditions for CaCO_3 biomineralization by *trichoderma reesei* with the perspective of developing fungi-mediated self-healing concrete. **GLOBAL CHALLENGES**, WILEY-VCH VERLAG GMBH, v. 8, 1 2024.

Xu, H. Y. *et al.* Self-healing concrete using rubber particles to immobilize bacterial spores. **MATERIALS**, v. 12, 2019. ISSN 1996-1944.

Yan, Y. F. *et al.* Application of expanded perlite immobilized microorganisms in cementitious materials. **JOURNAL OF BUILDING ENGINEERING**, v. 76, 2023. ISSN 2352-7102.

Yuan, X. Z. *et al.* Predicting the crack width of the engineered cementitious materials via standard machine learning algorithms. **JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY-JMR&T**, v. 24, p. 6187–6200, 2023. ISSN 2238-7854.

Zaerkabeh, R. *et al.* Crack healing and mechanical properties of bacteria-based self-healing cement mortar. **Periodica Polytechnica Civil Engineering**, Budapest University of Technology and Economics, v. 66, p. 581–592, 2022. ISSN 05536626 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85128419624&doi=10.3311%2fPPci.18803&partnerID=40&md5=11a2e6cfb330eaf7fddbe956ffb4f1f5>>.

Zhang, G.-Z.; Ma, X.; Liu, Y. Study on the synergistic effect of superabsorbent polymer and crystalline admixture on self-healing performance of mortar based on image binarization method. **Buildings**, Multidisciplinary Digital Publishing Institute (MDPI), v. 13, 2023. ISSN 20755309 (ISSN). Disponível em: <<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85180365569&doi=10.3390%2fbuildings13122953&partnerID=40&md5=5e3a2f37372cccb32c8df12660b6cbc5>>.

Zhang, X. *et al.* Study on the behaviors of fungi-concrete surface interactions and theoretical assessment of its potentials for durable concrete with fungal-mediated self-healing. **Journal of Cleaner Production**, v. 292, 2021. ISSN 09596526 (ISSN).

Ziegler, F. *et al.* Evaluation of internal and superficial self-healing of cracks in concrete with crystalline admixtures. **MATERIALS**, v. 13, 2020. ISSN 1996-1944.

Žáková, H.; Pazderka, J.; Reiterman, P. Textile reinforced concrete in combination with improved self-healing ability caused by crystalline admixture. **Materials**, v. 13, p. 1–18, 2020.