Alga polysaccharide based bacterial encapsulation technology for potential self-healing concrete

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Abstract. cracks are common in concrete due to its relatively low tensile strength, often caused by external loads that generate high tensile stress. Immediate and proper treatment is essential to prevent crack propagation and costly repairs. Self-healing concrete is designed to autonomously repair cracks without external intervention, commonly using encapsulated bacteria. This study investigates the effect of Bacillus megaterium encapsulated in algae based polysaccharide shells at 2% of concrete volume. Cylindrical specimens (15 cm diameter × 30 cm height) were tested for compressive strength at 7 and 28 days. Results showed that the highest compressive strength was achieved in concrete with 2% capsules, reaching 25.85 MPa on day 7 and 32.56 MPa on day 28. Visual observation revealed visible crack closure starting around the first week of curing. SEM analysis confirmed the presence of porous, irregular capsule surfaces that facilitate bacterial release upon cracking. EDS results detected dominant elements including Oxygen (56.02%), Silicon (21.99%), and Calcium (9.38%), indicating the formation of calcium carbonate ($CaCO_3$) as a result of bacterial activity. These findings demonstrate the potential of biopolymer encapsulation in enhancing both strength and self-healing performance of concrete.

1 Introduction

Concrete is one of the most commonly used construction materials worldwide. Despite its advantages, it suffers from a major limitation its susceptibility to cracking under internal or external stresses, which significantly reduces both structural strength and long-term durability [1]. This weakness is largely due to its low tensile capacity, making concrete less resistant to tensile stresses and therefore more prone to cracking [2]. Addressing this problem requires repair strategies that are not only effective but also efficient and sustainable, offering improvements over traditional practices such as manual patching and external crack sealing [3].

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Conventional repair methods often rely on applying surface coatings, such as epoxy, chlorinated rubber, silane, wax, or acrylic resin, to close visible cracks and external pores. However, these coatings are limited in performance due to weak adhesion with the concrete substrate and their vulnerability to degradation and delamination over time. While they may provide temporary benefits, they typically require repeated maintenance and cannot fully restore the structural integrity of the concrete [4]. With advances in construction materials technology, greater attention is now directed toward innovative and eco-friendly solutions, such as bacteria-based self-healing concrete, which can improve durability and extend service life. One widely studied mechanism is biologically induced calcite precipitation, shown to be effective in filling cracks while also supporting resource conservation [5].

The concept of self-healing concrete has been developed to produce advanced materials capable of autonomously repairing damage. In this system, bacterial activity leads to the formation of calcium carbonate ($CaCO_3$) deposits that seal cracks. At the same time, the metabolic process consumes oxygen within the concrete, indirectly lowering the risk of reinforcement corrosion and thereby prolonging service life [6]. Currently, microbial self-healing agents are incorporated into concrete mainly through two approaches: direct mixing or encapsulation. Previous research has demonstrated that encapsulation offers better protection for microbial activity, as it helps bacteria survive the highly alkaline concrete matrix and dense pore structure formed during cement hydration [7]. Among various encapsulation materials, algal polysaccharides have emerged as promising candidates for construction applications because of their proven performance in encapsulation systems [8]. Based on this background, the present study investigates the use of algal polysaccharides as encapsulation material and evaluates the role of Bacillus megaterium as a biological healing agent for crack remediation in self-healing concrete.

2 Material and methods

2.1 Research location

The experimental work involved concrete production in the Civil Engineering Materials Laboratory and bacterial culturing with encapsulation material preparation in the Bioprocess Laboratory of the Chemical Engineering Department, Politeknik Negeri Bandung.

2.1.1 Concrete

Concrete is composed of hydraulic cement (commonly Portland cement), fine and coarse aggregates, water, and, if required, admixtures or additives. Its formation begins with the hydration reaction between cement and water, producing cement paste. When combined with fine aggregates, the paste forms mortar, and with the addition of coarse aggregates, it becomes concrete. The strength of concrete develops with age, showing significant growth up to 28 days before gradually slowing. Key factors influencing its strength include material composition, mix design, curing practices, and conditions during casting [9].

2.1.2 Self-healing concrete

The autogenous healing technique is an effective method for repairing micro-cracks in concrete, where added bacteria induce calcium carbonate ($CaCO_3$) precipitation to seal cracks [10]. Since concrete is highly alkaline, only resistant bacteria such as Bacillus sphaericus can survive and precipitate $CaCO_3$ by converting urea into ammonium and carbonate [11].

The deposited $CaCO_3$ fills micro-cracks, binds aggregate particles, and reactivates bacteria whenever new cracks occur, making them durable self-healing agents through Microbiologically Induced Calcium Carbonate Precipitation (MICP) [12]. In bacteria-based self-healing concrete, dormant spores are activated by oxygen and water, then convert calcium lactate ($CaC_6H_{10}O_6$) into $CaCO_3$, following thecreaction: $CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$ [13].

2.1.3 Bacillus megaterium

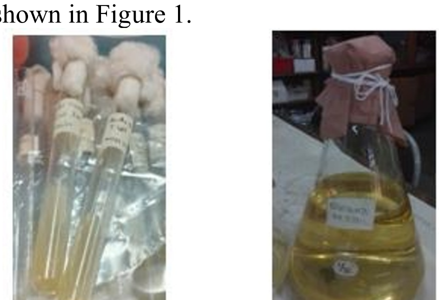
Bacillus megaterium is a mesophilic microorganism that grows well at around 30 °C, with an optimal temperature range of 25–37 °C, and is tolerant to pH levels between 5.5 and 8 [14]. Remarkably, it can remain viable in concrete for up to two centuries, making it an excellent candidate to improve concrete durability and extend service life through self-healing mechanisms [15].

2.1.4 Alga polysaccharides

Algal polysaccharides are a renewable, abundant, biodegradable, and biocompatible resource for biopolymer production. They are widely used in the food industry as thickeners, gelling agents, emulsifiers, and stabilizers, and are also applied as packaging materials. Polysaccharide based hydrogels have been reported to possess excellent transparency and mechanical properties. In addition, they can be combined with other active materials to provide additional characteristics to the hydrogel, such as antibacterial and antioxidant properties. Compared to conventional synthetic polymers, polysaccharide-based hydrogel films demonstrate comparable tensile strength [16].

2.2 Methods

This research is an experimental study that begins with the cultivation process of Bacillus megaterium using solid and liquid media. The solid medium used is Nutrient Agar (MERCK), while the liquid medium is Nutrient Broth (MERCK). Preparation of the solid medium is carried out by weighing 2.8 grams of Nutrient Agar, dissolving it in 50 mL of distilled water, and pouring it into slanted containers. For the liquid medium, 6.5 grams of Nutrient Broth is dissolved in 500 mL of distilled water and stirred until completely dissolved. The liquid medium is then sterilized using an autoclave at 121°C for 15 minutes under 15 psi pressure. Once the liquid medium is cool and sterile, the bacteria are inoculated into the medium using an inoculating loop, followed by incubation on a shaker for 24 hours at a temperature of 33-34°C until the medium appears turbid, indicating bacterial growth. Both solid mediums are shown in Figure 1.



(a) (b)

Fig. 1. (a) Nutrient Agar (b) Nutrient Broth.

The preparation of bacterial capsules, 1 gram of Algal Polysaccharide is dissolved into 50 mL of Nutrient Broth containing the bacteria. The solution is then pasteurized at 45°C for 10 minutes to inhibit other microorganisms without damaging the target bacteria. Once cooled, the mixture is dripped into a 2% $CaCl_2$ solution to form spherical capsules, with capsule size adjusted based on syringe pressure. After solidifying, the capsules are washed and dried. The mixture is shown in Figure 2.

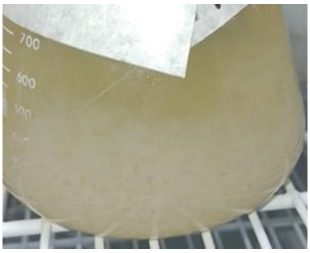


Fig. 2. Bacillus megaterium in Algal Polysaccharide capsule.

Before the capsules are incorporated into the concrete, the capsule material undergoes a compressive strength test using the Mechanical CBR Test to evaluate the mechanical properties of the capsules to be used, as shown in Figure 3.

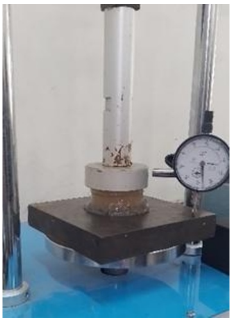


Fig. 3. Mechanical CBR Test.

The test specimens used are cylindrical, with a diameter of 15 cm and a height of 30 cm. The number of samples prepared is presented in Table 1

Table 1. The variations of sample.

Variations	7 Day	28 Day
Normal Concrete	3	3
Algal Polysaccharide 2%	3	3
Total	6	6

The selection of the 2% capsule variation is based on research conducted by [17], which showed that using capsules at a concentration of 2% provided the most optimal improvement in concrete quality. This study was conducted to confirm and further evaluate the effectiveness of the capsules through experimental testing to ensure that the 2% concentration enhances both the self-healing capability and the strength of the concrete.

The concrete mixing process begins by preparing the necessary tools and materials. The ready-mix concrete is placed into the mixer and mixed until evenly distributed, followed by the gradual addition of water. The mixture is stirred for 10 to 15 minutes. The mixer is then stopped, and the bacteria-containing capsules are added. Mixing continues for approximately

2 minutes; however, it is not recommended to mix for too long to prevent the capsules from breaking before they are properly incorporated into the concrete. Once the mixture is homogeneous, a slump test is conducted with a target of approximately ±12 cm, after which the mixture is poured into cylindrical molds. Test specimen mold and the specimen is shown in Figure 4.

(a) (b)

Fig. 4. (a) Test specimen mold 15 × 30 (b) The specimen.

3 Results

Based on the results of compressive strength tests and visual observations conducted over approximately one month, it was found that the highest compressive strength was achieved in concrete with the addition of 2% Algal polysaccharides on both the 7th and 28th day. In addition, visual observations also indicated that cracks began to close within less than one month after testing.

The compressive strength test results are presented in Figure 5. The unit of measurement used for compressive strength is Megapascal (MPa).

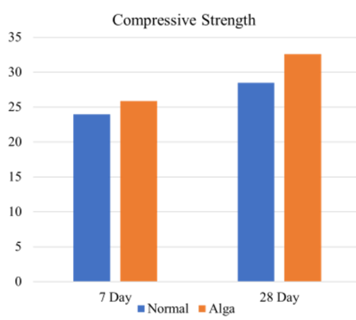


Fig. 5. Compressive strength normal vs algal encapsulated concrete

The results of compressive strength tests and visual observations conducted over approximately one month indicate that the addition of 2% Algal polysaccharides enhances concrete performance. The compressive strength of normal concrete was recorded at 23.97 MPa on day 7 and 28.48 MPa on day 28. In contrast, concrete with 2% Algal polysaccharide variation showed an increase in compressive strength to 25.85 MPa on day 7 and 32.56 MPa on day 28. This increase indicates that the addition of 2% Algal polysaccharides is effective in enhancing the crack-sealing ability of concrete. The Algal polysaccharides protect the bacteria within the concrete and help maintain moisture, so when cracks occur, the bacteria actively produce calcium carbonate ($CaCO_3$), which fills the gaps and increases concrete density.

Visual observations were carried out after the compressive strength test, during which the concrete was immersed in a curing tank. One of the concrete samples with 2% capsule variation was observed for 28 days as shown in Figure 6. The observations revealed that the capsules, which ruptured due to cracking, released Bacillus megaterium, which subsequently reacted with air to form calcium carbonate that sealed the cracks. The formation of calcium carbonate became visible starting on the 7th day after the compressive strength test, as shown in Figure 7.

Fig. 6. Specimen with 2% capsules after curing and compressive testing

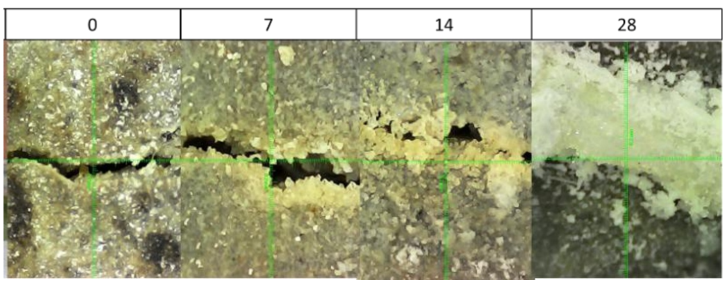


Fig. 7. Algae in 28-day concrete observed with a digital microscope

The SEM analysis revealed that the algae-based polysaccharide microcapsules possessed a rough, porous, and non-homogeneous surface structure. Dense regions within the capsule structure maintained stability during the dormancy phase, while pores and cracks facilitated the release of Bacillus megaterium bacteria when the capsules ruptured due to cracking. The biodegradable nature of the polysaccharide material further accelerated the breakdown of the capsule walls, allowing for timely bacterial activation and initiation of the self-healing process.SEM images also showed the presence of crystal formations along the crack paths, providing strong evidence of active self-healing, as shown in Figure 8.

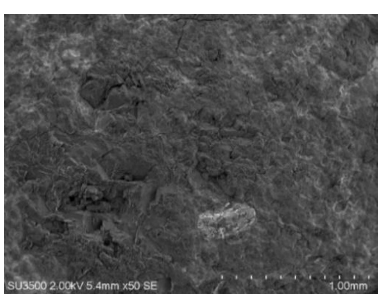


Fig. 8. SEM Observation at 50× Magnification of Algal Polysaccharide.

Complementary EDS analysis indicated a high presence of Oxygen (56.02%) and Silicon (21.99%), suggesting the presence of silicate compounds originating from the concrete matrix. The detection of Calcium (9.38%) confirmed the formation of calcium carbonate ($CaCO_3$) as a result of bacterial biomineralization. Other elements such as Aluminum (8.33%), Magnesium (1.43%), and Iron (2.84%) were also present in smaller amounts, contributing to the mineral composition of the healed areas, as shown in Figure 9.

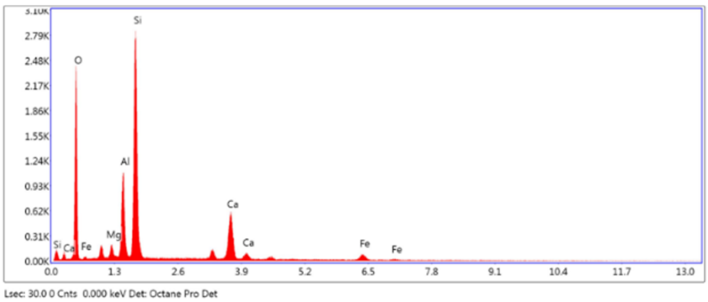


Fig. 9. EDS Analysis of Algal Polysaccharide Specimen

4 Conclusion

The objective of this study was to observe the behavior of Bacillus megaterium encapsulated using algae based polysaccharide biopolymers and evaluate its effect on the compressive strength of normal concrete. The selected biopolymer is environmentally friendly, biodegradable, and widely available on the market.

The test results showed that the addition of 2% algae-based capsules led to a significant improvement in compressive strength. On days 7 and 28, the compressive strength reached 25.85 MPa and 32.56 MPa respectively, representing an increase of up to 28.7% compared to normal concrete. This enhancement is attributed to the bacterial release triggered by cracking, which initiates calcium carbonate ($CaCO_3$) precipitation. The $CaCO_3$ fills pores and microcracks, resulting in a denser and more homogeneous concrete structure.

Visual observation over a 28 day period confirmed that crack closure began as early as the first week, indicating an active self-healing process in the 2% capsule variation. Supporting microstructural analysis was conducted using SEM-EDS. SEM images revealed that the capsules had porous and brittle surfaces, allowing for bacterial release upon cracking. Crystalline formations of $CaCO_3$ were observed within the cracks, further confirming the healing mechanism. EDS analysis identified dominant elements such as Oxygen (56.02%), Silicon (21.99%), and Calcium (9.38%), indicating the presence of silicate compounds and calcium carbonate as a result of bacterial biomineralization.

In conclusion, the addition of 2% algae-based polysaccharide capsules proved effective in enhancing both the compressive strength and self-healing capability of concrete. Further research is recommended to evaluate higher capsule concentrations and their influence on strength, porosity, and durability.

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