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HEALING EFFICIENCY OF *BACILLUS MEGATERIUM* FOR MICROCRACKS IN CONCRETE: A STUDY OF BIOPOLYMER ENCAPSULATION PERFORMANCE

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ABSTRACT: Cracks are a primary cause of degradation in concrete structures, typically arising from plastic shrinkage, excessive loading, or environmental exposure. Traditional repair methods, such as epoxy or cement grouting, often involve toxic chemicals and are not economically sustainable. As an alternative, self-healing concrete integrating microbial agents like *Bacillus Megaterium* offers a sustainable solution for autonomous crack repair. This study explores the encapsulation of bacteria within biopolymer microcapsules using sodium alginate and xanthan gum. The research aims to identify the optimal microcapsule dosage that balances mechanical integrity and healing efficiency. Concrete specimens with 1-5% microcapsule content were tested for compressive strength and crack recovery. Results show that 2% microcapsule addition offers the best balance of strength and healing performance. Analytical tools such as Scanning Electron Microscopy (SEM) and CT scans were employed to observe healing activity and microstructural changes. Self-healing concrete demonstrates high potential for reducing maintenance needs, enhancing structural longevity, and contributing to environmentally sustainable construction practices.

Keywords: Self-Healing Concrete, Bacillus Megaterium, Biopolymer Encapsulation, Sustainable Construction Materials.

1. INTRODUCTION

Concrete is among the most widely used materials in the construction industry due to its high compressive strength and relatively low cost. However, it is inherently prone to cracking, particularly microcracks, which often occur due to plastic shrinkage, thermal stress, environmental exposure, and excessive loading [1]. Although these cracks may be microscopic and initially harmless, they can compromise the durability and integrity of the structure over time by allowing water and harmful substances to penetrate the concrete matrix [2]. This leads to corrosion of embedded reinforcement, reduced service life, and an increase in maintenance requirements [3].

Conventional crack repair techniques—such as epoxy injection, polyurethane, or cement grouting—are widely used, yet these methods tend to be costly, labor-intensive, difficult to apply in inaccessible areas, and often involve environmentally hazardous chemicals [4-5].

In light of these limitations, recent advances in material science have brought attention to self-healing concrete technology as a promising alternative to conventional maintenance approaches. This technology enables concrete to autonomously seal microcracks, thereby enhancing the structure's serviceability and longevity [6].

One of the most promising methods of self-healing involves *Microbiologically Induced Calcium Carbonate Precipitation* (MICP), in which bacteria are embedded into the concrete matrix. Upon the formation of cracks, these bacteria become active in the presence of water and nutrients, precipitating calcium carbonate to seal the cracks [7]. Previous research has demonstrated the effectiveness of several bacterial species such as *Bacillus sphaericus*, *Bacillus subtilis*, and *Bacillus pseudofirmus* in promoting self-healing in concrete [8-9].

However, *Bacillus megaterium*, a member of the same genus, has received relatively little attention in this context despite its favorable biological characteristics. This species is known for its large cell size, availability in diverse environments such as soil, seawater, and rice fields, and its high tolerance to environmental stressors, including drought and nutrient deprivation [10]. These properties make *Bacillus megaterium* a promising candidate for application in concrete environments, particularly in regions subject to harsh weather conditions.

To ensure bacterial viability and controlled release, encapsulation techniques using biopolymers have been widely explored. Materials such as sodium alginate and xanthan gum offer biocompatibility, biodegradability, and cost-effectiveness, making them suitable candidates for encapsulating bacterial spores intended for self-healing applications [11-12].

This study evaluates the healing efficiency of *Bacillus megaterium* encapsulated in sodium alginate and xanthan gum for repairing microcracks in concrete. It focuses on identifying the optimal dosage of microcapsules that ensures both effective healing and adequate compressive strength. Additionally, it examines the viability of the encapsulated bacteria through microstructural analysis using Scanning Electron Microscopy (SEM) and CT scanning. The results aim to support the development of more sustainable and durable construction materials, promoting improved longevity and performance in concrete structures.

The Viability of *Bacillus subtilis* bacteria as a Self-Healing Agent in Geopolymer Mortar shows promising results [13]. The study was conducted using *Bacillus subtilis* bacteria media and calcium lactate, in geopolymer concrete, namely fly ash. This study was conducted on 3 types of NaOH concentrations, namely 4M, 10M and 16M, with a mixing ratio of $NaOH/Na_2SiO_3$ solution = 2.5. Variations of *Bacillus subtilis* bacteria and calcium lactate are 1% + 2%; 1.5% + 3% and 2% + 4%. The test objects used were 10x10x10 cm mortar cubes with a total of 48 test objects, testing was carried out at the ages of 14, 21 and 28 days. The results obtained in this study were that the optimum use of *Bacillus subtilis* bacteria was at a percentage of 1% - 2% calcium lactate with 10M NaOH, and the bacteria were able to cover the crack area by 38.45% [13].

There are several species of *Bacillus* that produce urease enzymes to precipitate calcite associated with biomineralization [14]. Research that reviews the comparison of various types of bacteria on the addition of compressive strength in concrete has been conducted [15]. The bacteria analyzed were *Bacillus subtilis*, *Bacillus sphaericus*, and *Bacillus megaterium*. The results of the study showed that of the three types of bacteria observed, *Bacillus megaterium* was proven to be able to increase the compressive strength of concrete by 48% [16]. The results of the study showed that the bio-mineralization process will not interfere with the setting time of concrete. Therefore, any standard concrete mix design can be used for bacterial concrete. Based on the mechanism of bio-mineralization (precipitation of $CaCO_3$), this new technique can significantly reduce the maintenance costs required for bacterial concrete due to its longer service life growth, which will further reduce CO_2 emissions in the atmosphere to help reduce some of the global warming and thus reduce the demand/need for cement [17], the Eq. (1) showing the sequence of biochemical reactions that occur to form calcium carbonate in cementitious materials with the help of ureolytic bacteria is as follows [18] :

$$CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

A further benefit of the calcite precipitation method for producing self-healing concrete is its ability to autonomously seal minor fissures, thereby diminishing the necessity for manual repairs. The deposition of $CaCO_3$ within the pores and cracks enhances the concrete's density, consequently augmenting its compressive strength and structural integrity [19]. Due to its self-healing properties and enhanced tolerance to harsh conditions, concrete exhibits greater durability and necessitates reduced maintenance. Microencapsulation is a technology to wrap or coat a core substance with a layer of polymer walls, so that it becomes small particles of micro size [20]. These microcapsules will be able to protect calcium carbonate-producing bacteria, so that in the process they are able to fill cracks [21].

This study proposes the development of an innovative self-healing concrete system by incorporating *Bacillus megaterium*, a bacterial strain that remains relatively unexplored in this context, in combination with microcapsule technology to improve bacterial viability within the concrete matrix. Calcium lactate is utilized as a nutrient source that also functions as a binding and hardening agent, supporting bacterial activity for autonomous crack repair. The engineered microcapsule system facilitates crack detection and healing by releasing bacterial agents upon structural damage, thereby enhancing the material’s durability. *Bacillus megaterium* contributes to the healing process by producing calcium carbonate ($CaCO_3$) in the presence of calcium and carbon dioxide, which effectively seals cracks. The ultimate objective of this research is to develop a functional prototype of smart self-healing concrete suitable for practical implementation in the construction industry. The self-healing process of microcapsules-based concrete is illustrated as in Fig. 1.

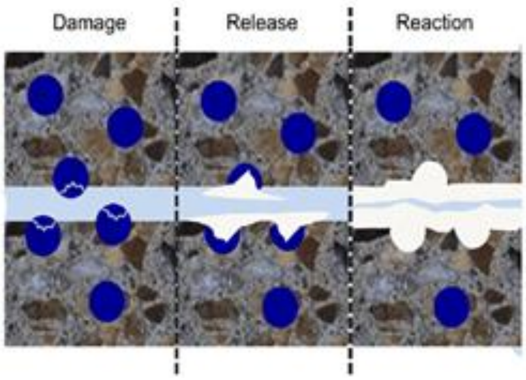

Fig. 1 Illustration of the self-healing process of microcapsule-based concrete [10]

There are various types of materials for the encapsulation methods. In general, the materials that are often used are Maltodextrin, Gum arabic, Alginate, Chitosan, Carrageenan, *Cyclodextrin*, Mesquite gum, Pullulan, and Xanthan gum [22].

In this study, Xanthan gum and Sodium Alginate were used as encapsulation coating materials for *Bacillus megaterium* bacteria. Other biopolymer materials have been tried, but those that are able to form gels and have good durability are alginate and xanthan gum. Xanthan gum itself is a natural polysaccharide biopolymer made from Xanthomonas campetris bacteria and was discovered in 1950 at the Northern Regional Research Laboratories (NRRL) [23]. Xanthan gum can be used as an encapsulation material because it has several properties, including high solubility in cold and hot water, high viscosity, natural emulsifier, low heat, pseudoplasticity, high pH resistance, and high temperature resistance [24].

Sodium alginate is a natural polymer derived from brown algae (Phaeophyta) and is known for its ability to form gels without the need for heating [25]. Gel formation occurs through an ionic reaction between a sodium alginate solution and a calcium salt, in which calcium ions replace sodium ions and bind to the long alginate molecular chains. Compared to other materials such as agar, this method is advantageous due to its ability to form gels at temperatures below 40°C without the need for high heat [26]. Based on these characteristics, this study aims to evaluate the encapsulation method of *Bacillus megaterium* using sodium alginate as a coating material in comparison with xanthan gum. It is hypothesized that different encapsulating materials will affect the viability and self-healing efficiency of the bacteria, with one material potentially offering better protection and prolonged bacterial activity, thereby enhancing concrete durability and crack repair performance.

2. RESEARCH SIGNIFICANCE

This study presents a novel approach to sustainable infrastructure by developing microbial self-healing concrete using biopolymer-encapsulated *Bacillus megaterium*. Unlike conventional chemical-based repair methods, this research introduces an eco-friendly alternative through the use of sodium alginate and xanthan gum microcapsules, optimizing dosage for both mechanical performance and healing efficiency. The originality lies in identifying the 2% microcapsule threshold as the optimal balance, supported by advanced imaging tools like SEM and CT scans. This work pioneers the integration of natural polymers in microbial concrete design, offering a scalable, low-impact solution to extend service life and reduce the carbon footprint of concrete infrastructure.

3. MATERIALS

3.1 *Bacillus megaterium*

Bacillus sp. is a Gram-positive, rod-shaped bacterium that can grow under both aerobic and anaerobic conditions. It produces heat-resistant spores and is capable of degrading xylan and various carbohydrates. Due to its ability to break down organic compounds, this bacterium plays an important role in various biotechnological applications [27]. In this study, *Bacillus megaterium* was obtained commercially and subsequently cultured in the laboratory. The morphology of the *Bacillus megaterium* in Fig. 2.

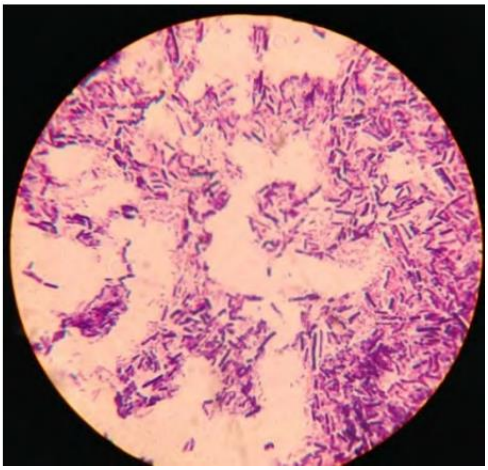

Fig. 2 *Bacillus megaterium*

3.2 Biopolymers

Biopolymers are organic compounds found in natural sources; the phrase comes from the Greek word's "bio" and "polymer," which stand for nature and living things. Biopolymers are large macromolecules composed of many repeating units [28]. There are two types of biopolymers: (1) natural biopolymers, such as cellulose, alginate, and xanthan gum; and (2) synthetic biopolymers, such as polylactic acid, polycaprolactone, and polyvinyl alcohol.

3.2.1. Alginate

Alginate is a natural polymer found in brown algae (Phaeophyta). This polymer is formed from alginic acid salts, which are basically copolymers of two main blocks, namely β-dmannuronic acid (M) and α-l-guluronic acid (G) as C-5 epimers. These two blocks are linked together to form a linear polysaccharide with (1,4)-glycosidic bonds [29]. Alginate can create a gel that can be kept at room temperature and is stable when heated. Alginate's propensity to create a gel is one of its features, which is why it was used in this investigation. When calcium salt and sodium alginate solution are mixed, a gel will form [25].

3.2.2. Xanthan gum

Xanthan gum is a heteropolysaccharide with a complex structure derived from β-D-glukosa with 1-

4 bonds, containing branched β-D-mannose and potentially containing piruvat and asetat [30]. Because it has properties as an emulsifier, xanthan gum can be used for encapsulation materials.

4. METHODOLOGY

This study employs an experimental method conducted in the chemical engineering bioprocess laboratory at Bandung State Polytechnic for bacterial culture, and in the civil engineering materials laboratory at the same institution for the making and testing of concrete samples. The used microorganisms are from the *Bacillus sp*. species, namely *Bacillus megaterium*, with xanthan gum and sodium alginate functioning as the microcapsule material. The generated concrete samples possess a cylindrical form with a diameter of 15 cm and a height of 30 cm. The stages of this research begin with the cultivation of *Bacillus megaterium* bacteria, followed by the production of xanthan gum and sodium alginate microcapsules, the creation of concrete cylinder specimens containing the microcapsules, subsequent sample testing, and finally, the analysis and conclusion phase.

4.1 Bacterial Cultivation

The initial stage of this study focused on the cultivation of *Bacillus megaterium*, conducted in the Bioprocess Laboratory of the Chemical Engineering Department at Bandung State Polytechnic. The process began by preparing a liquid growth medium, in which 14 grams of Nutrient Broth (HIMEDIA) were dissolved in 500 mL of distilled water and stirred using a magnetic stirrer on a hotplate at 60°C for approximately 10 minutes until fully homogenized. The solution was then sterilized in an autoclave at 121°C and 15 psi for 15 minutes. This sterilized medium served as a nutrient-rich environment to support bacterial growth. Inoculation was carried out by transferring 2 to 3 bacterial smears of *Bacillus megaterium* into the sterile medium using a loop needle. The inoculated culture was then incubated in a shaker incubator at 30–35°C for 2 to 3 days. Successful bacterial growth was indicated by increased turbidity of the liquid medium.

4.2 Microcapsules Preparation

4.2.1 Sodium Alginate Microcapsules

The method of making microcapsules, also known as the encapsulation process, starts with the weighing of 3.64% (w/v) sodium alginate powder dissolved in 140 milliliters of distilled water. The sodium alginate solution is made sterile by pasteurizing it for 15 minutes at 80°C. Once the bacterial solution has cooled, it is combined with the sodium alginate solution in a 1:4 ratio (1 mL of bacteria: 4 mL of sodium alginate solution). Microcapsule balls are created by putting the solution combination into a syringe and then dripping it into a 0.2 M $CaCl_2$ solution.

4.2.2 Xanthan Gum Microcapsules

A 4.2% (w/v) xanthan gum solution was prepared and pasteurized at 80°C for 15 minutes. After cooling, it was mixed with bacteria in the same 1:4 ratio and dispensed into 0.2 M $CaCl_2$ solution to produce gelled microcapsules.

4.3 Concrete Samples Preparation

Cylindrical specimens (15 cm diameter × 30 cm height) were made based on SNI 1974:2011 and ASTM C192. Mixtures included fine and coarse aggregates, cement, 1% calcium lactate (by cement weight), water, and microcapsules (1–5% by volume). A slump test was performed targeting 10 ± 2 cm. Fresh concrete was cast into molds, cured in water, and tested at 7 and 28 days. The quantity of samples produced is detailed in Table 1.

Table 1. Details amount of cylindrical samples

Test	Materials	Microcapsules Percentage (%)	7 Days	28 Days	Sam-ples
Com-pressive Strength	Sodium Alginat/ *Xanthan Gum*	0 (Virgin Concrete)	3	3	6
		1	3	3	6
		2	3	3	6
		3	3	3	6
		4	3	3	6
		5	3	3	6
Total Samples					36

The fabrication of test specimens began with the preparation of all necessary tools and materials. Fine aggregate, coarse aggregate, cement, and 1% calcium lactate (by cement weight) were mixed, followed by the gradual addition of water to achieve the desired water-cement ratio. A slump test was then performed in accordance with ASTM C-143, with a target slump of 10 ± 2 cm. Microcapsules were added to the fresh concrete mixture and blended for approximately two minutes to minimize capsule rupture. The concrete was subsequently cast into block molds measuring 50 × 10 × 10 cm. Flexural strength tests were conducted on days 7 and 28 after curing. The curing process involved submerging the specimens fully in water, beginning immediately after demolding and concluding one day prior to compressive strength testing.

4.4 Compressive Strength Test

Compressive strength is defined as the load per unit area that induces failure in a concrete specimen when subjected to a specific compressive force from a compression testing apparatus. In this study, the compressive strength test was based on SNI 1974 – 2011.

5. RESULT AND DISCUSSION

5.1 Tensile Strength Testing for Alginate and *Xanthan Gum* Microcapsules

Prior to being embedded in concrete, the mechanical performance of alginate and xanthan gum microcapsules was evaluated using a 250 kN Instron 5985 Universal Testing Machine (Fig. 3). The results are summarized in Table 2 and illustrated in Fig. 4.

Fig. 3 Instron Testing Machine 5985 250 kN

Table 2 Tensile strength test results of sodium alginate and *xanthan gum* microcapsules

Microcapsules Materials	Dimensions of Sample			Max Load (N))	Tensile Strength (MPa)
	Length (mm)	Width (mm)	Thickness (mm)		
Sodium Alginate	70.00	27.00	5.00	2.806	0.021
Xanthan Gum	51.00	25.00	4.10	0.929	0.0044

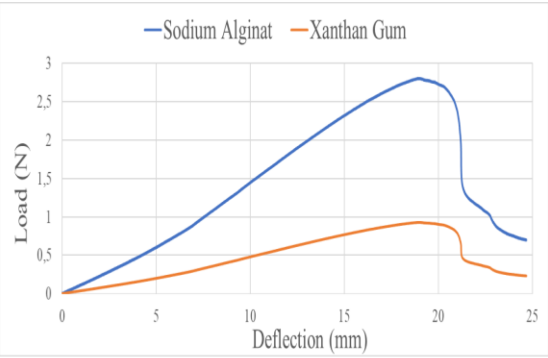

Fig. 4 Graph of test results for alginate and *xanthan gum* microcapsules

The microcapsule materials tested included alginate and xanthan gum, with sample dimensions of 60 × 27 × 5 mm and 51 × 25 × 4.1 mm, respectively. Tensile strength testing using a Universal Testing System (UTS) revealed that alginate microcapsules exhibited a higher average tensile strength (0.0208 MPa) and maximum load capacity (2.8064 N) compared to xanthan gum (0.00441 MPa and 0.9292 N, respectively). These results indicate that alginate possesses superior mechanical properties, making it a more suitable candidate for microcapsule production in self-healing concrete applications. The relatively low tensile strength of xanthan gum raises concerns regarding its structural integrity and durability when embedded in concrete. Due to equipment and methodological limitations, the produced microcapsules lacked uniformity; however, representative samples were randomly selected for evaluation. The resulting microcapsules measured approximately 1–3 mm in diameter, with measurements taken using a screw micrometer. Based on the properties tests that have been carried out, the differences in the properties of several encapsulation materials are presented in Table 3**.**

Table 3 Encapsulation material properties

Encapsulation Materials	Advantages	Disadvantages
Alginat	For manotex type alginate (textile thickener) the price is cheap and easy to get.	Alginate gels have weaknesses in terms of mechanical strength and can be brittle, making them unsuitable for applications requiring high mechanical strength.
	Alginate easily forms a gel when interacting with calcium ions (Ca^{2+}). This allows the formation of capsules in a simple way and conditions that do not damage the active ingredients.	Alginate is sensitive to pH changes, so its stability can be compromised in strongly acidic or basic environments, limiting its application to certain conditions.
Xanthan Gum	It easily binds with Calcium (Ca) ions so that it easily forms a gel, although the gel strength is not as good as alginate, but not as bad as carrageenan. This material is easy to get and affordable.	Xanthan gum is a polysaccharide so it is very easy for other bacteria to grow if it is not sterile.

5.2 Compressive Strength Test

5.2.1 Compressive Strength Test Results of Alginate Microcapsule Variation Concrete

The data from the concrete compressive strength test is displayed in both graphical and tabular formats to offer a detailed overview of the strength variation caused by the addition of alginate microcapsules in concrete mixtures. The displayed findings encompass the mean concrete compressive strength and its evolution at 7 and 28 days.

Table 4 Summary of the compressive strength test outcomes for 7-day-old alginate variation concrete

Variations	Microcapsules Percentage	Compressive Strength (MPa)	Standard Deviation
Virgin Concrete	0%	30.1	0.946
Alginate Variation Concrete (AVC)	1%	23.9	1.144
	2%	25.6	2.829
	3%	24.3	1.233
	4%	23.6	0.844
	5%	15.3	6.763

Table 5 Summary of the compressive strength test outcomes for 28-day-old alginate variation concrete

Variations	Microcapsules Percentage	Compressive Strength (MPa)	Standard Deviation
Virgin Concrete	0%	30.8	0.999
Alginate Variation Concrete (AVC)	1%	27.8	5.508
	2%	31.6	2.012
	3%	25.1	1.815
	4%	23.4	1.171
	5%	14.7	1.863

Based on the test results and calculations that have been carried out, the following graph can be made.

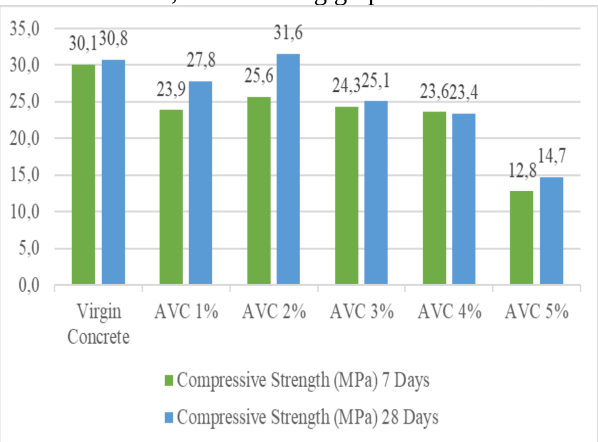

Fig. 5 Concrete compressive strength testing graph of alginate microcapsule variation

According to Table 4, Table 5 and Fig. 5, concrete incorporating sodium alginate microcapsules exhibits reduced compressive strength compared to standard concrete at both 7 days and 28 days of curing. Incorporating 2% alginate microcapsules results in a maximum compressive strength of 25.6 MPa at 7 days and 31.6 MPa at 28 days of concrete age. The graph indicates that an increase in the proportion of alginate microcapsules correlates with a reduction in the average compressive strength of concrete. Following the initial test, the concrete will undergo an additional 28 days of curing, accompanied by visual inspection, and will be subjected to a second compressive strength assessment. The outcomes of the second test are displayed in Table 6 below**.**

Table 6 The compressive strength test results of the second sodium alginate microcapsule variation concrete

Sample Name	First Test (MPa)	Second Test (MPa)	Strengh Recovery
	28 days	28 days	
AVC 1%	27.8	4.5	16.27 %
AVC 2%	31.6	11.9	37.66 %
AVC 3%	25.1	13.6	54.17 %
AVC 4%	23.4	16.9	72.45 %
AVC 5%	14.7	17.3	117.4 %

The results of the second compressive strength test indicated that the highest percentage of return strength for the alginate variation was 117.4%, achieved with the addition of 5% alginate microcapsules. The test results indicate that an increase in the percentage of alginate microcapsules correlates with a rise in return strength. The addition of microcapsules to the concrete leads to an increased proportion of fractured microcapsules. The increased fragmentation of microcapsules will correspondingly elevate the proliferation of *Bacillus megaterium* bacteria within the concrete. The *Bacillus megaterium* bacteria will interact with air and water to produce calcium carbonate. The quantity of *Bacillus megaterium* bacteria correlates positively with the calcium carbonate content resulting from bacterial processes.

5.2.2 Compressive Strength Test Results of Xanthan Gum Microcapsule Variation Concrete

This section presents the results of concrete compressive strength testing with changes in the incorporation of xanthan gum microcapsules containing *Bacillus megaterium* bacteria as additives. The results from the concrete compressive strength test are displayed through graphs and tables to illustrate the fluctuation in strength due to the incorporation of alginate microcapsules in concrete mixtures. The displayed findings encompass the mean concrete compressive strength and the strength progression at 7 and 28 days. Based on the test results and calculations that have been carried out, the following graph can be made.

Table 7 Summary of concrete compressive strength test outcomes for xanthan gum microcapsule variations at 7 days of age

Variations	Microcapsules Percentage	Compressive Strength (MPa)	Standard Deviation
Virgin Concrete	0%	30.1	0.946
Xanthan	1%	23.8	5.521
Gum	2%	27.9	1.446
Variation	3%	24.6	2.954
Concrete	4%	24.3	0.719
(XVC)	5%	21.1	1.847

Table 8 Summary of concrete compressive strength test outcomes for xanthan gum microcapsule variations at 28 days of age

Variations	Microcapsules Percentage	Compressive Strength (MPa)	Standard Deviation
Virgin Concrete	0%	30.8	0.999
Xanthan	1%	31.9	0.465
Gum	2%	34.1	0.639
Variation	3%	29.7	0.195
Concrete	4%	27.2	6.896
(AVC)	5%	26.6	3.422

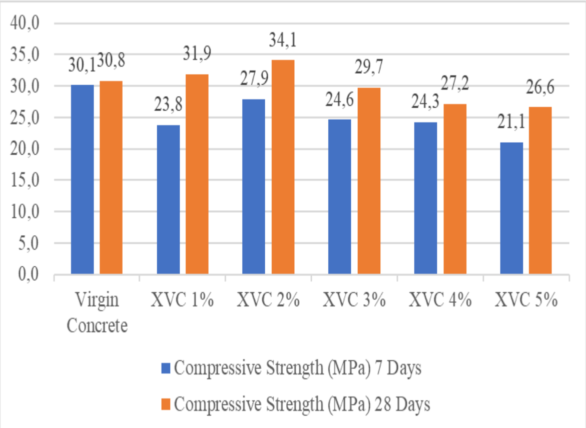

Fig. 6 Chart for evaluating the compressive strength of concrete with varying xanthan gum microcapsules

According to Table 7, Table 8 and Fig. 6, the average compressive strength of concrete variations including xanthan gum microcapsules at 7 days has not attained the target quality of fc' = 30 MPa. The maximum compressive strength of xanthan gum microcapsule variant concrete is achieved with the addition of 2% microcapsules, resulting in a strength of 27.9 MPa. Upon reaching 28 days, the average compressive strength of the concrete surpassed the specified quality of fc' = 30 MPa. The maximum compressive strength of concrete with xanthan gum microcapsule variation occurs at the addition of 2% microcapsules, measuring 34.1 MPa. Following the assessment of the concrete's compressive strength, the concrete was re-saturated and visually examined at intervals of 7, 14, and 28 days. Additionally, the concrete underwent a second evaluation for compressive strength to assess its recovery of strength. Table 9 below presents the comparative results of the initial and subsequent compressive tests.

Table 9 Compressive strength test results of concrete of the second xanthan gum microcapsule variation

Sample Name	First Test (MPa)	Second Test (MPa)	Strength recovery
	28 days	28 days	
XVC 1%	31.8	30.8	96.75 %
XVC 2%	34.1	32.3	94.59 %
XVC 3%	29.7	26.6	89.58 %
XVC 4%	27.2	28.01	103.13 %
XVC 5%	26.6	29.1	109.42%

According to Table 9, the highest strength recovery was recorded at 109.42% with the addition of 5% xanthan gum microcapsules. The test results demonstrated that the incorporation of both types of microcapsule materials contributed to an overall improvement in the compressive strength of concrete. However, further increases in microcapsule content beyond an optimal level led to a decline in mechanical strength. This reduction is attributed to the premature rupture of microcapsules before the formation of cracks, resulting in voids and poor internal cohesion within the concrete matrix.

The lack of effective bonding negatively impacts the structural integrity of the concrete, a finding supported by (Milla J et al., 2020). Interestingly, this trend is inversely proportional to the material's self-healing performance. Higher concentrations of microcapsules enhanced the healing process, as observed through visual inspection. Concrete containing 5% microcapsules exhibited a greater presence of white calcium carbonate compared to samples with 1%, indicating a higher rate of bacterial activation and calcium carbonate formation due to a larger number of ruptured capsules releasing healing agents. The mechanism of self-healing is shown by Fig. 7.

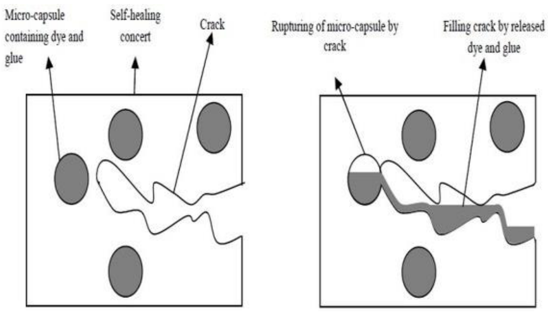

Fig. 7 Illustration of self-healing process

5.3 Scanning Electron Microscope Test

5.3.1 Scanning Electron Microscope (SEM) Test Results on Virgin Concrete

Scanning Electron Microscope analysis of virgin concrete specimens reveals a texture characterized by a rough and irregular surface, with numerous gaps and crevices present between particles. The particles in conventional concrete are dispersed randomly, lacking the influence of other elements that could enhance their cohesion or compaction. Virgin concrete possesses the coarsest texture and most pores among the aggregates. The increased porosity renders the concrete more vulnerable to water or chemical infiltration, thereby hastening its deterioration. The SEM results for the normal concrete are shown in Fig. 8.

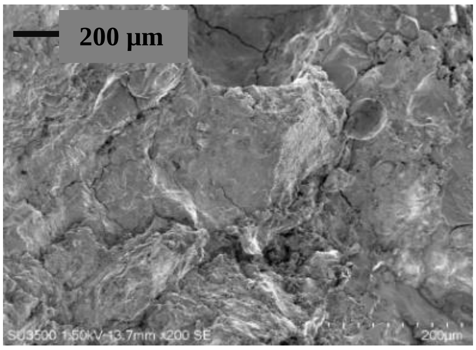

Fig. 8 Scanning Electron Microscope (SEM) test results on virgin concrete

5.3.2 Scanning Electron Microscope (SEM) Test Results on Alginate Variation Concrete 2%

The test results indicate that the texture of the alginate variant concrete appears somewhat smoother and more uniformly dispersed than that of conventional concrete. Concrete with alginate microcapsules has a more uniform particle distribution and a denser surface than conventional concrete. The generated layers may assist in filling minor gaps or fissures.

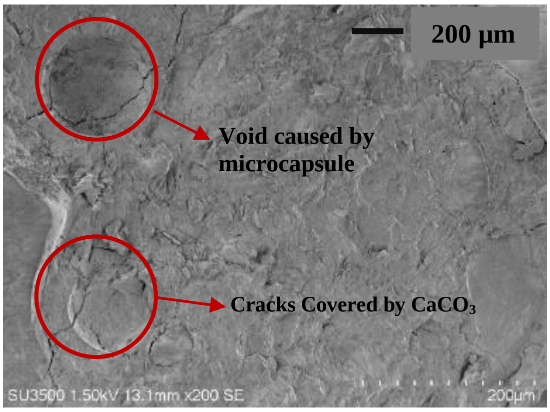

Fig. 9 Scanning Electron Microscope (SEM) test results on alginate variation concrete 2%

The incorporation of alginate microcapsules seems to diminish roughness and enhance microstructure density in concrete, perhaps leading to increased water resistance and structural longevity. The SEM results for the Alginate Variation Concrete 2% are shown in Fig. 9.

5.3.3 Scanning Electron Microscope (SEM) Test Results on Xanthan Gum Variation Concrete 2%

The test results indicate that the concrete containing *xanthan gum* microcapsule additions exhibits a denser and tighter texture. The surface exhibits greater homogeneity with reduced gaps and pores in comparison to standard concrete. The enhanced and more consistent texture signifies a notable decrease in porosity, perhaps augmenting the concrete's resistance to water or corrosive material penetration. Increased density may enhance structural strength. The SEM results for the Xanthan Gum Variation Concrete 2% are shown in Fig. 10.

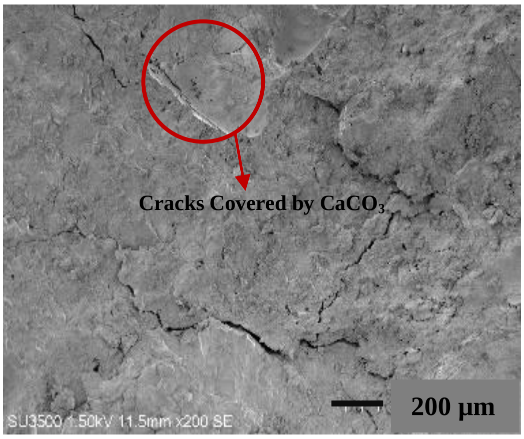

Fig. 10 Scanning Electron Microscope (SEM) test results on *xanthan gum* variation concrete 2%

5.4 X – Ray Computed Tomography Test

The X-Ray CT test was conducted to non-destructively examine the internal structure of concrete specimens. This method allows for the visualization of crack formation and the distribution of encapsulated microcapsules within the concrete matrix. The resulting CT images provide insight into whether the microcapsules are uniformly dispersed and if they remain intact or are ruptured due to internal stress, supporting the evaluation of the self-healing performance of the material.

Fig. 11 shows the results of the CT scan performed on concrete containing microcapsules. X-ray computed tomography (CT) scan results indicate a uniform distribution of alginate microcapsules within the concrete matrix, as visualized in the 2D scans. Such homogeneous dispersion is critical for ensuring the effectiveness of the self-healing mechanism, as it enables the microcapsules to be optimally positioned for rupture upon crack formation. When cracks occur, the microcapsules break and release healing agents that react to form calcium carbonate ($CaCO_3$), which precipitates and seals the cracks. The scans also revealed the presence of irregular voids, which are attributed to desiccated microcapsules. This desiccation is a consequence of the concrete hydration process, during which the internal water content of the microcapsules is consumed, making them less visible in CT imaging. Despite this, the observed voids along crack lines support the conclusion that the microcapsules were uniformly dispersed throughout the concrete.

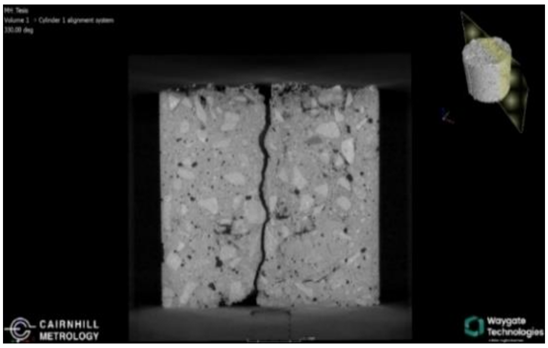

Fig. 11 X-ray test results in lateral view

6. CONCLUSION

Based on the experimental results and analysis conducted, the following conclusions can be drawn:

Both sodium alginate and xanthan gum are affordable and widely available biopolymers. However, the encapsulation process requires sterile conditions, which may limit large-scale production unless optimized.

The optimal microcapsule dosage for balancing compressive strength and healing performance is 2% for both materials. At this concentration, strength recovery reached 110% for alginate and 94% for xanthan gum after 28 days.

While higher dosages (up to 5%) improved healing performance, they also introduced more voids, reducing overall mechanical strength due to premature rupture of microcapsules.

SEM and CT scan analysis confirmed that the microcapsules enhanced concrete density and were uniformly distributed, supporting the healing process upon crack occurrence.

Although higher microcapsule dosages increased the crack healing capacity (up to 117.4% recovery for 5% dosage), they caused significant strength loss due to excessive voids and premature capsule rupture. The 2% dosage achieved the highest compressive strength (31.6 MPa) and adequate healing, thus representing the optimum balance for structural performance and durability

Further research is needed to evaluate long-term durability, the effect of environmental conditions, and cost-effectiveness for real-scale applications. Optimizing the mixing technique and capsule preservation during storage are also critical for practical implementation.

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