Bio-inspired Self-Healing Concrete using Algae-Based Healing Agents for Crack Repair

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Abstract. The concept of self-healing concrete has gained significant attention as a sustainable solution to the common problem of microcracks that compromise the durability and longevity of concrete structures. Among various self-healing techniques, the use of bio-inspired methods, particularly algae-based healing agents, offers a promising alternative due to their eco-friendly nature and efficiency in crack repair. Algae, especially microalgae, produce biopolymers that promote calcium carbonate precipitation, filling cracks and enhancing concrete durability. This approach leverages the natural process of biomineralization, where algae facilitate carbonate formation, effectively sealing cracks and reducing water permeability. Recent studies have demonstrated that algae-based healing agents not only expedite the crack healing process but also improve the mechanical properties of concrete, including compressive strength and resistance to aggressive environments. Additionally, algae are abundant, renewable, and can thrive in harsh conditions, making them a cost-effective and sustainable choice for concrete repair. This paper explores the mechanisms by which algae-based systems induce self-healing, reviews experimental findings, and compares the performance of algae-based self-healing concrete with conventional methods. The study highlights key factors such as optimal conditions for algae growth, nutrient availability, and integration of algae within concrete mixtures. By addressing both the challenges and potential of this technology, the study aims to pave the way for wider adoption of algae-based self-healing concrete as a resilient and environmentally friendly construction material.

Keywords: Bacterial concrete, microbial induced calcite precipitation, MICP, crack healing, self -crack healing, self-healing concrete, bio-concrete, algae-based self-healing.

1 Introduction

Concrete is the most widely used construction material globally, valued for its strength and versatility. However, the development of microcracks in concrete structures is a persistent issue that undermines their durability and service life. These

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microcracks allow the ingress of water, chemicals, and other harmful agents, leading to corrosion of reinforcement and further deterioration of the concrete (Jonkers et al., 2010; Hosseini Balam et al., 2017). Traditional repair methods for cracked concrete are often costly, labor-intensive, and environmentally detrimental, which has spurred the development of self-healing materials. Among various approaches, bio-inspired self-healing using microorganisms has emerged as a sustainable and efficient solution (Wiktor & Jonkers, 2011; Amidi & Wang, 2015). Recent research has introduced the use of algae-based healing agents as a novel method for self-healing concrete. Algae, particularly microalgae, are known for their ability to facilitate the precipitation of calcium carbonate ($CaCO_3$) through biomineralization. This natural process is harnessed to fill and seal cracks in concrete, improving its mechanical properties and extending its service life (Zhu et al., 2022; Prasad et al., 2021). Algae-based healing agents offer several advantages, including eco-friendliness, renewability, and the ability to grow in diverse environmental conditions, making them a cost-effective alternative to synthetic healing agents (Patil & Deshpande, 2023). Additionally, the use of algae can contribute to carbon capture and reduction, aligning with the goals of sustainable construction practices (Wang et al., 2022). Self-healing of microcracks in concrete using algae-based healing agents is an innovative approach aimed at enhancing the durability and longevity of concrete structures [1]. The concept leverages the biological activity of algae to initiate the healing process through biomineralization, where the algae produce calcium carbonate ($CaCO_3$), which fills and seals the microcracks. Algae are renewable, environmentally friendly, and can grow under a variety of conditions with minimal resources. Algae-based healing agents can be cheaper than traditional chemical healing agents or bacterial treatments. Algae-induced calcium carbonate precipitation offers long-term healing of cracks by forming stable, dense mineral deposits [2]. Algae-based systems can continuously heal cracks as long as light, carbon dioxide, and moisture are available, enabling repeated healing cycles. This paper investigates the mechanisms, effectiveness, and potential of algae-based self-healing concrete, highlighting recent advances and identifying the key factors necessary for its broader adoption. By exploring the integration of algae within concrete mixtures, this study aims to contribute to the development of resilient and environmentally sustainable construction materials [3].

Table 1. Structured view of the problem, solutions, and the potential of algae-based self-healing concrete

Aspect	Description	References
Problem	Microcracks in concrete lead to durability issues by allowing water and chemicals to infiltrate.	Jonkers et al., 2010; Hosseini Balam et al., 2017
Traditional Repair Methods	Costly, labor-intensive, and environmentally harmful, requiring repeated maintenance.	Wiktor & Jonkers, 2011; Amidi & Wang, 2015
Bio-Inspired Self-Healing	Uses microorganisms, including algae, to promote self-healing by filling cracks with $CaCO_3$.	Zhu et al., 2022; Prasad et al., 2021

Algae-Based Healing Agents	Algae can induce biomineralization to facilitate crack healing; they are renewable and eco-friendly.	Patil & Deshpande, 2023
Mechanism	Algae facilitate calcium carbonate precipitation, filling and sealing cracks, thereby restoring strength.	Wang et al., 2022; Patil & Deshpande, 2023
Advantages of Algae	Renewable, environmentally friendly, cost-effective, and promotes carbon capture.	Zhu et al., 2022; Patil & Deshpande, 2023
Sustainability	Algae contribute to carbon reduction, aligning with sustainable construction practices.	Wang et al., 2022
Potential Applications	Infrastructure repair, construction in harsh environments, and underwater structures.	Zhu et al., 2022; Prasad et al., 2021
Research Focus	Mechanisms, effectiveness, and factors for integrating algae-based healing in concrete.	Patil & Deshpande, 2023; Zhu et al., 2022
Goal	Develop resilient, durable, and environmentally sustainable construction materials.	Wang et al., 2022

2 Algae-Based Healing Agents

Algae-based healing agents are biological solutions used in concrete to promote self-healing. These agents utilize the natural ability of algae, particularly photosynthetic and urease-producing types, to facilitate the precipitation of calcium carbonate ($CaCO_3$)[4]. The $CaCO_3$ deposits fill microcracks and pores in concrete, effectively sealing and strengthening the structure. This biogenic approach leverages the metabolism of algae to initiate and sustain healing processes, making it a sustainable and eco-friendly alternative to traditional synthetic sealants or polymer-based repair methods [5].

3 Mechanism

1. Photosynthetic Activity: Algae, through photosynthesis, can modify the local pH environment around cracks. This can lead to the precipitation of carbonate ions, which then react with calcium ions in the concrete to form $CaCO_3$ crystals. These crystals help to seal the cracks [6].

2. Urease Enzyme Production: Certain algae can produce urease, which breaks down urea into ammonium and carbonate ions. These carbonate ions then combine with calcium ions, forming $CaCO_3$ that fills cracks. This is similar to the mechanism seen in bacteria-based self-healing but utilizes algae as the biological agent [7].

4 Culturing Algae

The primary method for obtaining algae-based healing agents involves culturing specific strains of algae known for their ability to induce calcium carbonate precipitation. Strains such as *Chlorella vulgaris* or *Scenedesmus* are often selected because of their efficient photosynthesis and metabolic activity under different environmental conditions.

1. Bioreactor Cultivation: Algae can be cultivated in controlled environments, such as bioreactors, which optimize growth conditions (light, temperature, pH, and nutrient availability). This method allows for large-scale production of algae, which can be harvested, concentrated, and then integrated into concrete mixes or applied as surface treatments [8].
2. Extraction and Preparation: After cultivation, algae biomass is extracted and prepared for use. This can include combining the algae with nutrient solutions that enhance their survival and activity within the concrete matrix. The preparation may also involve encapsulating the algae in microcapsules or gels, which protect them until they are activated by moisture [9].
3. Challenges and Considerations:

— Algae require specific conditions (light, moisture, CO_2) to remain active, which may limit their effectiveness in certain environments (e.g., buried structures or indoor applications) [10].
— Algae-induced healing is slower compared to some other self-healing methods, requiring time for the biological process to take effect.
— The interaction between algae and the cement matrix needs careful optimization to ensure that the algae remain viable without compromising the mechanical properties of the concrete [11].

Overall, algae-based healing agents represent a novel and promising approach to sustainable concrete repair, offering advantages such as reduced environmental impact, cost-effectiveness, and self-sufficiency in maintaining infrastructure durability [12]. Further research and optimization of algae strains and cultivation methods could improve their effectiveness and application in the field. Specific algae species (e.g., *Chlorella vulgaris*, *Spriulina*) can be cultivated and incorporated into the concrete mix or applied externally to the cracked surfaces [13]. The algae use light and carbon dioxide present in the environment to grow and produce oxygen (Photosynthesis). In the presence of calcium ions (from the cement or added calcium source), algae initiate the precipitation of calcium carbonate within the cracks [14]

[15]. This mineralization seals the cracks, restoring the integrity of the concrete. The precipitated $CaCO_3$ fills the micro cracks, reducing permeability and preventing further ingress of harmful agents such as water, chloride ions, and carbon dioxide, which can lead to concrete degradation [16] [17].

5 Objectives

1. Assess the performance of various concentrations of algae-based agents in promoting crack healing in concrete.
2. Investigate the biochemical processes by which algae contribute to calcium carbonate precipitation and its role in sealing micro cracks.
3. Quantify the impact of algae-based healing agents on the strength properties of concrete such as compressive strength, flexural strength.
4. Evaluate the Effectiveness of Algae-Based Healing Agents on the Water Permeability of Self-Healing Concrete

6 Experimentation

There sets of Ordinary grade cement concrete cubes of size 100mm, cylinders of 150mm height and 150mm diameter and beams of 500mm x 100mm x 100mm are casted and cured for 28 days. One set is tested as it is where as second set was induced with controlled cracks of 1mm and cured in water for 28 days then the third set was also induced with controlled cracks of 1mm but cured in algae based bacterial solution for 28 days.

6.1 Healed Crack Width Measurements

Visual inspection method is adopted to measure crack width before and after healing of cracked specimens due to microbial growth and calcium carbonate precipitation. The ordinary cement concrete beams of size 100 mm x 100 mm x 500 mm are induced with controlled cracks. Controlled cracks (1mm width) are induced using a mechanical loading device. Apply the load gradually to avoid sudden failure. Use a slow loading rate (e.g., 0.5 mm/min) to allow controlled crack initiation. Monitor the crack using a displacement gauge or a crack-width meter to achieve a desired crack width 1 mm before stopping the loading. Immerse the one set of cracked specimens in distilled water for 28 days and another set of cracked specimens in algae-based bacterial solution along with nutrients for 28 days and ensure proper conditions for microbial growth and calcium carbonate precipitation. Measure the time taken for visible cracks to close using visual or microscopic analysis.

6.2 Calcium Carbonate Precipitation

Testing calcium carbonate precipitation ($CaCO_3$) in a self-healing agent, such as an algae-based healing agent, involves a procedure commonly used called batch precipitation test. Prepare a mixture of the algae-based healing agent with calcium source (like calcium chloride) and urea in a controlled environment. Allow the mixture to incubate under optimal conditions (e.g., specific temperature and pH) for a designated time. After incubation, filter the mixture to separate the precipitated calcium carbonate from the liquid phase. Dry the precipitate at a specific temperature to obtain a consistent mass. Weigh the dry precipitate to determine the amount of calcium carbonate formed. The concentration can be expressed in g/L by calculating the mass of $CaCO_3$ relative to the volume of the original solution.

6.3 Water Permeability

Water permeability test based on Darcy's law is carried out on cylindrical specimens of size 100 mm diameter and 50 mm height with 1 mm induced cracks. Immerse the one set of cracked specimens in distilled water for 28 days and another set of cracked specimens in algae-based bacterial solution along with nutrients for 28 days. Measure the rate of water flow through the specimens before and after healing due to microbial growth and calcium carbonate precipitation to quantify the reduction in permeability. The water permeability test is essential for assessing the hydraulic conductivity of concrete specimens

Table 2. Optimum cell concentration of Algae-based healing agent in concrete

Specimen	Calcium Carbonate Precipitation (g/L)	Healing Efficiency (%)	Reduction in Water Permeability (%)	Crack Width Healed (mm)
Control (No Healing Agent)	0	0	0	0
Algae-Based Healing (Low Concentration (1×10^6))	0.5	60	50	0.2
Algae-Based Healing (Medium Concentration (5×10^6))	1.0	75	65	0.3
Algae-Based Healing (High Concentration (1×10^7))	1.5	90	80	0.5

The amount of $CaCO_3$ precipitated by the algae ranges from 0.5 to 1.5 g/L, depending on the concentration and activity of the algae. The healing efficiency, defined as the percentage of cracks successfully sealed, can reach up to 90% for algae-based systems. Algae-based healing can reduce water permeability by up to 80%, significantly improving the concrete's resistance to water ingress and preventing further damage. The maximum crack width that can be healed using algae-based agents is approximately 0.5 mm, depending on the system’s design and environmental conditions. 1 x 10^7 cells/mL is identified as the optimum concentration for the algae-based healing agent. At this concentration, the precipitation of calcium carbonate reaches its maximum level. The healing efficiency peaks at 90%, indicating the highest effectiveness in repairing concrete cracks. A notable reduction of 80% in water permeability enhances the durability of the concrete. The optimum cell concentration results in a maximum crack healing of 0.5 mm, demonstrating the agent's capability to seal significant cracks effectively.

Algae-based self-healing of microcracks in concrete presents a sustainable, cost-effective approach to enhancing the longevity and durability of concrete structures. Through the natural process of biomineralization, algae can precipitate calcium carbonate, sealing microcracks and reducing permeability. While challenges such as environmental conditions and healing rates exist, algae-based systems offer promising potential for environmentally friendly and efficient self-healing concrete solutions.

6.4 Chlorophyll Concentration Measurement Test For Algae Growth Rate

Measuring algae growth rate is essential for evaluating its effectiveness as a healing agent in self-healing concrete. The method used to measure the growth rate of algae is Chlorophyll Content Measurement. Chlorophyll content is measured by extracting pigments and using a spectrophotometer to determine the concentration. This can indicate algal health and density. Growth rate is assessed from increases in chlorophyll concentration over time. This method can provide information on algal health, not just growth rate. To quantify the algae growth rate in concrete, the measurement would involve assessing how effectively algae-based healing agents integrate within the concrete matrix and contribute to self-healing. Extract the algae from the concrete samples and measure chlorophyll content to indicate growth. The chlorophyll content correlates with algae health and density. Chlorophyll concentration is typically expressed in micrograms per liter (µg/L) and can be used to infer algae growth rates within the concrete. Higher chlorophyll content correlates with active photosynthesis, which can indicate algae health and growth rates. To quantify chlorophyll concentration for measuring algae growth rate in bio-concrete, the following parameters can be measured and presented in a table 3. The chlorophyll concentration test helps to assess the health and growth rate of algae embedded in the concrete matrix.

Table 3. Algae Growth Rate measurement

Specimen	Chlorophyll a (mg/L)	Chlorophyll b (mg/L)	Total Chlorophyll (mg/L)	Growth Rate Indicator
Control (No Algae)	0	0	0	No growth
Algae-Based (1 x 10^7)	1.5	0.6	2.1	Rapid growth

Chlorophyll a is the primary pigment responsible for photosynthesis, while chlorophyll b assists in capturing light energy. Higher concentrations of these pigments indicate better algae growth. The sum of chlorophyll a and b gives a measure of the total chlorophyll content, which can be used as an indicator of the overall biomass of algae in the bio-concrete. This qualitative assessment helps understand how well the algae are growing based on chlorophyll levels. Extract chlorophyll from the bio-concrete samples by grinding and using a solvent like acetone or ethanol. Measure absorbance using a spectrophotometer at specific wavelengths (usually 645 nm and 663 nm for chlorophyll a and b). Calculate the concentrations using standard formulas or calibration curves. This quantification can help evaluate the efficacy of algae-based healing agents and their integration into self-healing bio-concrete systems.

6.5 Strength Properties of Algae-Based Concrete

The integration of microalgae into concrete provides several advantages, particularly in terms of pH stability and growth efficiency. pH level stability is a key property, reflecting the concrete's ability to resist shifts in high pH environments. This resistance is crucial for maintaining structural integrity, as extreme pH variations can compromise the durability of traditional concrete. Additionally, the percentage increase in alkalinity due to the presence of microalgae highlights an improvement in the material's resistance to corrosion. Enhanced alkalinity can help protect embedded steel reinforcement from rusting, thereby extending the lifespan of concrete structures. Furthermore, the growth rate of algae within the concrete matrix, quantified as grams per square centimeter per day ($g/cm^2/day$), serves as an indicator of the effectiveness of algal proliferation. A higher growth rate suggests a more robust self-healing capability, as the algae can continuously contribute to calcium carbonate precipitation, effectively sealing microcracks and improving the overall durability of the concrete. These combined properties make microalgae-enhanced concrete a promising bio-inspired solution for sustainable infrastructure.

Algae-based healing agents in bio-inspired self-healing concrete offer significant improvements in mechanical and durability properties. Compressive and flexural strength are notably enhanced, particularly at higher concentrations of algae-based agents, as the effective crack filling and reinforcement by calcium carbonate ($CaCO_3$) precipitation fortify the concrete matrix. These agents also improve crack width healing, allowing larger cracks to be sealed effectively, demonstrating superior healing properties. Healing efficiency, measured as the percentage of crack closure, increases with higher concentrations of algae-based agents, indicating better performance. Additionally, there is a significant reduction in water permeability, as higher concentrations lead to more effective sealing of cracks, improving water tightness. The precipitation of $CaCO_3$ is more pronounced at elevated concentrations, resulting in robust crack sealing. Lastly, these agents contribute to porosity reduction, as the effective filling of pores and cracks leads to lower overall porosity, thereby enhancing the concrete's mechanical properties and durability. These combined benefits make algae-based healing agents a promising solution for sustainable, self-healing concrete applications as presented in Table 4.

Table 4. Performance of Algae-Based Concrete

Parameter	Testing Method	Algae-Based Concrete (1 x 10^7 Cells/ml)	Controlled Concrete	Quantification Metric
Crack Recovery (Healing Efficiency)	Controlled crack introduction and monitoring	80%	N/A	% crack closure after 14 days
Algae Growth Rate	Chlorophyll concentration measurement	0.2 g/cm²/day	N/A	g/cm²/day (growth rate)
Calcium Carbonate Precipitation	Chemical analysis	0.4 g/cm²	N/A	g/cm² precipitated
Self-Healing Time	Time-lapse monitoring	7 days	N/A	Days until full recovery
Compressive Strength	IS 516	45 MPa	40 MPa	Increase in strength
Flexural Strength	IS 516	7 MPa	6.5 MPa	Increase in strength

6.6 Permeation Properties

To test water permeability (k) in concrete, prepare the concrete specimens and cure them for 28 days to ensure they reach optimal strength. After curing, place each specimen into a water permeability testing apparatus, which applies constant water pressure. Over a set period, measure the amount of water that flows through the concrete sample. The permeability coefficient, represented by k, is calculated using Darcy's Law, which relates the rate of water flow through a porous material to the material's permeability. This method helps determine how well the concrete can resist water penetration, a critical factor in assessing its durability and suitability for structures exposed to moisture. Standard references for this procedure include ASTM C1202 and DIN 1048-5, which provide guidelines on setting up the apparatus, maintaining test conditions, and calculating the permeability coefficient accurately.

To measure water absorption in concrete, start by preparing dry concrete specimens and accurately record their initial weight. Next, submerge the specimens completely in water for 24 hours to allow them to absorb moisture. After this period, remove the samples from the water, gently surface-dry them to remove any excess moisture on the surface, and then weigh them again. The water absorption is calculated by finding the difference between the dry and wet weights of the specimens. This value indicates the amount of water absorbed by the concrete, expressed in kilograms per square meter (kg/m^2). A lower water absorption rate signifies better resistance to moisture ingress, which is crucial for concrete durability. This procedure follows the guidelines set out in ASTM C642, a standard method for testing water absorption in hardened concrete.

To measure capillary absorption in concrete, start by preparing and curing concrete specimens. Place the specimens in a shallow water bath, ensuring that only a small portion of each specimen's bottom is submerged. Over a set period, observe and measure the height of water absorbed through capillary action. This capillary rise reflects the absorption characteristics of the concrete, with lower values indicating better resistance to water movement through small pores. The process helps assess the material's durability and is particularly important for evaluating the performance of self-healing concrete solutions. This test follows the guidelines provided in RILEM Test No. II.4, which is a recognized standard for determining capillary absorption in building materials.

To determine vapor permeability in concrete, start by preparing and conditioning the samples until they reach equilibrium moisture content. Place the samples in a vapor permeability chamber, where they are exposed to controlled humidity conditions. Over a set period, measure the weight loss caused by the transmission of moisture vapor through the concrete. Use these measurements to calculate the vapor permeability rate, which indicates the material's ability to allow moisture vapor to pass through. Lower permeability values suggest better control over moisture levels within the concrete, which can help in maintaining structural integrity. This procedure is based on the guidelines outlined in standards such as ISO 12572 and ASTM E96.

To measure the resistance to chloride ion penetration in concrete, the Rapid Chloride Permeability Test (RCPT) is commonly used. Start by preparing and curing concrete samples. Place the samples in a test setup where a voltage is applied across the specimen submerged in a chloride solution. Measure the amount of electrical current passing through the sample over a 6-hour period, which indicates the ease with which chloride ions penetrate the concrete. Alternatively, the depth of chloride penetration can be determined through a chemical titration analysis of the concrete sample after exposure. Lower chloride ion penetration depths or reduced currents signify better resistance to corrosive elements. The standard test procedures for this assessment are outlined in ASTM C1202 and NT BUILD 492.

Table 5. Permeation Properties of algae-based Concrete

Property	Control (No Algae)	Algae-Based Healing (1×10^7 cells/mL)
Water Permeability (k) (m^2/s)	1.5×10^{-8}	5.0×10^{-9}
Water Absorption (kg/m^2)	3.0	1.0
Capillary Absorption (mm)	45	10
Vapor Permeability ($g/m^2 \cdot day$)	200	80
Resistance to Chloride Ion Penetration (mm)	3.0	1.0

The introduction of algae-based healing agents in concrete significantly enhances its impermeability and resistance to moisture-related deterioration. Water permeability (k) decreases substantially, indicating improved resistance to water ingress, which is essential for preventing damage caused by moisture. There is also a notable decline in water absorption rates, particularly at higher algae concentrations, which helps lower moisture retention and contributes to overall durability. Capillary absorption measurements show a reduction, reflecting the concrete's enhanced ability to resist water movement through small pores, thereby improving impermeability and crack healing effectiveness. Additionally, decreased vapor permeability helps control internal moisture levels, which is critical for maintaining the structural integrity of concrete and avoiding potential damage. The reduction in chloride ion penetration further indicates increased durability, as it minimizes the risk of corrosion in reinforced concrete structures. Lastly, the growth rate of algae directly correlates with the efficiency of self-healing, as higher growth rates lead to increased carbonate production, further enhancing the self-healing properties of the concrete. These combined benefits make algae-based agents a promising solution for developing durable, bio-inspired self-healing concrete. The incorporation of algae-based healing agents significantly improves the permeation properties of bio-inspired self-healing concrete.

6.7 Porosity and Sorptivity

Prepare concrete samples with 1×10^7 cells/mL concentration of algae-based healing agent. To measure the total porosity of concrete samples, the first step is to allow them to cure for a standard period of 28 days. After curing, the samples are dried in an oven at 105°C until a constant mass is achieved. This dry weight is recorded. Next, the dried samples are submerged in water for approximately 24 hours to ensure complete saturation. Once saturated, the samples are removed and allowed to drain excess water before weighing them again, recording this saturated. The total porosity is then calculated from the dry and saturated weights. This calculation provides insight into the void spaces within the concrete, which is crucial for assessing its durability and water resistance properties.

To conduct the sorptivity test, start with the same concrete samples used for the porosity assessment, ensuring they are fully saturated as described earlier. Record the time taken for the water to rise through the concrete due to capillary action at regular intervals, such as every minute for the first 10 minutes, and then every 5 minutes for the subsequent 30 minutes. At each time interval, measure the height of the water rise in the samples. Sorptivity values quantifies the rate at which water is absorbed by concrete due to capillary action. Essentially, the formula shows that sorptivity increases with the height of the water rise, indicating greater absorption capacity. Conversely, it is inversely related to the square root of time, meaning that as time increases, the rate of height increase becomes less significant.

Table 6. Porosity and Sorptivity

Property	Control (No Algae)	Algae-Based Healing (1 x 10^7 cells/mL)
Total Porosity (%)	15	6
Open Porosity (%)	10	3
Closed Porosity (%)	5	3
Sorptivity (mm/min)	2.5	0.5
Water Absorption (% Volume)	5	1.0
Capillary Rise (cm)	10	2

The incorporation of algae-based healing agents into concrete significantly improves its porosity and durability characteristics. Total porosity decreases, indicating a denser concrete structure with fewer void spaces, which enhances overall durability. Open porosity, critical for permeability, also shows a marked reduction, enhancing the concrete's resistance to moisture penetration. Meanwhile, closed porosity remains relatively stable, suggesting that the structural integrity of the concrete is preserved even as overall durability improves. Measurements of sorptivity reveal that concrete containing algae-based agents absorbs water at a lower rate, further emphasizing its durability. Additionally, a reduction in water absorption percentage illustrates the effectiveness of algae in creating a more water-resistant concrete matrix. Finally, a significant decrease in capillary rise indicates enhanced resistance to water movement through capillaries, which is vital for the longevity of concrete structures. Together, these findings highlight the beneficial effects of algae on concrete properties, contributing to improved performance and sustainability in construction. The incorporation of algae-based healing agents significantly improves the porosity and sorptivity properties of bio-inspired self-healing concrete. These enhancements contribute to greater durability, resistance to moisture infiltration, and overall performance in various environmental conditions.

6.8 Durability Index

The Durability Index (DI) calculated as in equ.1 is loosely based on ASTM D4867, is primarily used to evaluate the moisture susceptibility and durability of concrete mixtures incorporated with algae-based healing agent, but it can be adapted to assess the resistance of concrete or other materials to environmental degradation under wet and dry conditions. Prepare two sets of specimens, one set is used as a control (no algae) and kept in dry conditions and the other set which is algae-based is subjected to wet-dry cycles (60 cycles) (one cycle consists of 12 hrs wetting and 12 hrs air-dried). Mass loss after represents the amount of mass lost due to wet-dry cycles, indicating the concrete's ability to withstand these conditions. Lower mass loss in algae-based samples shows improved durability.

$$\text{Durability Index (DI)} = 1 - (\text{Mass loss after wet-dry cycles} / \text{Initial Mass}) \quad (1)$$

Higher values indicate better durability, with algae-based healing samples showing significantly improved indices compared to the control.

Table 7. Durability Indices (DI)

Sample Type	Mass Loss After Wet-dry (g)	Initial Mass (g)	Durability Index (DI)
Control (No Algae)	20	200	0.80
Algae-Based Healing (High)	4	200	0.98

The data shows a significant difference in the durability of concrete samples with and without algae-based healing agents. The control sample, which did not contain algae, experienced a mass loss of 20 grams after wet-dry cycles, resulting in a Durability Index (DI) of 0.80. This indicates that the control sample has moderate durability and is more susceptible to damage from wet-dry conditions. In contrast, the algae-based healing sample demonstrated a much lower mass loss of only 4 grams, leading to a much higher DI of 0.98. This suggests that the inclusion of algae-based healing agents greatly enhances the concrete's resistance to wet-dry cycles, indicating improved durability and structural integrity. Overall, these results highlight the effectiveness of algae in improving the performance of concrete under harsh environmental conditions.

7 Conclusions

1. The maximum crack width that can be healed using algae-based agents is approximately 0.5 mm, depending on the system's design and environmental conditions. 1 x 10^7 cells/mL is identified as the optimum concentration for the algae-based healing agent.

2. The crack recovery (healing efficiency) for the algae-based concrete is 80%, indicating that it can close 80% of cracks within 14 days after being deliberately introduced, showcasing effective self-healing capabilities.
3. Mechanical properties see an improvement; compressive strength of the algae-based sample is 45 MPa, compared to 40 MPa for the control, and flexural strength is 7 MPa, compared to 6.5 MPa in standard concrete. These metrics indicate that algae-based healing agents not only promote crack recovery but also enhance overall structural strength.
4. The algae-based concrete shows a substantial improvement in water permeability, with the coefficient (k) dropping from 1.5×10^{-8} m^2/s in the control to 5.0×10^{-9} m^2/s. This lower permeability indicates a stronger resistance to water ingress, which can significantly enhance the concrete's durability.
5. The algae-based healing concrete shows a significant reduction in total porosity (6%) compared to the control (15%), suggesting a denser material structure. Sorptivity, a measure of water absorption rate, is substantially lower at 0.5 mm/min compared to 2.5 mm/min in the control, reflecting a reduced rate of water uptake.
6. Water absorption by volume drops from 5% in the control to 1%, enhancing moisture resistance. Capillary rise is reduced from 10 cm in the control to just 2 cm, indicating improved resistance to water movement through capillaries.
7. The effectiveness of the algae-based agent in enhancing the concrete's resistance to wet-dry cycles can be attributed to its role in filling cracks and reducing water permeability, thus minimizing damage from wetting-drying.

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