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Durability Assessment of Self-Healing Concrete Incorporating Microcapsules and Microorganisms: A Novel Approach for Sustainable Infrastructure

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Abstract

The durability of reinforced concrete structures is heavily reliant on the integrity of the concrete, which serves as a protective barrier against environmental factors. Concrete, being a brittle material, is susceptible to cracking. This can lead to the infiltration of detrimental agents into the structure, resulting in early deterioration. The incorporation of microcapsules containing chemical healing agents into concrete materials for self-healing purposes, as well as the utilization of shape memory alloys (SMAs) as reinforcement in concrete structures to self-close cracks, are advanced techniques that have significant potential to improve the durability of concrete infrastructure. This work combines both strategies as an alternative to achieve greater self-healing of cracks in concrete materials, thus preventing early deterioration of structures. This research aimed to investigate the effectiveness and long-term durability of self-healing concrete systems that utilize microcapsules containing healing agents or microorganisms to autonomously repair cracks and enhance the service life of concrete structures. The different approaches taken by different studies to evaluate the self-healing concrete's performance lead to a lack of standardization, which poses a serious obstacle to the widespread practical use of this technology. These restrictions offer a chance for mathematical modeling, which could accelerate the development of self-healing systems. Ultimately, in order to expand the widespread application of self-healing concrete in next building projects, efforts should be undertaken to address and minimize the aforementioned constraints.

Keywords: self-healing, healing agent, durability, cracks, early deterioration

1- Introduction

1.1. Research Background

Concrete is a very adaptable and important product in the present era of ongoing urbanization (Palanisamy et al., 2020). While typical concrete structures can have a lifespan of 50 years or more (Sangadji, 2017), they are prone to problems such as settling, thermal cracking, corrosion cracking, premature drying, and other circumstances (Jena et al., 2020; Yoo et al., 2019). The formation of these cracks can create a cohesive network, leading to heightened permeability of the concrete. The severity of cracks may vary between different structures. Reinforced concrete constructions primarily rely on reinforcing to control the size of allowable cracks. Typically, the permissible crack width is 0.3 mm (Roig-Flores et al., 2015). While these fissures may not compromise the structural integrity, they do diminish the durability of the concrete, making it susceptible to moisture and chemical-induced corrosion of the steel reinforcement, ultimately resulting in structural collapse (Jena et al., 2020; Lee et al., 2014; Park, R., & Paulay, T., 1991). Annually, a substantial global budget is allocated for the restoration of existing concrete structures. On the one hand, the production costs of concrete range from $60 to $80 per cubic meter. On the other hand, the costs associated with maintenance and repairs increase significantly to $147 per cubic meter (Danish et al., 2020). Conventional crack repair techniques that include the use of synthetic healing agents such as resin and epoxy have several limitations. These include short-term effectiveness, environmental concerns, high cost, time-consuming procedures, and the need for professional supervision (Mignon et al., 2017; Chahal et al., 2012). Furthermore, these agents possess the capability to repair an external fracture, but they lack the ability to fix internal damage or micro-cracks (Verma et al., 2021).

According to a study, a significant portion of the repairs in certain construction projects deteriorate over time. Specifically, 20% of the repairs deteriorate during a 5-year period, while 55% deteriorate within a 10-year period. This indicates that the solution is not sustainable (Al-Tabbaa et al., 2019). The estimated annual cost of maintaining and repairing concrete structures worldwide is projected to reach $147 per cubic meter (Danish et al., 2020). Consequently, there has been a significant rise in spending on maintenance and repairs, leading to a reallocation of resources away from new construction projects (Li, V. C., & Herbert, E., 2012). In addition, structural maintenance not only results in capital loss but also affects operational effectiveness, with anticipated consequences that might be tenfold the expense of building a new structure in the United States (Freyermuth, 2001).

In addition, the construction industry contributes to its carbon footprint through the extraction of aggregates and the production of cement (Akhtar, A., & Sarmah, A. K., 2018; Tam et al., 2016). Construction waste accounts for 59% of the global waste, of which 40% is disposed of in landfills (Gopinath, 2020; Tam et al., 2019; Gupta et al., 2018; Osmani, 2011). Nevertheless, the implementation of strict environmental laws has resulted in a decrease in landfill utilization to 65% (Hao, et al., 2008). As a result, researchers are now focusing on finding solutions to the waste disposal problem and preserving natural resources (Evangelista et al., 2019; Blengini, G. A., & Garbarino, E., 2010; Marie, I., & Quiasrawi, H., 2012; Weil et al., 2006).

1.2. Research Problem

While microencapsulation has potential as a technology to improve the durability of concrete, the use of microencapsulation for applying healing agents to self-healing cementitious materials is still in the early stages of development. Several healing agents have been examined in recent years, such as sodium silicate, polyurethane, epoxy, cyanoacrylates, and bacterial spores (Wang et al. 2014; Li et al. 2013; Huang & Ye 2011; Pelletier et al. 2011; Maes et al. 2014; Van Tittelboom et al. 2011).

Yang et al. (2011) have also examined dual-component, self-healing systems that comprise a healing agent and a catalyzer, such as methylmethacrylate monomer and triethylborane. However, although several tactics were effective in improving the ability of cementitious materials to enhance self-healing, a significant number of these healing agents are costly and/or necessitate a catalyst to initiate the self-healing mechanism. Currently, numerous compounds are readily accessible and possess the potential for self-healing applications but have not yet been investigated.

The effectiveness of achieving robust self-healing via a microencapsulation method depends largely on how the healing agent interacts with concrete to generate healing substances when cracks occur. The healing mechanism will determine the crack healing efficiency over time, as well as the sort of healing products generated, hence determining the reliability and quality of healing. In addition, the healing mechanism will ascertain the existing constraints of self-healing, such as reliance on ambient circumstances, microcapsule dosage, and crack breadth. Examining healing mechanisms is of tremendous significance due to the potential to optimize self-healing methods and provide conditions for correct execution.

1.3. Aim & objectives

This research aimed to investigate the effectiveness and long-term durability of self-healing concrete systems that utilize microcapsules containing healing agents or microorganisms to autonomously repair cracks and enhance the service life of concrete structures by means of the following objectives:

- Measure of healing efficiency of unreinforced mortar specimens with microcapsules
- Healing products characterization of unreinforced mortar specimens with microcapsules.
- Evaluation of crack size, microcapsules dosage, and environmental conditions for self-healing of unreinforced mortar specimens with microcapsules.

1.4. Research Significance

The significance of the research resides in its capacity to substantially enhance the durability and sustainability of concrete infrastructure. Concrete is the predominant construction material globally, however, it is prone to cracking and deterioration as it ages, necessitating expensive repairs and upkeep. Self-healing concrete systems provide a viable way to address these problems by automatically fixing cracks and prolonging the lifespan of concrete structures.

The integration of microcapsules containing therapeutic substances or microorganisms into concrete signifies an innovative method for self-repair technology. This research aims to enhance the resilience and sustainability of infrastructure by examining the efficacy and long-term robustness of self-healing concrete structures. This is especially crucial in light of the growing urbanization and the requirement for resilient infrastructure capable of enduring the difficulties posed by climate change and aging.

Moreover, the findings also hold wider ramifications for the construction sector and society at large. The advancement of self-healing concrete systems has the potential to save maintenance expenses, prolong the lifespan of structures, and eventually contribute to a more environmentally friendly built environment. This has the capacity to not only advantage the construction sector but also the economy, the environment, and public safety.

Because self-healing concrete that incorporates microcapsules and microorganisms has the potential to transform the way concrete infrastructure completely is designed and maintained, research on how durable it is is extremely important. This research has the potential to enhance the development of more durable and environmentally-friendly constructed environments, benefiting society in several ways by tackling the challenges of cracking and deterioration.

2- Literature Review

2.1. Causes of structure damage/deterioration

Concrete is extensively utilized in the building industry worldwide because of its remarkable compressive strength (CS), affordability, cost-effectiveness, abundance of raw resources, and durability (Huseien et al., 2022; Luhar et al., 2022). Nevertheless, concrete is highly susceptible to cracking and various forms of damage, such as degradation and deterioration. This vulnerability enables the infiltration of highly hazardous substances, including acid rain, salts, and other corrosive components, into the structure (de Souza Lima, E. H., & Carneiro, A. M. P., 2022).

Understanding the impact of cracking is crucial due to its high frequency as a cause of structural damage and degradation. Figure 1 presents the primary results of Gardner et al.'s (2018) market research on the prevalent problems encountered in structures (both old and new construction) in projects where respondents had a work experience of over five years. Cracking is a prevalent cause of structure damage and deterioration, as demonstrated in Figure 1(a). It is a matter of concern for designers, contractors, and clients. Furthermore, as depicted in Figure 1(b), bridges, irrespective of their age, were found to be especially susceptible and were characterized as a type of structure that frequently necessitated maintenance.

Structures built in the 1960s and 1970s were susceptible to damage due to possible shortcomings in design codes and workmanship during their construction. Subterranean constructions were also considered to be particularly susceptible. These results may have been impacted by the presence of hidden damage within buried structures. Furthermore, additional types of structures that were deemed susceptible to damage encompassed parking facilities, tunnels, underground structures, and structures designed to store water (Gardner et al., 2018).

Danish et al. (2020) identified plastic shrinkage, formwork movement, and plastic settlements as the primary causes of cracking in the Plastic state. In the Hardened state, detailing errors, chemical reaction external overloading, and thermal stress were found to be the most probable causes of cracking.

While concrete cracks may not have an immediate impact on concrete structures, they can lead to significant long-term repercussions (Bernard, 2023). Annually, a significant amount of funds is allocated for the rehabilitation of existing concrete structures worldwide. Aside from the actual costs of producing concrete, which range from $60 to $80 per cubic meter, an additional $147 per cubic meter is necessary for maintenance and repair. A survey conducted by the American Society of Civil Engineers (ASCE) reveals that the United States and Asian countries will collectively need approximately $22 trillion and $20 trillion for structural repairs in the next five years (Danish et al., 2020). Despite the significant amount of money invested, the majority of repair cases have minimal impact on prolonging the lifespan of a structure. Structural deterioration adversely affects a nation's economic, social fabric, and natural environment.

To address the issue of cracking and escalating structural damage, researchers devised a technique called self-healing to mitigate the deterioration of concrete structures. Researchers have been exploring various methods to include self-healing properties into concrete since its initial observation in 1836 (Kanellopoulos, A., & Norambuena-Contreras, J., 2022; Hearn, N., & Morley, C. T., 1997).

Conventional repair and maintenance are important methods to prolong the lifespan of concrete structures. Nevertheless, the expense associated with manual maintenance can be excessively burdensome for extensive infrastructures. Furthermore, repairing cracked buildings may be challenging or even unfeasible, taking into account factors such as the specific position and size of the fracture, as well as the continuous maintenance needs of critical infrastructure like highways and tunnels. In such circumstances, self-healing concrete is expected to provide a highly beneficial function by autonomously and promptly

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repairing cracks, without the need for any external intervention (Wu et al., 2012). Concrete, being an open composite structure, allows for the easy integration of various modifying elements such as polymers, fiber fillers, and powder fillers. Many of these compounds have been demonstrated to effectively enable concrete to self-heal or self-repair (Choi et al., 2018).

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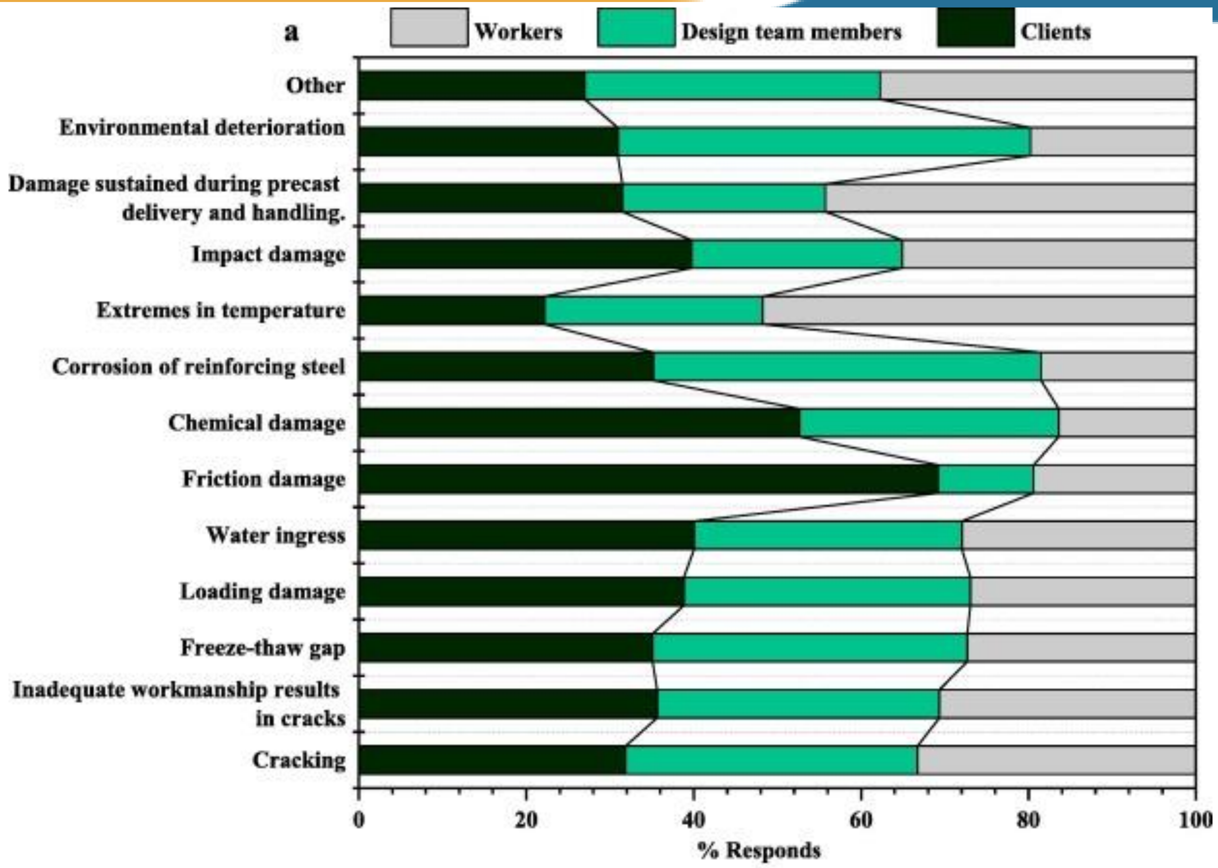

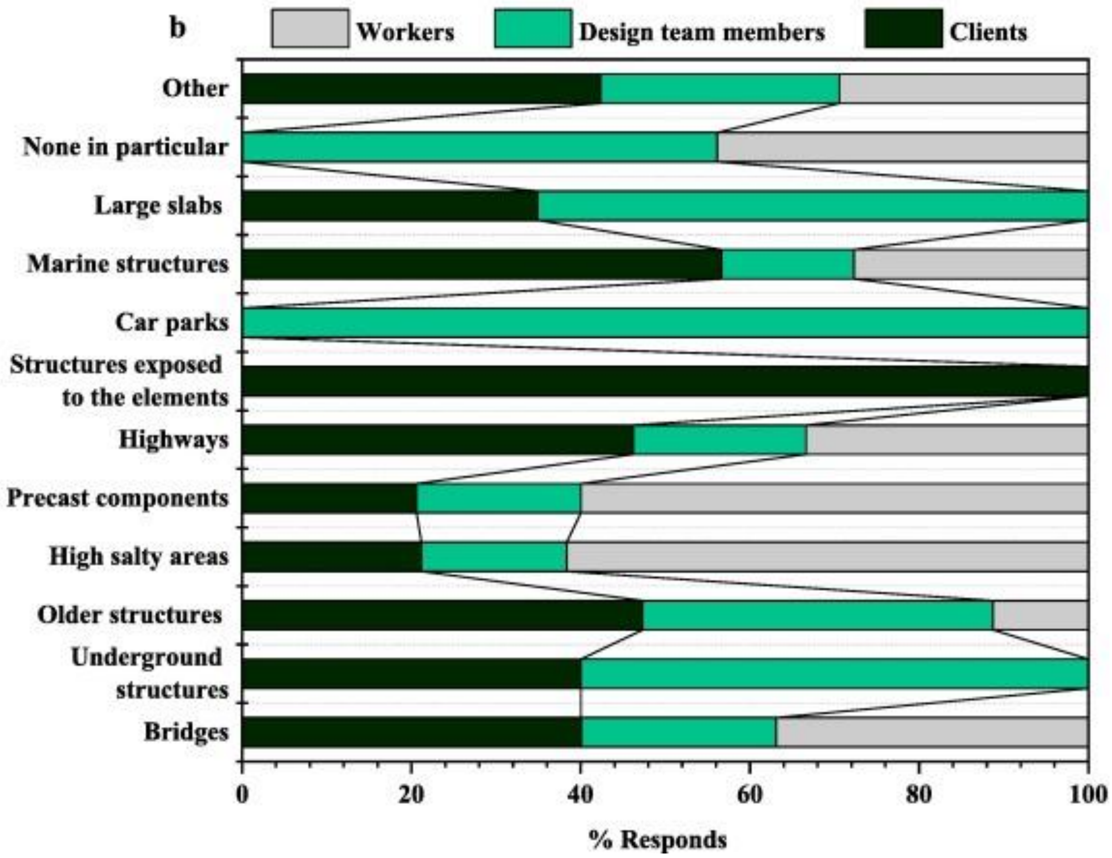

Figure 1: (a) A multitude of factors have a role in the deterioration of concrete structures. (b) prone to damage concrete structures

2.2. Concrete Self-Healing Techniques

Conventional concrete remediation methods are both time-consuming and environmentally detrimental. Bacterial concrete, a sustainable option, is receiving increasing interest due to its potential to continually refit and enhance the longevity of concrete (Ariyanti, et al., 2023). Implementing calcite precipitation using bacteria on concrete prior to the occurrence of fractures has the potential to be cost-effective and efficient in terms of resources (Zhao, et al., 2022). Bacterial-mediated self-healing decreases maintenance expenses and prolongs the lifespan of concrete buildings (Khushnood, et al., 2020). Moreover, developing a self-healing system can decrease the amount of resources needed for concrete manufacturing and minimize the waste generated by demolitions by extending the lifespan of current structures (Khushnood, et al., 2020).

Extending the lifespan of the structure has an indirect effect on reducing carbon emissions by reducing the need for construction materials (Ariyanti et al., 2023; Song et al., 2021). To overcome the constraints of standard crack care, it is necessary to investigate repair procedures that are both cost-effective and environmentally friendly. This has resulted in a shift from traditional approaches to sophisticated concrete self-healing techniques, offering a promising solution to effectively address these challenges (figure 2).

Autogenous healing facilitates concrete self-healing. Autogenous healing occurs when unhydrated cement particles chemically react with external water, resulting in the filling of fissures. On the other hand, autonomous healing involves the use of artificial techniques, such as the addition of chemical substances such as crystalline admixtures, polymers, and fibers, or the utilization of biological mechanisms including alkaliphile bacteria. Out of all the self-healing strategies, the bacterial-based approach has demonstrated the most encouraging outcomes because of its long-lasting efficacy (Mondal, S., & Ghosh, A., 2017; Roig-Flores et al., 2015; Wang et al., 2014).

The bacteria's continued efficiency is due to its capacity to produce protracted fracture repair by transforming vegetative bacterial cells into spores, guaranteeing vitality for more than 200 years (Vijay, K., & Murmu, M., 2019; Jonkers et al., 2010). The presence of water in a fresh fracture triggers the activation of dormant bacteria, leading to their multiplication and the subsequent precipitation of minerals like calcite ($CaCO_3$). This mineral deposition ultimately results in the healing of the fissure. After the crack has fully healed, the bacteria enter a state of hibernation. If a fracture develops in the future, the bacteria will become active once more and proceed to fill the crack. Therefore, bacteria function as a durable curative agent, a process usually known as microbially induced calcium carbonate precipitation (MICP). Consequently, the infiltration of corrosive chemicals, moisture, and other external factors into the concrete is greatly diminished.

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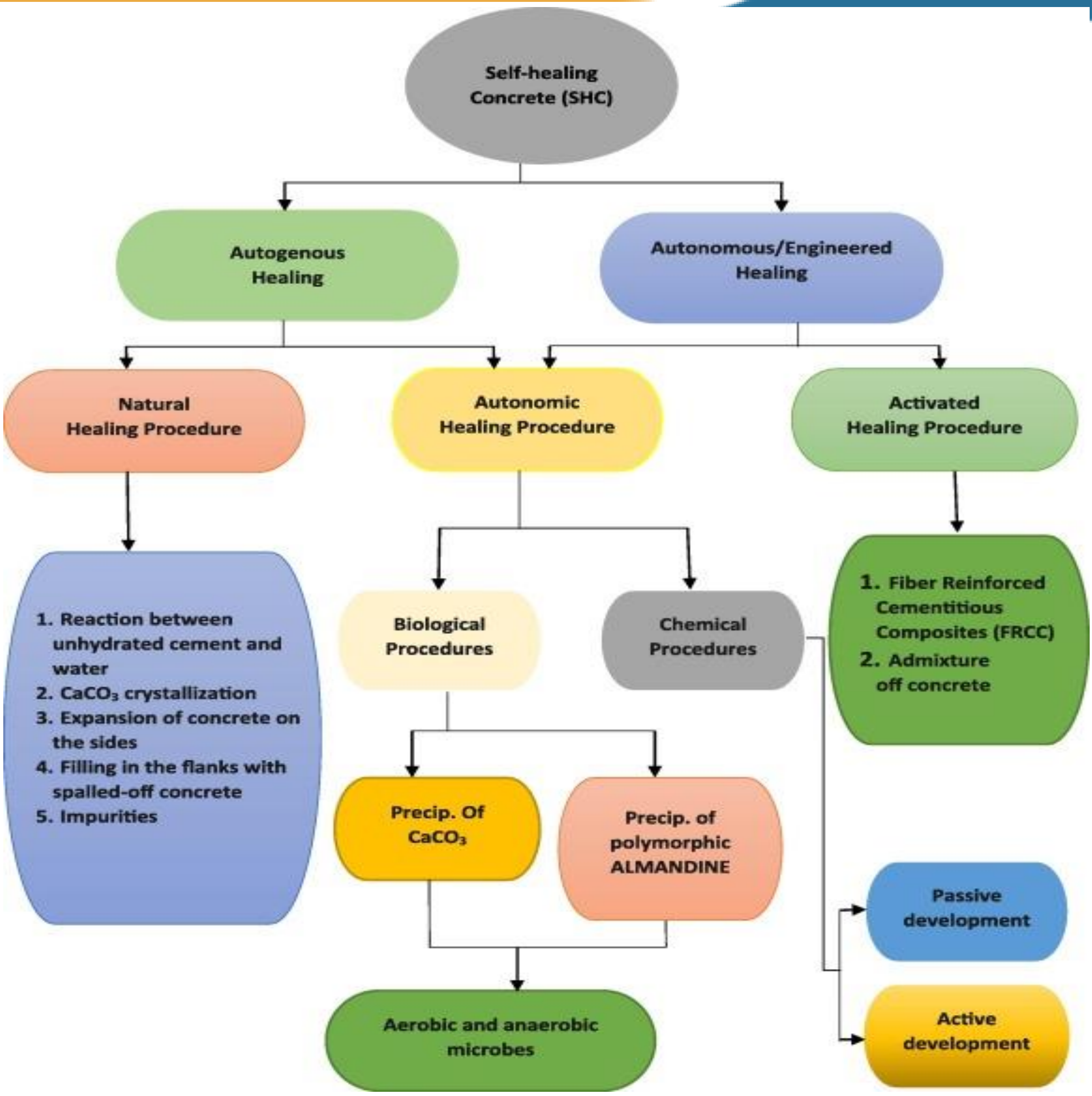

Figure 2: Self-healing processes are set up in an orderly manner.

In a study conducted by Bang et al. (2001), the researchers examined the use of S. pasteurii in microbial concrete. They discovered that the bacteria caused the formation of calcium carbonate by breaking down uric acid or urea. This process helped in repairing cracks in the concrete. Subsequently, numerous comprehensive investigations conducted by a range of researchers have analyzed different facets concerning the characteristics of microbial concrete in both its fresh and hardened states.

Incorporating different strains of bacteria, such as Bacillus aerius, Bacillus subtilis, Bacillus acetophenoni, Bacillus odysesyi, and Sporosarcina pasteurii, led to significant enhancements in splitting tensile strength, flexural strength, and compressive strength. These improvements reached up to 35.2%, 29.1%, and 17.8% respectively, compared to conventional concrete after 28 days. Consequently, microbial self-healing concrete technology has emerged as a prominent area of research in recent years. Its objectives include minimizing repair expenses, mitigating environmental harm, enhancing the durability of concrete, and improving concrete qualities (de Brito, J., & Kurda, R., 2021; Jena et al., 2020; El-Newihy et al., 2018).

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The self-healing process, which is of biological origin, can be affected by a range of biotic and abiotic variables (Wong, 2015). Important biological parameters that influence bacterial development include the quantity, age, and physiological condition of bacterial cells. These characteristics are influenced by environmental circumstances such as temperature and pH (Bundur et al., 2017). With the exception of spore-forming bacteria, the majority of bacteria necessitate suitable pH and temperature conditions in order to survive. Under environmental conditions characterized by a pH level exceeding 12, bacteria are only able to exist in a dormant state known as a spore, and are unable to reproduce (Khodadadi Tirkolaei, H., & Bilsel, H., 2017).

The pH of standard concrete typically ranges from 12 to 13 (Nguyen et al., 2019). However, during concrete mixing, the pH can rise to 13 at a temperature of 90 °C due to the exothermic process of cement hydration. This increase in pH has the potential to affect the survival of bacteria and the availability of nutrients (Kim et al., 2020; Nguyen et al., 2019; Wang et al., 2017). Furthermore, several bacteria display diverse development strategies at distinct temperatures. Bacillus sphaericus has optimal growth at temperatures ranging from 35 to 37 °C, but Streptococcus pasteurii and Streptococcus saprophyticus flourish at a temperature of 30 °C. The precipitation rate of $CaCO_3$ is markedly reduced at 50 °C compared to the ideal temperature of 30 °C (Kim et al., 2020).

The growth rate of B. sphaericus is reduced at 10 °C in comparison to 28 °C (Wang et al., 2017). On the contrary, B. cercus exhibits enhanced growth at temperatures of 10, 28, and 40 °C (Wu et al., 2019). Therefore, it is clear that bacterial growth and the rate of $CaCO_3$ precipitation decrease at temperatures above 40 °C, emphasizing the crucial influence of temperature for bacterial survival. However, the research has mostly concentrated on traditional methods of cultivating bacteria, disregarding aspects that may impact bacterial growth, survival, and the speed of microbial calcium carbonate formation. Hence, additional comprehension is required to properly grasp the influence of pH and temperature on bacterial survival and efficacy.

Aside from environmental variables, preserving microorganisms in concrete to counter their limited lifespan necessitates the use of several implementation strategies. Enhancing the efficacy of self-healing bacteria poses a significant obstacle, which can be tackled through two viable methods: incorporation directly or encapsulation. The effectiveness of encapsulation has been demonstrated, particularly due to the alkaline nature and temperature of concrete. Nevertheless, pH levels over 12 can reduce bacterial efficacy and the process of concrete hydration may result in a decrease in the number of bacterial cells (Jonkers et al., 2010). Extended contact to an alkaline environment may also reduce bacterial germination. In order to surmount these obstacles, carrier technology takes a leading position. When Bacillus alkaliphilic is introduced directly into concrete, a significant mortality rate of 90% is seen within a month (Jonkers et al., 2010).

It is crucial to investigate carrier technologies, including zeolite, ceramsite, hydrogel, microcapsules, and lightweight aggregates (Jonkers et al., 2010). Furthermore, specific methods may lead to an unequal dispersion of self-healing substances as a result of a reduced concentration of carriers in comparison to cement paste. It is crucial to ensure the mechanical robustness of the capsule in order to endure internal forces during concrete mixing, which is essential for the successful integration of the self-healing concrete system. An in-depth examination of various implementation strategies and their impact on self-healing yields significant knowledge for improving the bacteria's capacity to heal cracks.

Another challenge in concrete is its inherent brittleness and limited tensile strength, resulting in a propensity for high tensile cracking. It is crucial to improve the tensile strength of concrete in order to prevent cracking and to prevent the steel reinforcement from rusting and deteriorating. In their study, Durga et al. (2020) discovered that by adding B. subtilis to concrete at a concentration of 108 cells/ml and a water-cement ratio of 0.41, the splitting tensile strength of the concrete rose by up to 16% after 28 days of crack curing, compared to the control concrete. In a similar manner, the inclusion of B. sphaericus resulted in a 13.75% increase in the splitting tensile strength of concrete after 3 days, a 14.28% increase after 7 days, and an 18.35% increase after 28 days (Su et al., 2021).

Gavimath et al. (2012) conducted a study that demonstrated the enhancement of splitting tensile strength in concrete by incorporating denitrifying bacteria into recycled coarse aggregate. This resulted in a significant increase of up to 24.1% within a 28-day period. Hence, enhancing the mechanical properties and crack-healing capacities of concrete can effectively alleviate the decrease in splitting tensile strength by minimizing the occurrence and spread of cracks.

Despite substantial research on the qualities and applicability of self-healing agents, there is currently no article accessible that offers a comprehensive assessment on the effectiveness and performance of past and present self-healing approaches in cementitious materials. This article examines methods of self-healing in concrete, focusing on their many types, qualities, effectiveness, and activation mechanisms. This work is based on unique self-healing technologies, including calcite-precipitating bacteria, microcapsules, and vascular networks that include healing agents and shape memory materials.

Initially, a multitude of methodologies for self-repair are examined and analyzed. Subsequently, this analysis delves into the substances utilized in contemporary research, their efficacy, and the advantages and disadvantages of different therapeutic agents, encapsulating methods, or microbiological strategies. Subsequently, a suggestion is made regarding the many trigger mechanisms that can be employed to initiate the process of self-healing.

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3- Materials and methods

3.1 Preparation and Characteristics of Microcapsules

Hassan et al. (2016) presented a method for microencapsulation and its optimization. The researchers chose urea-formaldehyde resin as the material for the microcapsule shell. They applied this resin using an in-situ polymerization technique during a water-in-oil emulsion chemical process. The control of encapsulation mechanisms was found to be dependent on several production parameters, including: (a) the temperature at which the emulsion is heated, (b) the choice and concentration of catalyst, (c) the allotted reaction time, (d) the agitation rate, (e) the water-oil ratio, and (f) the choice of core material (Hassan et al., 2016). SEM images of microcapsules synthesized at an agitation velocity of 800 rpm are shown in Figure (3).

The most favorable fabrication conditions were determined to be a temperature of 40°C for 1.5 hours, using 0.60 g of sulfonic acid as a catalyst. The agitation rates were tested at three different levels (450, 800, and 1500 rpm) to assess their impact on the sizes of the microcapsules, as presented in Table 1 (Milla et al., 2016).

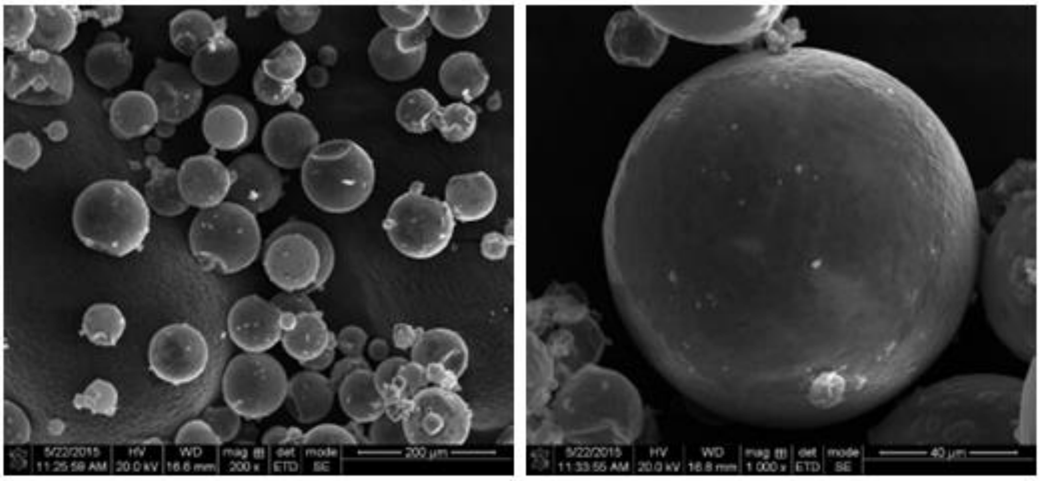

Figure 3: Secondary electron images were obtained for microcapsules synthesized with an agitation rate of 800 RPM.

Table 1: Impact of agitation rate on microcapsule size (Milla et al., 2016)

Agitation Rate (rpm)	Average Microcapsule Size (µm)
450	91.5
800	58.7
1500	45.2

3.2 Utilizing Calcium Nitrate as a Healing Agent

Calcium nitrate, which shares the same cations as C3S (tricalcium silicate) and C2S (dicalcium silicate),

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speeds up the process of hydration by promoting the formation of nuclei. This, in turn, enhances the crystallization of hydrates (Karagöl et al., 2013; Ramachandran, 1995). In the presence of calcium nitrate, calcium hydroxide can undergo a reaction to generate calcium hydroxynitrate. This compound is a double and basic salt that can serve as an initial structural framework for the formation of calcium hydrosilicates (Karagöl et al., 2013). The primary anticipated response of calcium nitrate is with cement particles that are not hydrated. However, it is crucial to observe that calcium ions (Ca2+) released by calcium nitrate in cracks can also aid in the formation of calcium carbonate by raising the saturation index Ω of calcite (Edvardsen, 1999). In accordance with these principles, calcium nitrate was employed as a therapeutic substance to fully utilize its capacity to interact with the cementitious matrix and enhance the self-healing process by promoting additional hydration and/or the formation of calcium carbonate on the surfaces of cracks when the healing agent is released.

It is noteworthy that the reaction between calcium nitrate and Portland cement has been examined by multiple researchers (Abdelrazig et al., 1999; Justnes, 1995; Justnes, 2003; Justnes, 2005; Ramachandran, 1995). However, a complete understanding of this reaction has not yet been achieved. Hence, it is crucial to build thermodynamic and kinetic models for the chemical reaction between calcium nitrate and Portland cement in order to gain a comprehensive understanding of the healing process and identify the optimal conditions for self-healing. Although the building of such models is quite complex, it provides the chance for more exploration.

3.3 Materials and Specimens

The study utilized cement mortar with a water to cement ratio (w/c) of 0.48, a common practice in Louisiana. The water to cement ratio was chosen to facilitate a comparative analysis with the findings of Milla et al. (2016). The mortar mixture was formulated using Type I Portland Cement, graded sand from Louisiana with a maximum particle size of 4.76 mm, tap water, and microcapsules. The specific ratios of the base mortar mix are outlined in Table 2(a). Five distinct mortar mixes were created with varying amounts of microcapsules, namely at dosages of 0 (control), 0.5, 0.85, 1.0, and 2.0% of the cement content by weight. The selection of microcapsule contents was based on previous research that demonstrated successful self-healing outcomes (Yang et al. 2011; Li et al. 2013; Gilford III et al. 2014; Wang et al. 2014; Milla et al. 2016).

Table 2: (a) Proportions for Mortar Mix (b) Factorial Experimental Test

(a)

Material Description	Proportions (kg/m³)
Sand, Denis Mills, LA	1375
Cement, Type I	500
Water	242
Water/Cement Ratio (W/C) = 0.48	

(b)

Specimen ID	Microcapsules Content (% of cement by weight)	Number of Specimens
1	0.5	6
2	0.85	6
3	1.0	6
4	2.0	6
Control	N/A	6

Additionally, the study conducted by Lv et al. (2014) focused on a probability model that examines the healing of ellipsoidal cracks in a self-healing matrix using spherical capsules. Similarly, Zemskov et al. (2011) analyzed analytical models that investigate the impact of cracks on encapsulated particles. These studies were reviewed to better understand how the dosage of microcapsules relates to the likelihood of capsule breakage.

Under the conditions typical for this study (with a microcapsule concentration of 2%), it was seen that the likelihood of a capsule being intercepted by a crack was close to 20% according to the model proposed by Yang et al. (2011), and roughly 82% and 87% according to the models proposed by Zemskov et al. (2011) Nevertheless, these models rely on geometrical probability and stereology, neglecting the influence of physical qualities of materials that greatly impact the likelihood of a fracture intersecting a microcapsule. Therefore, the probability predicted by these models will be a conservative approximation of the real probability, as fractures are more likely to form in the weakest areas of the material, specifically the microcapsule sites (Lv et al., 2014; Zemskov et al., 2011).

The specific compositions and samples created are presented in the experimental matrix outlined in Table 2(b). A total of six specimens were manufactured for each mortar mixture, with three specimens designated for exposure to air healing circumstances and the remaining three specimens designated for exposure to water healing conditions following the occurrence of cracks. The specimens were molded into prisms measuring 40 mm x 40 mm x 160 mm (as shown in Figure 4a). They were removed from the molds after 24 hours and then subjected to a 40-day curing process in a humid chamber with a temperature of 23 ± 2°C and a relative humidity exceeding 95%. Due to limitations in equipment availability, the curing process was extended to 40 days, preventing the conduction of three-point bending tests at the 28-day mark.

Figure 4: (a) Mortar Specimen with ID Number 3 containing 1% Microcapsules (b) Prepare Mortar Specimen

3.4. Self-Healing Mortar Testing

Prismatic mortar specimens measuring 40 mm x 40 mm x 160 mm were subjected to three point bending in order to create cracks. The crack width was regulated by applying a load at a controlled rate of 0.01 mm/min, ensuring that the test could be stopped immediately after reaching the maximum load to prevent abrupt failure. Regarding the control specimens, which exhibited extensive cracking, they demonstrated the maximum strength and were notably more fragile compared to the specimens containing microcapsules. It proved exceedingly challenging to induce cracking in these specimens without full failure occurring. To obtain the cracks, indirect tensile tests were conducted on cylindrical specimens measuring Ø5 x10 cm, which had the same mix design as the control prismatic specimens.

Light microscopy was employed to quantify the temporal progression of the healing process in cracked specimens. Varying magnification rates were employed for distinct crack diameters. The specimens were promptly inspected during breaking and subsequently underwent a 28-day healing phase in a controlled environment. Specimens were examined at intervals of 3, 7, 14, and 28 days during the healing phase. The width of each crack was assessed using digital image analysis. In addition, Environmental Scanning Electron Microscopy (ESEM) with Energy Dispersive Spectroscopy (EDS) was used to examine and describe the healing products after a 28-day healing period.

3.5 Environmental Conditioning for Self-Healing

In order to facilitate the process of self-repair following breaking, the test specimens were subjected to both air and water environments. The specimens that had been cured in air were subjected to a regulated temperature of 23 ± 2 °C and a relative humidity of 50 ± 4%. The water-cured specimens were immersed in tap water and maintained at a temperature of 23 ± 2°C. Hermetic vessels were employed to minimize carbonation resulting from the dissolution of CO_2 into the curative water, and the water was replenished on days 3, 7, 14, and 28 during the healing process.

3.6 Measurement and Characterization of Self-Healing Products

The quantification of healing products, which were generated throughout time, was performed using digital analysis of light microscopy pictures. The original area of each crack was measured prior to the commencement of the healing process. Subsequently, the area of healing was measured at two time points throughout the 14 and 28-day healing period. This was done to quantify the extent of self-healing by calculating the ratio of the healed area to the initial cracked area. Crack widths were measured for all specimens prior to healing. The Zeiss SteREO Lumar.V12 was the specific light microscope used for data collecting. Following a 28-day healing period, the specimens were dissected using a diamond blade saw to get the midspan section where cracks were intentionally created, as depicted in Figure 4 (b).

Two incisions were made, each one located approximately 15 mm away from the center of the beam, in order to remove a tiny portion of the specimen that contained the cracks. The specimens were studied immediately after being cut using an ESEM equipped with EDS to observe their morphology and investigate the chemical composition of the healing products. A plot displaying the atomic ratio and EDS maps were created as components of the EDS microanalysis. The specific instrument employed for this experiment was an FEI Quanta 3D Dual Beam SEM/FIB, which is an environmental scanning electron microscope.

4- Results and discussion

4.1. Determination of Healing Mechanism

As previously stated, a crucial element for the effectiveness of self-healing microencapsulation technology is the microcapsules' capacity to rupture when a fracture occurs, allowing the healing agent to be released and the crack to be filled by a capillarity process. Figure 5 displays a microscopic view of a fractured microcapsule discovered on the surface of a crack. This microcapsule was examined extensively during the inquiry. It is noteworthy that despite being damaged, the microcapsule maintained its spherical form, indicating its strength and resistance to the mixing process. Additionally, it exhibited a strong attachment to the fracture surface, indicating a sufficient connection between the cementitious matrix and the microcapsule surface.

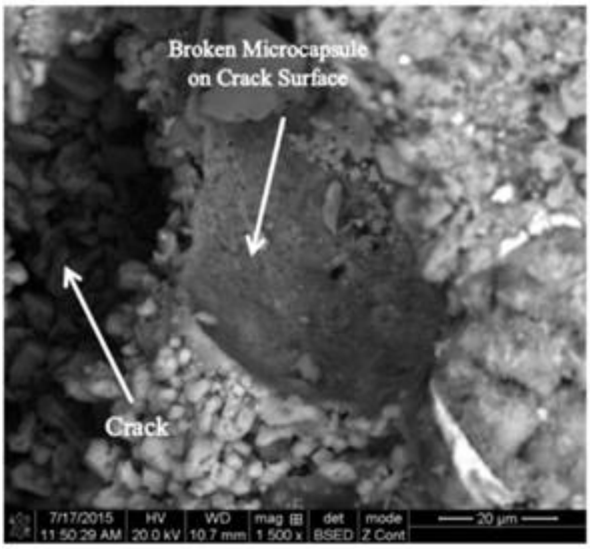

Figure 5: Microcapsule fracture seen on the surface of Mortar Specimen ID 1 containing 0.5% microcapsules.

4.2 Measurement of Crack Width

Light microscopy photos of the cracks were obtained immediately after breaking the mortar sample. The six specimens for each mortar mixture type from Table 3.3 were separated into two groups: Group A for specimens exposed to air-healing conditions and Group B for specimens exposed to water-healing conditions. The first average crack width, as determined by digital image analysis, ranged from 27.7 to 386.5 µm for series A specimens and from 27.0 to 231.9 µm for series B specimens. Tables 3 and 4 provide the specific measurements of the crack widths for specimens that were air and water-cured.

It should be emphasized that while strain-controlled conditions were used for the indirect tensile tests, the control specimens had much higher strength, which limited the ability to control crack width. As a result, the control specimens exhibited a highly brittle behavior, in contrast to the specimens containing microcapsules. The control specimens displayed a high level of brittleness, resulting in the formation of larger cracks. The Flexural Strength data of specimens cured in air are presented in Table 5.

Table 3: Crack width at the beginning of the air-curing process for specimens

Microcapsules		Crack Width (μm)											
		A1				A2				A3			
ID	Content (%)	n*	Mean	Std.Dev	CV	n	Mean	Std.Dev	CV	n	Mean	Std.Dev	CV
1	0.5	30	30.7	7.6	24.6	30	52.4	16.9	32.3	30	33.9	10.3	30.2
2	0.85	30	130.4	27.8	21.3	30	87.3	21.1	24.1	30	51.6	9.8	18.9
3	1.0	30	54.0	12.1	22.4	30	48.0	15.9	33.1	30	45.7	10.4	22.8
4	2.0	60	38.7	9.0	23.3	60	46.6	12.8	27.6	60	27.7	7.6	27.4
Control**	N/A	30	386.5	160.9	41.6	30	221.3	78.7	35.5				

*Number of measurements across the crack
**Control cracks from cylindrical specimens

Table 4: Crack width at the beginning of the water-curing process for specimens

Microcapsules		Crack Width (μm)											
		B1				B2				B3			
ID	Content (%)	n*	Mean	Std.Dev	CV	n	Mean	Std.Dev	CV	n	Mean	Std.Dev	CV
1	0.5	20	54.5	7.8	14.3	20	60.5	12.1	20.0	20	27.0	7.0	26.1
2	0.85	47	48.9	16.0	32.6	78	65.7	21.1	32.0	63	46.4	17.5	37.7
3	1.0	24	32.1	8.0	25.0	43	45.6	11.9	26.1	41	43.3	15.1	34.9
4	2.0	102	30.0	11.8	39.4	94	35.8	10.8	30.1	101	38.5	16.5	42.8
Control**	N/A	30	230.3	132.0	57.3	30	231.9	56.7	24.5				

*Number of measurements across the crack
**Control cracks from cylindrical specimens

Table 5: Flexural strength of air-cured specimens

Microcapsules		Flexural Stress (MPa)					
ID	Content (%)	A1	A2	A3	Avg.	Std. Dev.	CV
1	0.5	3.43	3.44	3.96	3.61	0.30	8.4
2	1	4.13	4.07	4.05	4.09	0.04	1.1
3	2	2.72	3.11	3.07	2.97	0.22	7.3
4	0.85	5.57	6.36	4.79	5.57	0.78	14.1
Control	N/A	10.64	11.05	9.30	10.33	0.91	8.9

4.3 Healing Quantification

Once the initial light microscopy pictures were obtained, the specimens were placed in a curing chamber for conditioning. During the healing process, specimens were imaged using light microscopy at 3, 7, 14, and 28 days. Upon analyzing these images, it was seen that water-cured specimens exhibited indications of healing in the form of minute crystalline structures along the edges of the cracks following a 7-day healing period. By the 14th day of the healing process, the presence of healing substances could be observed around the cracks of the majority of specimens that were cured with water. The healing process continued to advance over time until it reached 28 days of healing.

There was no evidence of healing in the specimens that were subjected to air healing conditions for a duration of 28 days. This suggests that the calcium nitrate solution released when the microcapsules break may not be sufficient to facilitate a substantial hydration reaction or calcium carbonate precipitation without an additional supply of moisture. Figure (6) displays photos depicting the cracks both before and after the healing process for specimens containing microcapsules with 0.5%, 0.85%, and 1.0% contents. Quantification of self-healing after 14 and 28 days was achieved by the application of digital image analysis. The quantification was conducted by comparing the crack area at 14 and 28 days with the initial crack area prior to healing, in order to determine the healing efficiency of the fractures.

Figure (7) displays the findings of quantifying the healing process. Specimens containing 0.85% and 1.0% microcapsules exhibited the most effective self-healing performance after a healing period of 14 days. The recovery rates after the completion of the healing phase (28 days) for the specimens containing 0.85% and 1.0% microcapsule content were quite similar to the control group, with rates of 44% and 42% respectively. Conversely, the microcapsule content of 2% exhibited the lowest level of self-healing performance, with a healing efficiency of only 31% after 28 days. These results suggest the presence of an optimal microcapsule content that would yield the highest healing effectiveness.

It is noteworthy that mortars containing 0.85% and 1% microcapsules exhibited superior self-healing efficiency compared to the control after 14 days. However, the disparity in healing efficiency between the most effective mortar mix (with 1% microcapsule content) and the control was minimal, approximately 5%. These results raise the question of whether the crack surfaces met the necessary conditions for continued hydration. Additional research should be undertaken using mortar mixes containing microcapsules and a lower water to cement ratio. This would result in a higher presence of unhydrated cement particles within the cementitious matrix. The presence of unhydrated cement particles would enhance the conditions for the self-healing process to effectively operate. Moreover, it is recommended to use a curing duration of 28 days or less. The study found that the 40-day curing period used in this research resulted in a greater level of hydration in the cementitious matrix, which improved the circumstances for self-healing in the presence of calcium nitrate.

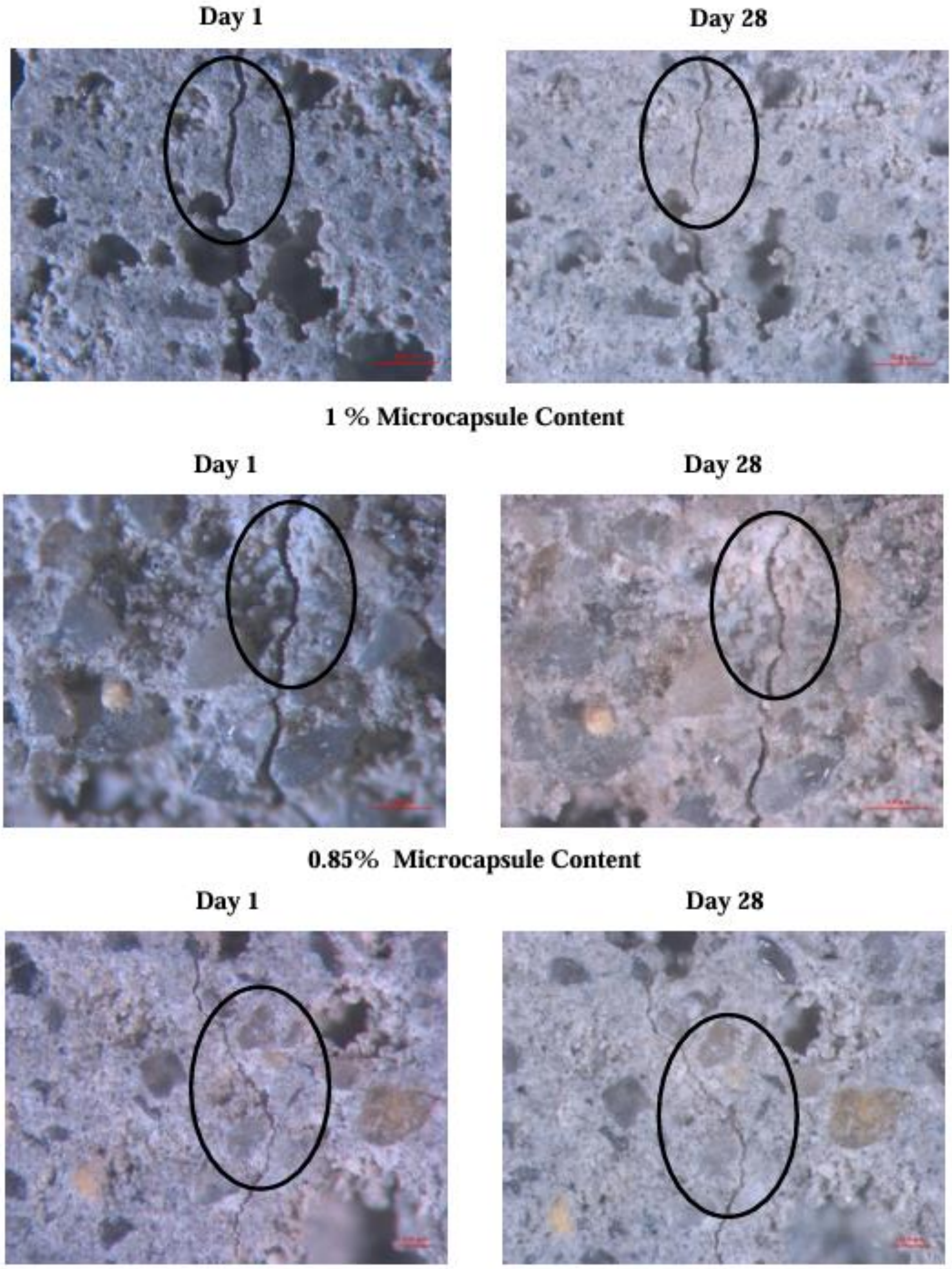

Figure 6: Pre and Post Healing Cracks

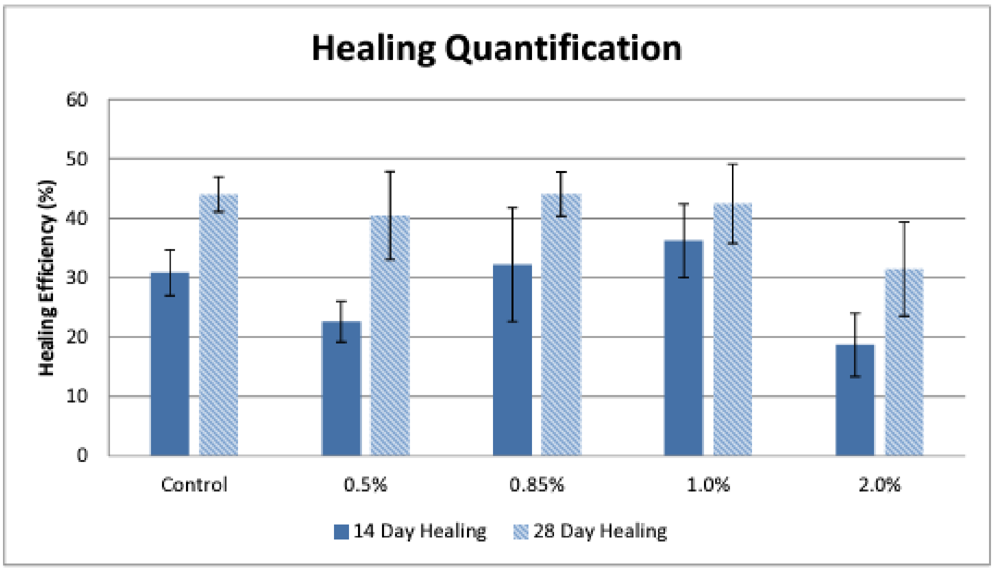

Figure 7: Healing efficiency variations with microcapsule concentration at 14 and 28 days

4.4 Healing Products Characterization

Following the completion of the 28-day healing period, a single sample of each mortar type listed in Table 2(b) was selected and subjected to direct analysis using ESEM. Acquired were backscatter electron (BSE) images of the healing products formed within the cracks. Figure (8) (a through d) demonstrates that the ESEM images showed a consistent morphology for the majority of the healing products in all specimens examined. The morphology exhibited crystal-like characteristics, resembling those of calcite crystals. Furthermore, gel-like healing materials were occasionally found, as shown in Figure (9).

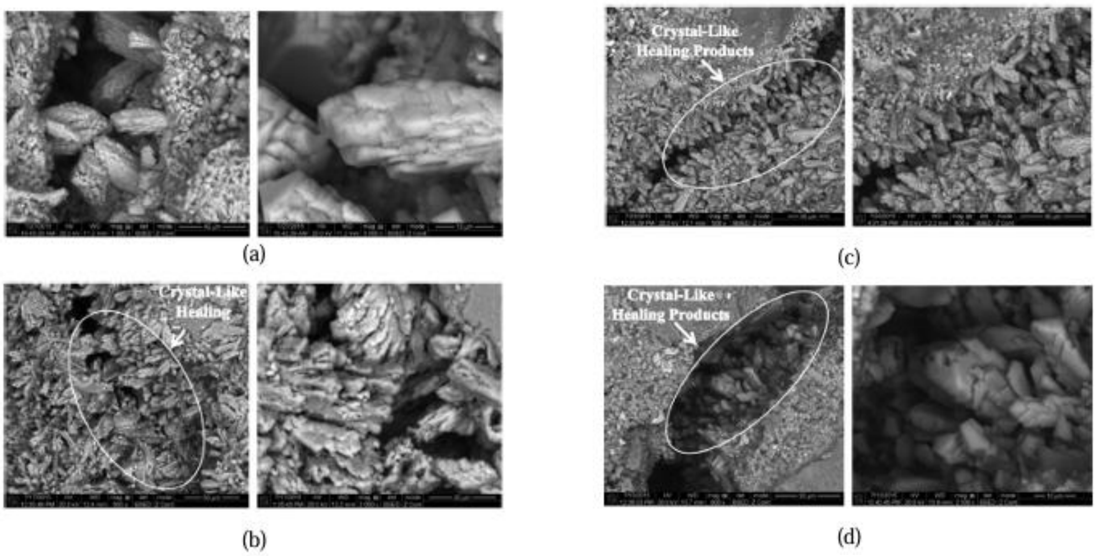

Figure 8: Healing products contained within a mortar specimen Crack for (a) Control, (b) 0.5% Microcapsules Content, (c) 0.85% Microcapsules Content, and (d) 2.0% Microcapsules Content.

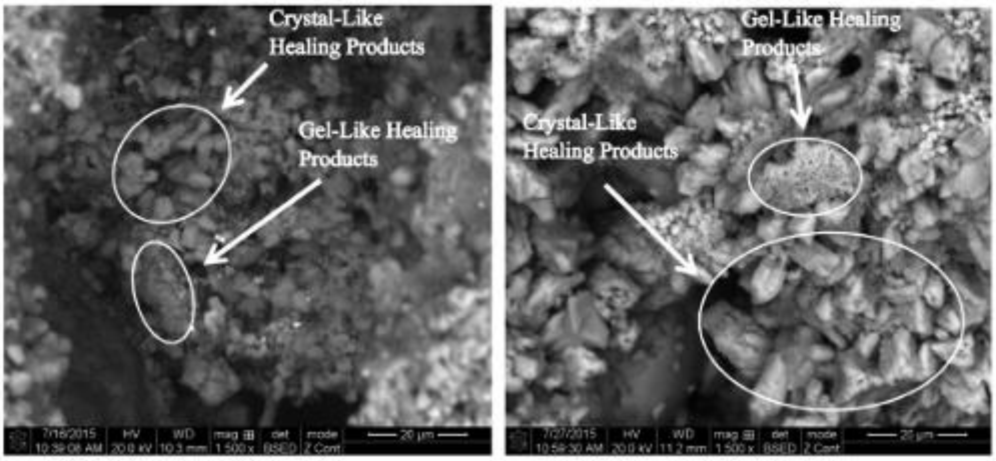

Figure 9: Healing Products in the Mortar Specimen Crack (Control: Left, 1% Microcapsule Content, Right)

One specimen of each type from Table 2(b) was subjected to EDS microanalysis in order to examine the healing products. We used an accelerating voltage of 20 kV and an ambient pressure of 0.6 mbar. EDS spectra were taken in spot mode at precise points within the cracks where healing products had developed. The majority of the spot spectrums that were recorded contained carbon, which is significant since it suggests that the calcium-rich crystals were most likely calcium carbonate in the form of calcite crystals. These results suggested that hydration goods might be included in the healing items.

The presence of CSH-like healing products is likely the result of the unhydrated cement grains in the fractures becoming progressively hydrated. Moreover, the CSH-like region and distant points from the origin were likely caused by high alumina phases like monosulfate, monocarbonate, and ettringite (high Al/Ca ratio) phases associated with additional hydration healing products in the cracks, or by silica sand particles (high Si/Ca ratio), which were occasionally observed in between the cracks (Figure 10). To get more understanding of the chemical makeup of the healing products, an EDS map was obtained in addition to the EDS spot analysis.

The elemental distribution maps of carbon and calcium demonstrate, as illustrated in Figure 10, a substantial correlation between the elements' respective abundances and the healing products found within the fissures. Furthermore, because of the high concentration of silicon found in those regions, one large silica sand particle in the cementitious matrix and one small silica sand particle in between the healing products were found. In addition to providing us with important evidence that the likely chemical composition of the crystal-like healing products found in the cracks was calcium carbonate in the form of calcite crystals, the elemental distribution maps proved to be effective tools for identifying phases in the material.

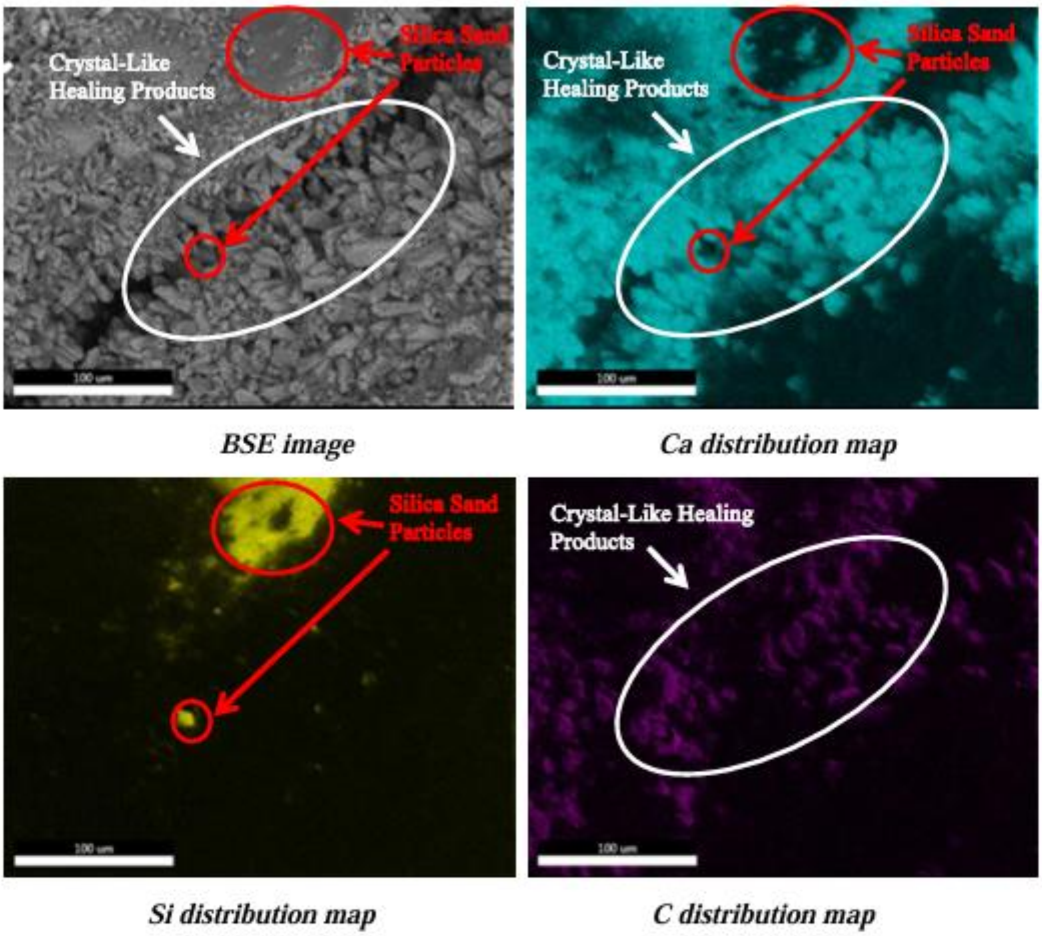

Figure 10: BSE Crack Healing Image Using corresponding Ca, Si, and C Distribution Maps

5- Conclusion

The paper investigates the strategies and factors contributing to concrete's self-healing capabilities. It wraps up a succinct classification that describes possible approaches to creating self-healing concrete. This paper offers workable ideas to improve the use of self-healing concrete in addition to future recommendations. First and first, bacterial selection is important. Future research should concentrate on finding carriers that can promote metabolic activity inside the concrete matrix in order to extend the bacteria's life. Although the majority of research has been on encapsulation and direct application, investigating alternate strategies like the spray method can shield bacteria from the harsh concrete environment, allowing a greater variety of bacterial species to be used and improving the efficacy of self-healing. Furthermore, the cost of encapsulating materials is not taken into account in the current research, which raises the initial costs of cement composites based on bacteria.

By cutting costs, using different waste materials for encapsulation may help bio-concrete become more widely accepted in the future. Understanding how well bacterial self-healing technologies work in actual environmental settings, taking into account elements like numerous fractures, aging concrete, indoor cracks with little water, and exposure to different sustained loads, would require more research. The majority of the current research on bacterial self-healing concrete takes place in environments with adequate water viability, which restricts application, particularly in situations when water is scarce. Although self-healing concrete has been successfully used in a number of applications, such as highways, irrigation canals, and dams, further research is required to solve the difficulties that come with using self-healing concrete in harsh environmental settings.

Furthermore, the different approaches taken by different studies to evaluate the self-healing concrete's performance lead to a lack of standardization, which poses a serious obstacle to the widespread practical use of this technology. These restrictions offer a chance for mathematical modeling, which could accelerate the development of self-healing systems. Ultimately, in order to expand the widespread application of self-healing concrete in next building projects, efforts should be undertaken to address and minimize the aforementioned constraints.

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