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

Amir Hares[1], Diaa Alrefaai[2], Mohammad Ismaeil[3], Mohamed Almahadi[4]
[1]*Civil Engineering Department, University of Prince Mugrin, Madinah, KSA.*
[2]*Civil Engineering Department, University of Prince Mugrin , Madinah, KSA.*
[3]*Associate Prof,Civil Engineering Department University Mugrin,Madinah,KSA.*
[4]*Civil Engineering Department, Om Durman Islamic University, Sudan.*

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*.

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I. 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.

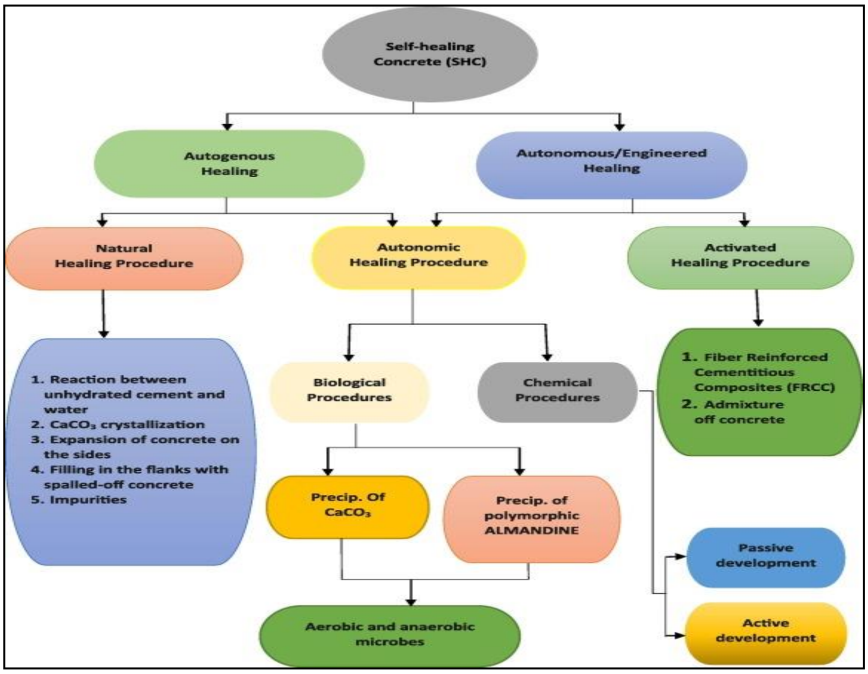
II. Cnocrete Self -Healing Techniques

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 (CaCO3). 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.



III. 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).

Fig2: Microcapsule Healing Agent.

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. 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/m^3)
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.

IV. 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.

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	54.4	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		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

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

Table 5: *Flexural strength of air-cured 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	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				

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.

Fig 3: Microcapsule Healing process after 28 days.

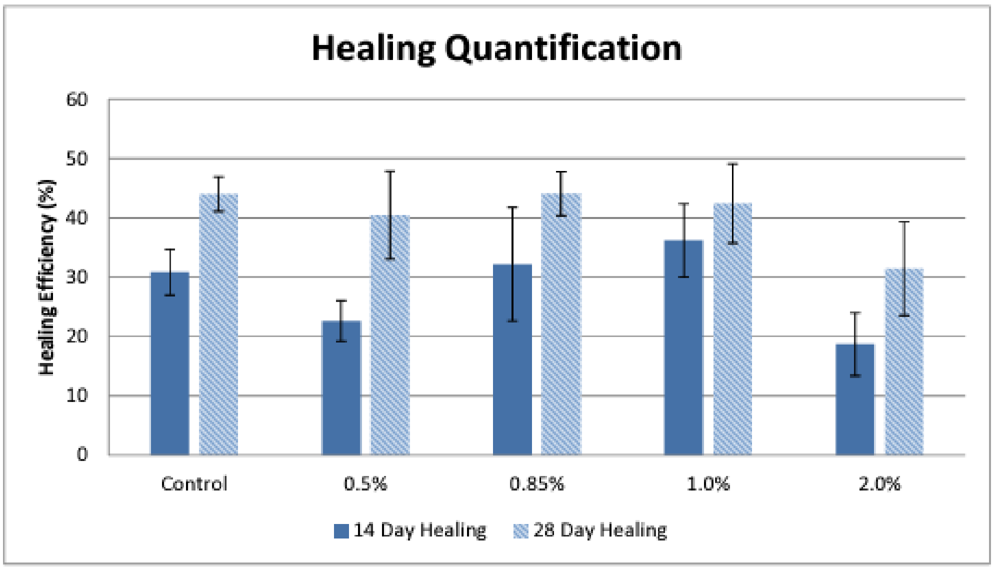


Fig 4: Healing efficiency variations with microcapsule concentration at 14 and 28 days.

V. 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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