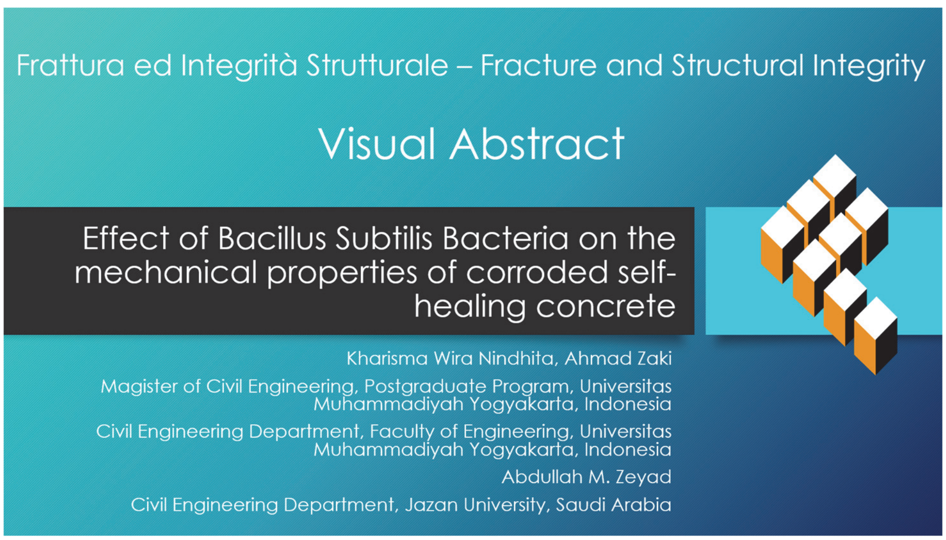
Effect of Bacillus Subtilis Bacteria on the mechanical properties of corroded self-healing concrete

Kharisma Wira Nindhita, Ahmad Zaki*
Magister of Civil Engineering, Postgraduate Program, Universitas Muhammadiyah Yogyakarta, Indonesia
Civil Engineering Department, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia
kharismawiranindhita2@gmail.com, ahmad.zaki@umy.ac.id

Abdullah M. Zeyad
Civil Engineering Department, Jazan University, Saudi Arabia
azmohsen@jazanu.edu.sa



OPEN ACCESS

Citation: Nindhita, K. W., Zaki, A., Zeyad, A. M., Effect of Bacillus Subtilis Bacteria on the mechanical properties of corroded self-healing concrete, Frattura ed Integrità Strutturale, 68 (2024) 140-158.

Received: 05.09.2023
Accepted: 22.01.2024
Published: 26.01.2024
Issue: 04.2024

KEYWORDS. Self-Healing Concrete, Bacillus bacteria, Corrosion, Mechanical Properties, Reinforced Concrete.

INTRODUCTION

Concrete is an excellent material in infrastructure development, including buildings, road pavements, drainage, dams, bridges, and railroad sleepers [1]. Concrete material usage has expanded globally from 2.8 to 4.08 billion tons in 2019 [2]. The type of concrete that is most widely used currently is reinforced concrete. Reinforced concrete combines conventional concrete's properties, which are resistant to compressive strength, and steel, resistant to bending or bending strength [3]. Adding steel reinforcement to concrete can increase the flexural strength value of concrete [4]. However, steel reinforcement also has a weakness against corrosion hazards. Steel reinforcement corrosion is considered a global problem in construction that leads to the deterioration of concrete structures [5]. Steel corrosion in concrete causes mass losses in reinforced concrete, including reduced structural strength and service life. It increases the cost and repair maintenance for reinforcement concrete structures [1, 5-7].

Steel reinforcement has a corrosion protection layer known as a passivity film. However, this layer can be destroyed by chloride ion or carbon reactions around the reinforcement [8, 9]. The formation of corrosion cells characterizes the corrosion initiation process. Corrosion cells can be micro- or macro-sized, which form general and pitting corrosion types [10]. The accumulation of corrosion product or rust on steel reinforcement occupies a larger volume than the original material, leading to cracking or spalling of the concrete cover [10-12]. The presence of cracks in concrete can further accelerate the corrosion process in reinforced concrete. Therefore, cracks must be repaired immediately to prevent further damage to the reinforcement concrete [1, 13]. To mitigate and prevent more severe cracks, it is necessary to carry out the concrete repair process as early as possible. Repairing concrete cracks early will be more cost-effective and labor-intensive than cracks that are already deep and wide [1, 13, 14].

Currently, the method of healing cracks in concrete, one of which is self-healing concrete, is increasingly being developed [15]. One of the methods to form Self-Healing Concrete is by adding certain chemicals or microorganisms to the concrete mixture, such as using bacteria as a healing agent [16]. Bacteria can convert dissolved organic nutrients into calcite crystals, which in turn serve to seal cracks and prevent corrosion [13, 17]. Bacillus sp. is often used in the self-healing concrete process, which can produce calcium carbonate crystals when cultured in a medium containing Ca^{2+} [18, 19]. The calcite group of Bacillus sp. experiences the deposition of $CaCO_3$, which includes ion exchange and pH. The negatively charged bacterial cell wall attracts positive ions such as Ca^{2+} from the environment and stores them on the cell surface [18]. Using Bacillus sp. also increases the compressive strength and significantly reduces the porosity of concrete [20, 21].

Research by Durga et al. [22] shows that self-healing agents can use several bacteria, such as Bacillus subtilis, bacillus cereus, bacillus licheniformis, and bacillus halodurans. Research conducted by Mirshahmohammad et al. [13] concerning the effect of sustained service load on steel corrosion and the self-healing process of reinforced concrete containing the sporosarcina pasteurii bacteria showed that the compressive and tensile strength of the specimens relative to the control treatment increased by 44% and 36%, respectively. In addition, the results show that the possibility of corrosion of the reinforcement decreases when using calcium nitrate as a bacterial nutrient. Research conducted by Osman et al. [23] discussed a comparison between the two species of Bacillus and the algae D. salina on compressive and flexural strength, corrosion rate, and the self-healing ability of concrete. The test results show that the percentage increase in the mechanical properties of concrete at the age of 3-7 days (35% on average) is more significant than at 28 days (8% on average). Adding bacteria and algae to concrete significantly reduced the corrosion rate with yields of 0.05 mm/year and 0.18 mm/year, respectively. The activity of bacteria and algae increases the passive layer protection on the reinforcement for corrosion inhibition.

In addition, research conducted by Reddy et al. [24] explained that the addition of bacteria as a self-healing concrete agent can be done using three methods, namely the direct, indirect, and vascular methods. The test results showed an increase in the flexural strength of concrete up to 4% compared to normal concrete. Research by Prayuda et al. [3] regarding the performance of the bacillus subtilis bacteria as a self-healing agent by injection into the cracked concrete beams showed that the repair of concrete cracks after 28 days reached 93.63%. It can be concluded that the bacillus subtilis bacteria can repair micro-cracks, but the injection method is not effective for repairing macro-cracks. Zhang et al. [25] said that to extend the survival time of bacteria in concrete, it is necessary to design a barrier using a low-alkaline cement material. Various examinations found that the protective coating can protect against bacteria for approximately 516 days.

Meanwhile, self-healing ability against cracks significantly increased after 122 days of age. The concrete still has a high repair area and water penetration rate for cracks. Qian et al. [15] tried to apply self-healing concrete to constructing the Maqun and Qilinmen stations for the Nanjing-Jurong Intercity Rail Transit Project. The study results showed that the curing method for self-healing concrete cracks with the help of wet burlap and nutrient solution was the best, followed by wet burlap and then water spray.

Research on bacteria-based self-healing concrete is still relatively new and rarely conducted in Indonesia. The use of Bacillus sp. in concrete mixtures has been known as a crack-healing agent in concrete and prevents concrete reinforcement corrosion. Hopefully, this will align with Indonesia's situation as a maritime country in its infrastructure development. Indeed, most large cities are in coastal areas prone to accelerated corrosion reactions. In the current research, the concept of self-healing in concrete will use the bacterial encapsulation method to increase the life of the bacteria to last longer in concrete conditions, which may be unsuitable. The corrosion process used in this study is an artificial corrosion method using the help of a DC power supply, commonly known as the corrosion acceleration method [7].

So, this research will focus on solving the corrosion problem, which always threatens the existence of reinforced concrete, especially if the structure is located in a humid area or frequently interacts with water, such as a coastal water structure or dam. In this study, the main ingredient for observation was the Bacillus subtilis bacteria, which is believed to have the ability to increase the strength of concrete. Therefore, this research will focus on assessing the influence of Bacillus subtilis bacteria on the mechanical properties of corroded self-healing concrete and its optimal values as an additive to self-healing concrete. The study analyzed the value of the flexural strength of concrete, the compressive strength of concrete, ductility, stiffness, and the effect of adding bacteria as a self-healing agent on the corrosion rate in reinforced concrete using Faraday's law. Crack patterns in reinforced concrete beams are observed to determine possible damage patterns. In addition, the self-healing process in concrete is also followed visually.

MATERIALS

The materials used to construct self-healing concrete in this study consisted of sand, gravel, cement, water, reinforcing steel, and encapsulated Bacillus subtilis bacteria. Sand with the criteria of passing filter no. 4 (4.75 mm) and retained on the No. Sieve. 200 (0.075 mm) [26] came from Progo, Yogyakarta. The gravel comes from Celereng, Yogyakarta, and meets the requirements of being hard, non-porous, not containing clay, and having a maximum diameter of 20 mm [27]. The cement used was Portland cement type I [28]. The reinforcing steel used was plain iron with a diameter of 8 mm and a diameter of 6 mm [29]. Meanwhile, the encapsulated Bacillus subtilis bacteria were obtained from the Agrobiotechnology Laboratory, Faculty of Agriculture, Universitas Muhammadiyah Yogyakarta. The bacterial encapsulation method functions as a protective layer for bacteria from concrete conditions that may not be compatible with the bacterial characters [18].

The encapsulation method used in this study was hydrogel encapsulation using the addition of a mixture of CMC or Carboxy Methyl Cellulose. The mix ratio between the bacterial solution and CMC powder is 1 milliliter to 3 grams or 1:3. The bacterial encapsulation process starts by mixing the bacterial solution with CMC powder. Then, it formed with a 5-15 mm diameter and arranged spaced on the tray. The pieces are allowed to dry naturally indoors for 2-4 days. The texture of the bacterial encapsulation, which was originally soft, will harden into pebbles after being air-dried. This bacterial encapsulation will become soft again when it reacts with water so that the bacteria contained in the encapsulation can fill the voids in the cracks in the concrete [18]. The Bacillus bacteria solution before encapsulation is shown in Figure 1, while the encapsulated Bacillus subtilis bacteria is shown in Figure 2.

Figure 1: Bacillus subtilis bacteria solution.

Figure 2: Encapsulated Bacillus subtilis bacteria.

Before the mix design process and the manufacture of the specimens are carried out, several tests are carried out: a specific gravity test, water absorption test, gradation test, abrasion test, and sludge content test. From the results of the sand test, it was found that the fine modulus value was 2.403, and the gradation criteria met the requirements, as shown in Figure 3 and Table 1. Meanwhile, the gravel test results are shown in Table 2.

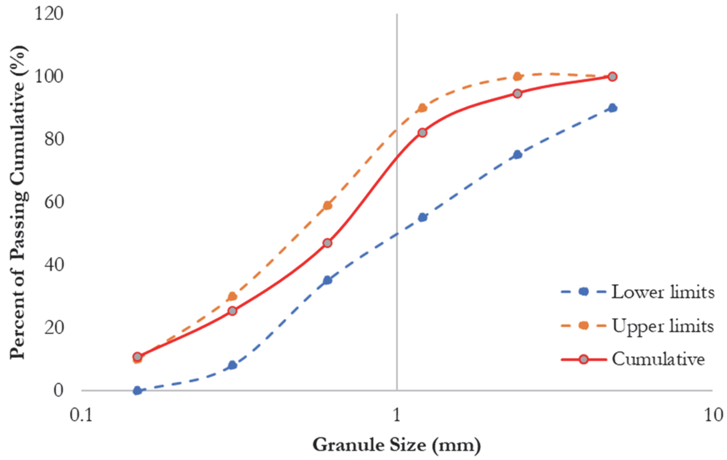


Figure 3: Fine grain gradation chart.

Test Type	Value	Unit	Standard
Fine modulus	2.403	-	SNI ASTM C136:2012 [26]
Bulk specific gravity	2.606	-	SNI 1970:2008 [30]
Saturated surface dry specific gravity	2.635	-	SNI 1970:2008 [30]
Apparent specific gravity	2.684	-	SNI 1970:2008 [30]
Water absorption	1.112	%	SNI 1970:2008 [30]
Mud content	1.60	%	SNI ASTM C117:2012 [31]

Table 1: Fine aggregate test data.

Test Type	Value	Unit	Standard
Bulk specific gravity	2.6614	-	SNI 1969:2008 [27]
Saturated surface dry specific gravity	2.6933	-	SNI 1969:2008 [27]
Apparent specific gravity	2.7493	-	SNI 1969:2008 [27]
Water absorption	1.2	%	SNI 1969:2008 [27]
Mud content	1.5	%	SNI ASTM C117:2012 [31]
Abrasion	21	%	SNI 2417:2008 [32]

Table 2: Coarse aggregate test data.

Methods

The planning of the concrete mixture uses ACI 211.1-91 concerning Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete [33] with a design concrete quality of 30 MPa and w/c ratio of 0.43. The number of proportions of Bacillus subtilis bacteria added to the concrete mixture, namely, 0%, 0.1%, 0.6%, and 1.5% by weight of sand. The proportions of the mix design concrete per 1 m^3 are shown in Table 3.

Materials	Total	Units
Sand	746.63	kg
Gravel	1077.12	kg
Cement	379.63	kg
Water	162.11	liter
0.1% encapsulated bacteria	0.75	kg
0.6% encapsulated bacteria	4.48	kg
1.5% encapsulated bacteria	11.20	kg

Table 3: Mix designs concrete per 1 m^3

Test specimens of reinforced beams measuring 620x150x150 mm are used to test the concrete's corrosion, self-healing, and flexural strength. Meanwhile, cylindrical specimens measuring 150x300 mm are only used to test concrete's compressive strength. All specimens were printed, cured using normal water, and then tested at 28 days. Details of the test specimens for beams and cylinders can be seen in Figure 4 and Figure 5. The test specimens for beams have a main reinforcement diameter of 8 mm and stirrups of 6 mm, which are attached to small wires on the reinforcement as a channel for the accelerated concrete corrosion process with the help of a DC power supply. The concrete cover is designed at 20 mm. Bacteria are not directly mixed when mixing fresh concrete but when pouring fresh concrete into the formwork. This aims to ensure that the encapsulation of bacteria is not damaged during the mixing process of fresh concrete due to the addition of water and collisions between aggregates. The example specimens after the age of 28 days or before the corrosion acceleration process are shown in Figure 6 below.

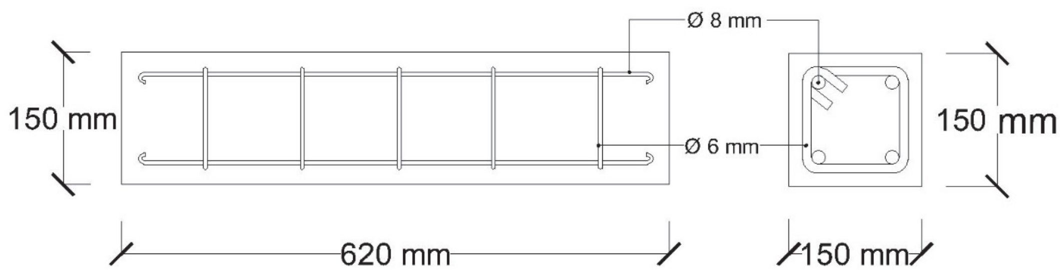


Figure 4: Schematic of the beam specimen

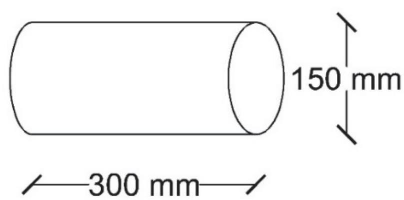


Figure 5: Schematic of the cylinder specimen.

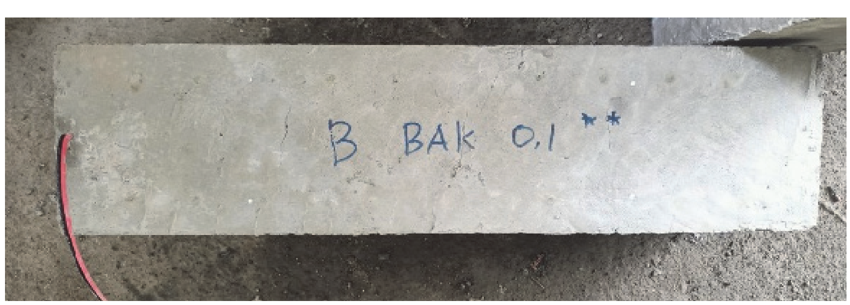


Figure 6: Example of a specimen before the corrosion acceleration process.

Corrosion testing uses the corrosion acceleration method by connecting the positive pole cable to the concrete reinforcement. In contrast, the negative pole is connected to the reinforcement submerged in a saltwater solution [14]. The solution used has a salinity of 5% and a corrosion percentage of 20%. The DC power supply has current specifications of 3 A and 5 A to accelerate the corrosion process on concrete. The corrosion acceleration scheme can be seen in Figure 7.

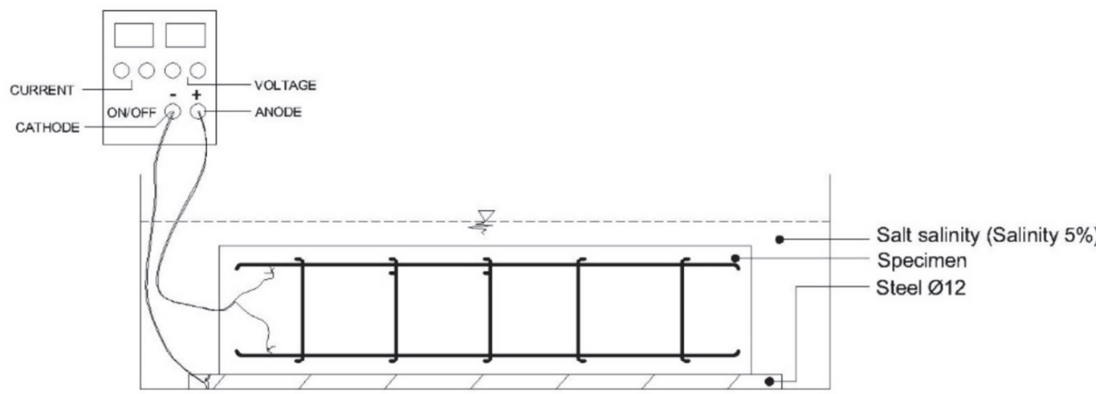


Figure 7: Corrosion acceleration scheme.

Meanwhile, testing for corrosion acceleration can be planned using the principles of Faraday's Law, which refers to the percentage loss of reinforcement mass due to the corrosion process. The formula for calculating the target corrosion acceleration plan is shown in Equation 1. Where Δm is the weight loss on the reinforcement (grams), M is the atomic weight of the metal (56 g/mol for steel), I is the electric current (A), t is the duration of corrosion (seconds), z is the number of electrons that react (2 for steel), and F is the Faraday constant (96500 A/s)[14].

$$\Delta m = \frac{M \times I \times t}{z \times F} \tag{1}$$

After the corrosion process has been completed, the flexural strength of the concrete is tested using the four-point bending test method. The test is carried out with two loading points in the middle span of the beam and at 5 cm between the supports and the edge of the beam. The flexural testing scheme is shown in Figure 8 below. The flexural strength test of the beam was carried out twice. The first bending test provides initial cracks in the form of hairline cracks in beams with a load of 20-30 kN. After that, the self-healing test was carried out on concrete with observations for 28 days. After the self-healing observation process, a second bending test is carried out by providing the maximum load the concrete beam can withstand.

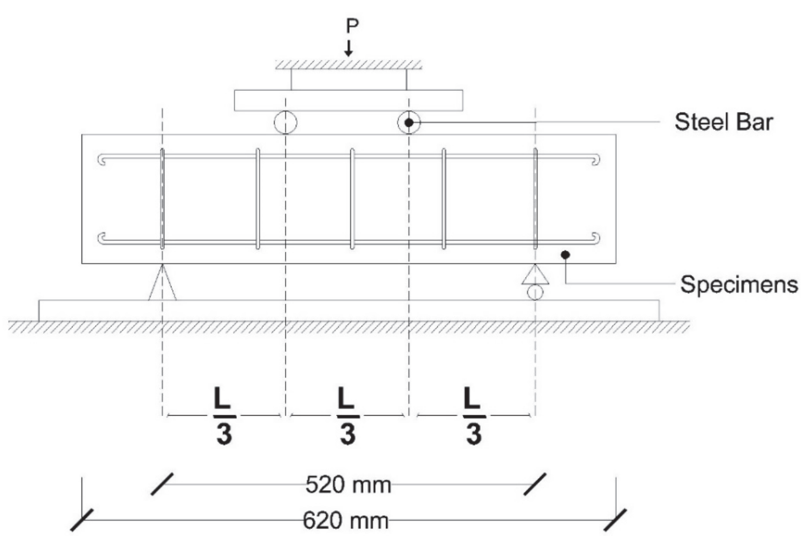


Figure 8: Flexural test scheme.

RESULTS AND DISCUSSIONS

Corrosion acceleration test results

The beam specimens were corrosion accelerated with a design target corrosion rate of 20%. After the corrosion acceleration, self-healing, and flexural strength tests have been completed, concrete demolition is carried out to determine the final reinforcement weight after the corrosion test. Figure 9 shows the example of a beam specimen after the corrosion acceleration process.

Figure 9: Example of beam specimen after the corrosion acceleration process.

From the results, the comparison of the planned corrosion rate to the actual corrosion results is not too different, namely in the 2-5% range. In addition, adding various bacteria also inhibits the corrosion rate in reinforced concrete. This can be seen from the results of the 0% bacterial variation, which shows the highest level of corrosion rate. The average corrosion rate of the 0% bacterial variation is 22.21%, then the corrosion rate decreased to 15.85% or has a difference of around 6.36% with the addition of 0.1% bacterial variation. However, additional bacterial variations at 0.6% and 1.5% indicate no enhancement in the concrete corrosion rate. The overall summary of the corrosion test results is shown in Figure 10 below.

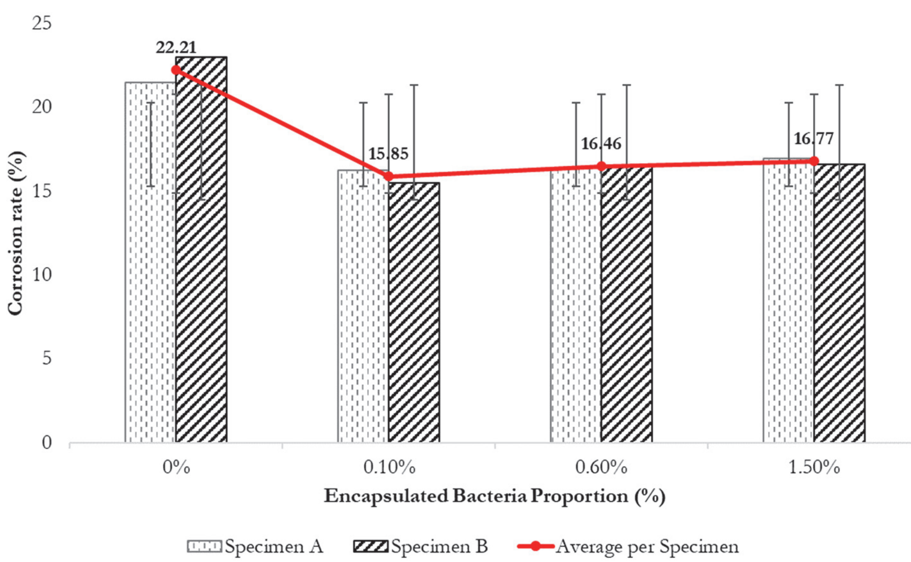


Figure 10: Concrete corrosion test results.

From the results of this research, adding bacterial encapsulation to concrete can reduce corrosion in reinforced concrete. A decrease in the level of corrosion of self-healing concrete using encapsulated bacteria can occur due to the formation of $CaCO_3$ in the concrete cavity. As is known, bacterial encapsulation can be active due to a reaction with water or a solution due to the dissolution of the CMC-based capsule, so the bacteria can be active and form $CaCO_3$ deposits that fill the voids in the concrete. In this case, the encapsulated bacteria may be active and form $CaCO_3$ deposits during the corrosion acceleration process due to the immersion process in the NaCl solution. As a result of the formation of $CaCO_3$, it is possible to inhibit the corrosion process in self-healing concrete reinforcement because calcite formation can act as a passive protective layer on concrete reinforcement and can interfere with the reaction of corrosion cell formation [17]. From this case, it can also be seen that the formation of $CaCO_3$ deposits can reduce the width of cracks in concrete. Thus, the permeability of concrete can be reduced, ultimately increasing the corrosion inhibition process in reinforced concrete [24, 34, 35].

Based on the research and analysis of corrosion levels, the results showed that the lowest level of corrosion was demonstrated by adding a 0.1% variation in bacterial encapsulation, and corrosion increased slowly along with the addition of variations in bacterial encapsulation levels. The linear increase in the level of corrosion with the additional level of bacterial encapsulation can be caused by the increasing number of cavities in the concrete and the increase in bacterial encapsulation in the concrete. In this case, the bacterial encapsulation has the property of shrinking quickly when exposed to water or liquid. This effect can be worse if the bacterial encapsulation is located on the outer part of the concrete and is in direct contact with the surrounding conditions. During the curing process, the encapsulated bacteria will come into contact with water so that it becomes soft for a long time. Then, when lifted into the air, the encased bacteria still need time to dry and harden under suitable conditions. If it is too dry, the water in the bacterial encapsulation will quickly evaporate, and the capsule will become brittle quickly. This can result in the formation of cavities in the concrete, which will increase its permeability and cause the reinforcement in the concrete to experience corrosion and rust processes more quickly. So, from this case, the most optimal variation in adding bacterial encapsulation as a corrosion inhibitor is 0.1% of the total weight of sand, where the density level of the concrete is still at a normal level, which then increases with the addition of bacterial encapsulation as a self-healing agent on concrete.

Self-healing concrete process

After the corrosion acceleration, the test object is cracked using the Universal Testing Machine (UTM). The cracking procedure is carried out until the concrete has hairline cracks. After the cracking process is complete, self-healing concrete is tested by spraying water on the cracked concrete to activate the function of self-healing bacteria. Then, observations are made for up to 28 days.

The load applied during the crack test varies according to the visual observation of the concrete when the first crack is produced. However, the average recorded in the test results ranges from 20-30 kN. The development of self-healing in concrete is shown in Figures 11 through 13.

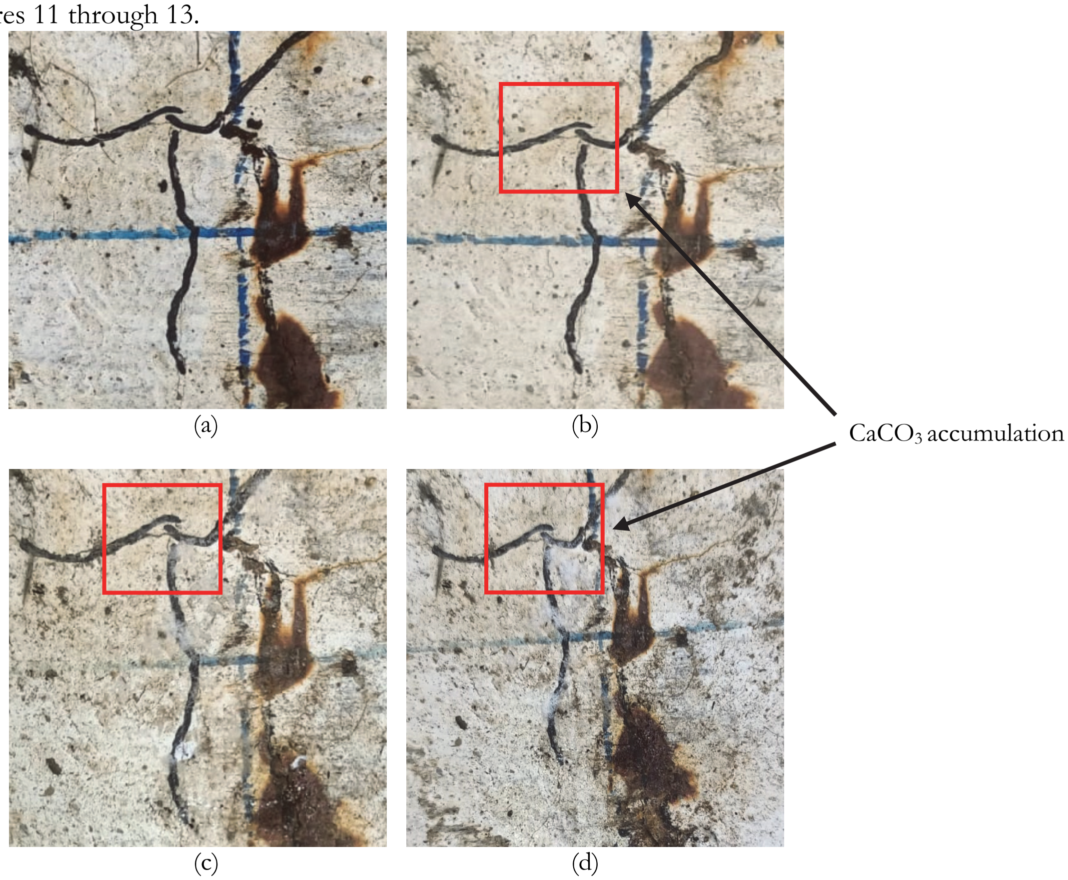


Figure 11: Bacterial self-healing process 0.1% (a) 7 days, (b) 14 days, (c) 21 days, (d) 28 days.

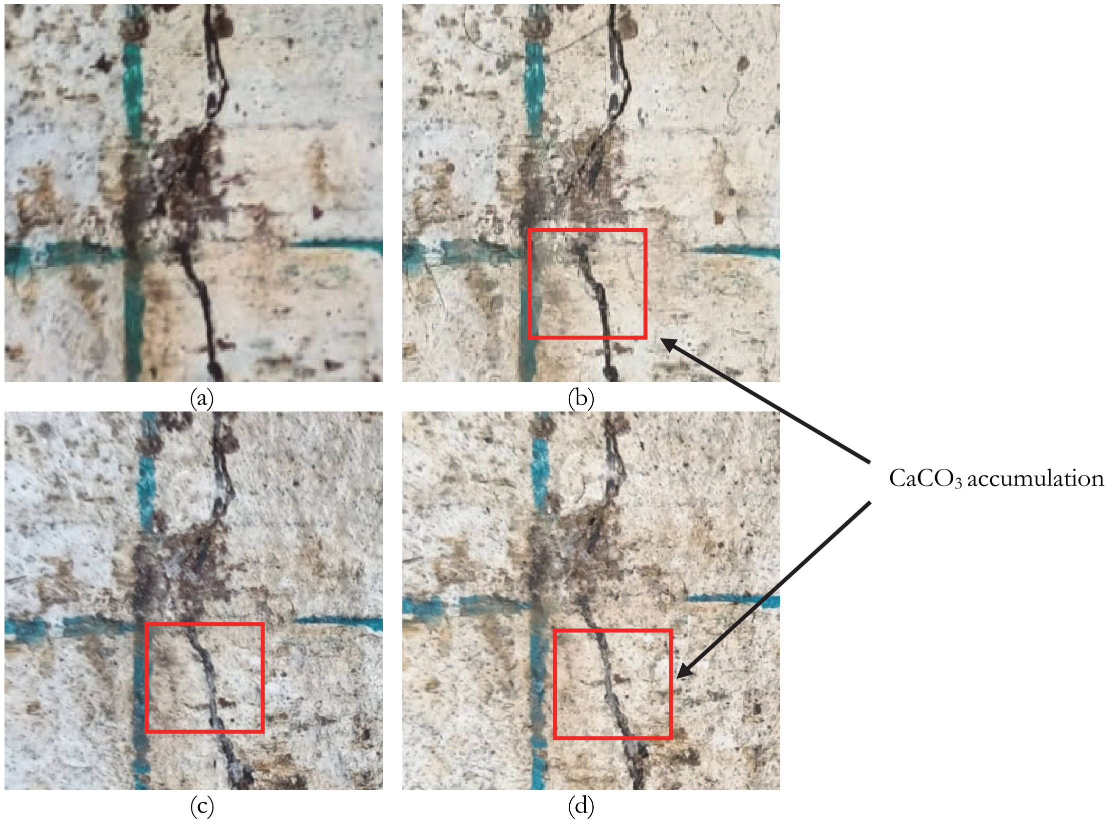


Figure 12: Bacterial self-healing process 0.6% (a) 7 days, (b) 14 days, (c) 21 days, (d) 28 days.

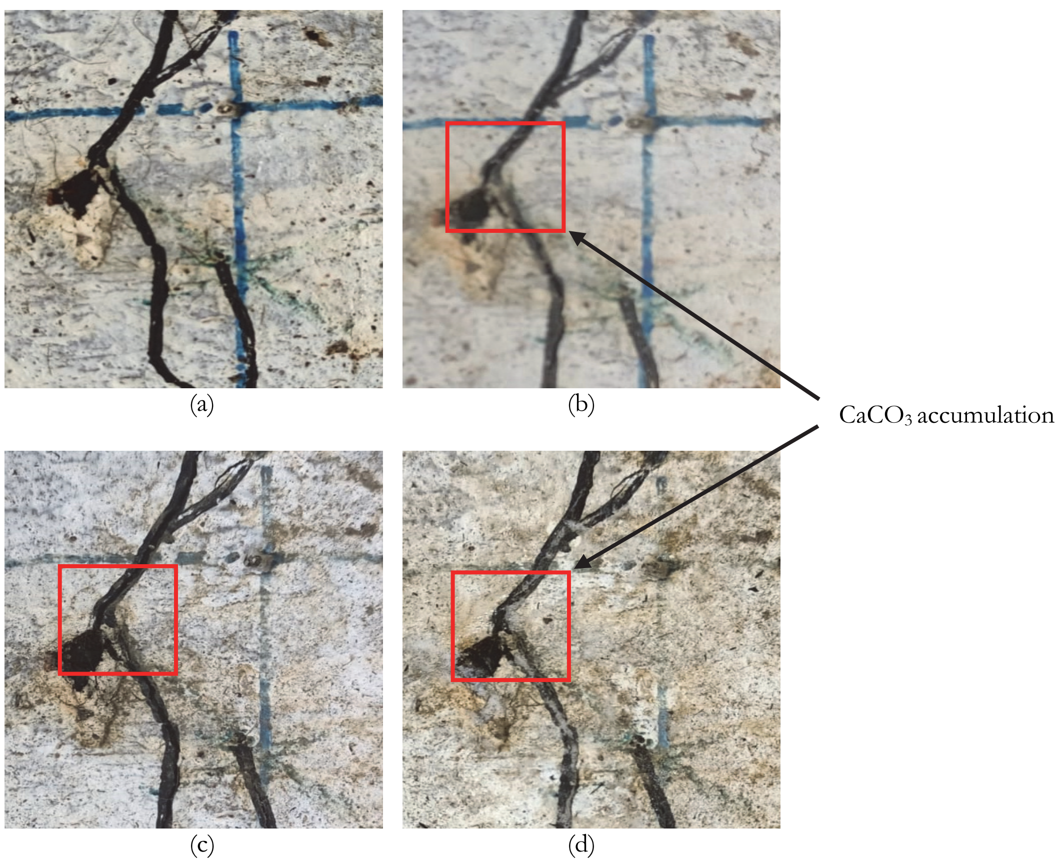


Figure 13: Bacterial self-healing process 1.5% (a) 7 days, (b) 14 days, (c) 21 days, (d) 28 days.

From the results of visual observations, it was found that the formation of calcite in corroded concrete began on the 14th day after the concrete cracked. From the results of the development of the self-healing process, it can also be seen that the accumulation of calcite formation is increasing as the days go by [36]. Thus, the accumulation of calcite increasingly fills the crack cavities, which in turn can close the cracks in the concrete [13]. The results of visual observations show that the higher the level of addition of variations in bacterial encapsulation in concrete, the more $CaCO_3$ will be formed in cracks. Visually, it can also be observed that the accumulation of calcite or $CaCO_3$ at the percentage of bacterial encapsulation addition of 1.5% on the 28th day appears to be greater and can close crack gaps compared to the closure of cracks at the addition of a variation of 0.1%.

Although the formation of calcite can visually close cracks in concrete, especially with the addition of a high percentage of bacterial encapsulation, likely, the bacterial encapsulation does not completely reach the cracked area, or in other words, the pores in the concrete are not completely closed by the formation of calcite. Another thing that might happen is that the particle bond between the concrete structure and the formation of calcite is less strong than the bond between cement and aggregate, but this requires further research and observation. However, what is most likely to happen in this case is caused by an uneven mixture of bacterial encapsulation with fresh concrete. The addition of bacterial encapsulation is not directly mixed during the fresh concrete mixing process but is done when pouring fresh concrete into the formwork. Apart from that, a less-than-optimal compaction process also greatly affects the level of pore density in the concrete, especially during the initial setting time of the concrete. The process of forming calcite in crack gaps is also known to be able to reduce the corrosion process in concrete reinforcement, but it cannot significantly affect the strength of the concrete. The percentage of its use as an additional material has an optimal limit that can influence the mechanical properties of concrete, such as the value of flexural strength and compressive strength of concrete.

Cylindrical concrete compressive strength test results

The compressive strength test was carried out on cylindrical concrete specimens after reaching the age of 28 days—compressive strength testing using a Compression Testing Machine. The results of the concrete compressive strength test are shown in Figure 14.

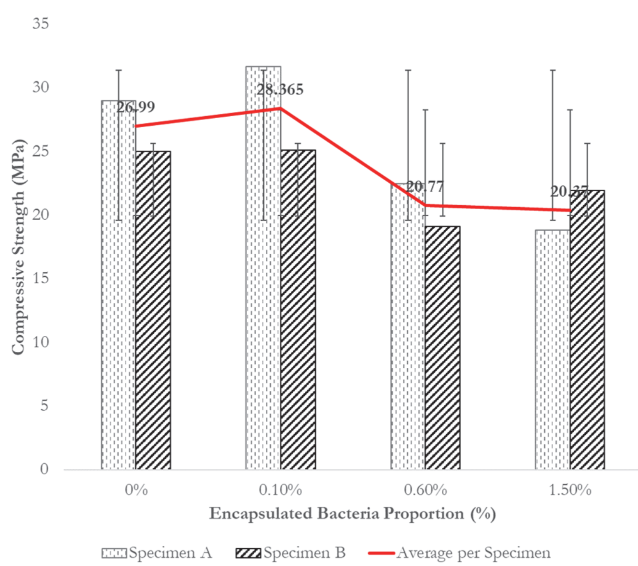


Figure 14: Concrete compressive strength test results.

From the results of the compressive strength test in Figure 14, there is an increase in the compressive strength value of 0.1% bacterial variation concrete compared to 0% variation concrete from 26.99 MPa to 28.365 MPa, with a difference of 1.375 MPa. Adding Bacillus subtilis bacteria to the concrete only gives little enhancement to the compressive strength of concrete, maybe due to microbial precipitation of calcium carbonate [21]. However, this increase in compressive strength values is not too different from the strength of normal concrete. This is possible because the size of the bacterial encapsulation is still relatively large, so they are less able to fill each other's cavities in the concrete. However, the calcite formation process can still occur, especially during the curing process in a water-soaking bath and during the initial setting. There is a decrease in the compressive strength value as the bacterial variation in the concrete increases. This can be caused

by the increasing number of cavities in the concrete as the bacterial encapsulation increases in the concrete. This is because bacterial encapsulation has the property of shrinking when exposed to water or liquid. Thus, when the concrete hardens, the bacterial encapsulation will shrink and then harden [37].
This can be further exacerbated when the position of the spread of encapsulated bacteria is in the concrete cover and directly in contact with the surrounding conditions. During the curing process, the encapsulated bacteria will meet water, making it soft for a long time. Then, when lifted into the air, the encapsulated bacteria still need time to dry and solidify under the appropriate conditions. If it is too dry, the water in the bacterial encapsulation will quickly evaporate and become brittle, resulting in cavities forming in the concrete and reducing its compressive strength. An increase in the compressive strength of concrete will also be in line with an increase in the ductility of the concrete [13].

Flexural Strength test results of reinforced concrete

Flexural strength is the ability of a concrete beam placed in two positions to withstand forces in a direction perpendicular to the axis of the specimen applied to the beam until the specimen breaks [38]. The flexural strength test was carried out using the four-point bending method, in which the concrete is supported on two supports with two-point loading. The result of the flexural strength of concrete beams can be calculated using a formula based on SNI 4431:2011 [39] shown in equation 2. Where σ is flexure strength (MPa), P is the highest load read on the test machine (ton), L is the distance (span) between two supports (mm), b is beam width (mm), and h is beam height (mm).

$$\sigma = \frac{P \times L}{b \times h^2} \qquad (2)$$

The results of the flexural strength test of corroded concrete with a mixture of various bacteria are shown in Figure 15 below. These results indicate that adding 0.1% bacterial variation to concrete can increase the flexural strength value of concrete by 0.31 MPa compared to normal concrete or 0% bacterial variation. However, the addition of 0.6% bacterial variation to concrete resulted in a lower flexural strength value compared to 0.1% bacterial variation concrete. Meanwhile, adding 1.5% of bacterial variation causes a decrease in the flexural strength of concrete. Thus, more and more variations of bacteria are added to the concrete, causing its flexural strength to decrease. From these results, the most optimal addition of encapsulated bacteria to concrete is 0.1%. This is in line with the results of the optimal value of concrete compressive strength, which will influence the flexural strength value of concrete due to calcite formation in the concrete cavity [13, 24].

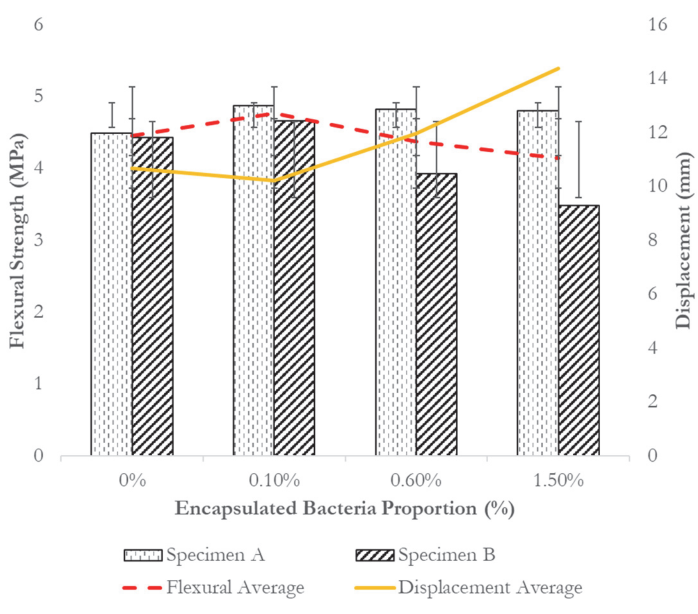


Figure 15: Flexural strength and displacement test results.

Reinforced concrete ductility test results

Ductility in concrete is when it experiences strain development from the first time it melts until it finally breaks. The ductility coefficient reflects the plastic capacity of the structural member deformation. Ductility can be calculated by comparing the maximum displacement with the deflection at the first yield [40]. The ductility formula is shown in Equation (3), where μ is ductility, Δ_u is maximum displacement (mm), and Δ_y is yield displacement (mm). Figure 16 shows the ductility values of self-healing concrete specimens with a corrosion rate of 20%.

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{3}$$

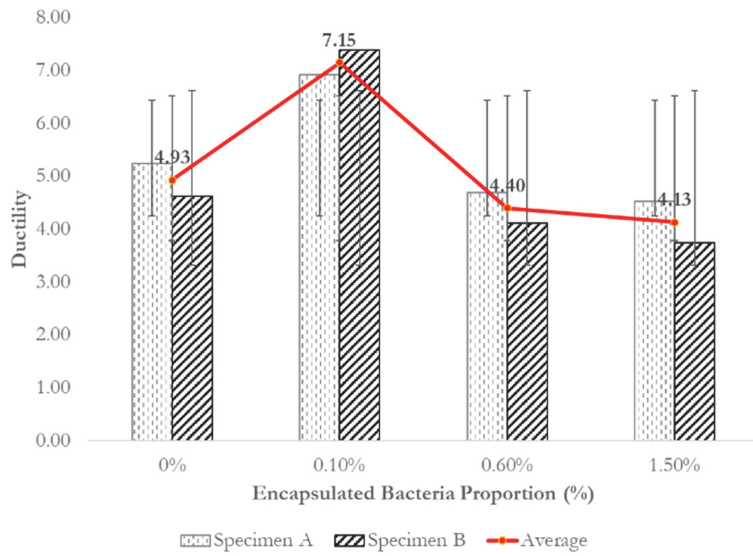


Figure 16: Concrete ductility test results.

Figure 16 shows that adding 0.1% bacterial variation causes an increase in the ductility value in concrete with a difference of 2.22 compared to normal concrete (0% variation). However, adding 0.6% bacterial variation to concrete resulted in a decreased ductility value compared to adding 0.1% bacterial variation with a decrease difference of 2.75. Meanwhile, adding 1.5% bacterial variation resulted in the smallest ductility value among all bacterial variations. It showed a decreasing trend after reaching its peak at the addition of 0.1% bacterial variation. This is caused by calcite precipitation or the formation of lime cells that fill the voids in the concrete. Thus, the concrete becomes denser and more compact [41]. However, from the study's results, it was found that adding more than 0.1% of bacterial variations resulted in decreased ductility due to the encapsulation nature of bacteria, which easily expands and shrinks when exposed to water. Thus, the most optimal level of encapsulated Bacillus subtilis bacteria as a self-healing agent is 0.1%.

Concrete stiffness test results

Stiffness is the ratio between the maximum load and the displacement in concrete [42]. Concrete stiffness can be calculated by comparing concrete's maximum force and maximum deflection [43]. The stiffness formula is shown in Equation (4), where K is stiffness (kN/mm), F is maximum force [44], and δ is maximum displacement (mm). The stiffness value of self-healing concrete with 20% corrosion can be seen in Figure 17.

$$K = \frac{F}{\delta} \tag{4}$$

Figure 17 shows the results of the stiffness values, where adding a bacterial variation of 0.1% increases the concrete stiffness value of 0.85 kN/mm when compared to 0% bacterial variation concrete (normal concrete). Meanwhile, adding 0.6% bacterial variation decreased the stiffness value compared to 0.1% bacterial variation concrete, and the stiffness value decreased when the concrete was given an additional 1.5% bacterial variation. This is caused by bacterial precipitation that accumulates and fills the concrete voids after cracks occur so that the concrete becomes denser and can withstand greater loads with small deflections [24]. However, the addition of bacteria to concrete reached an optimal point of 0.1% due to the effect of the encapsulated bacteria swelling when exposed to water. Thus, it also affects the cavity's size if the bacteria's encapsulation increases in the concrete.

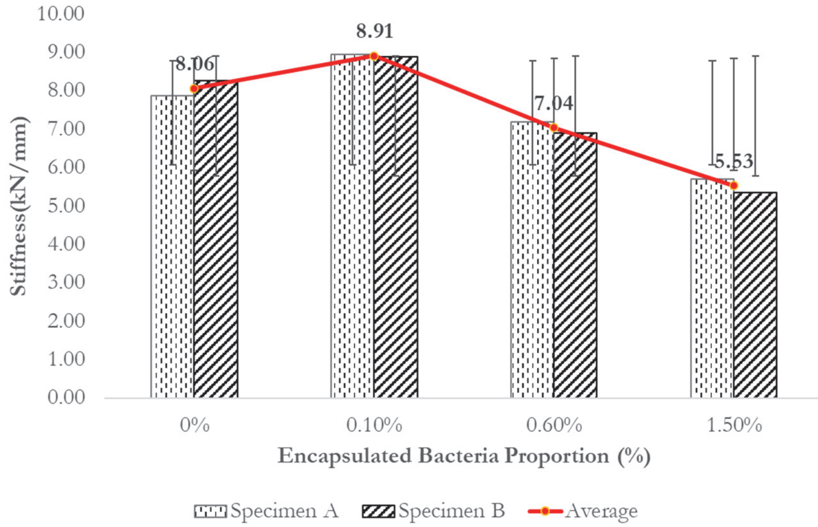
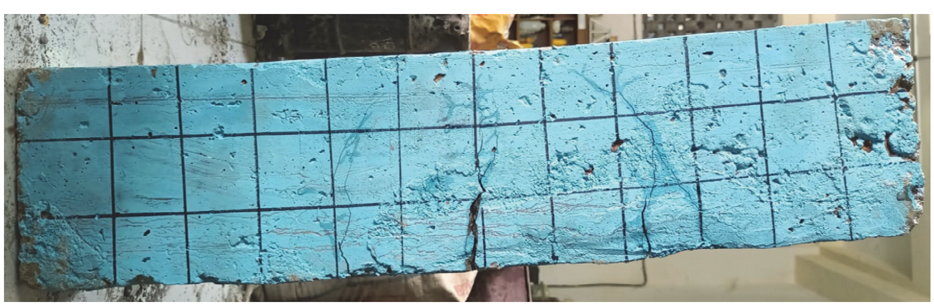


Figure 17: Concrete stiffness test results.

Reinforced concrete failure pattern

Flexure testing on concrete beams will result in cracks and deflection of the concrete. This is due to the pressure from the test load given by the concrete beam bending testing machine. Spread pattern and crack direction are used to determine the type of failure pattern on the beam. The process of determining the failure pattern is done by visual observation. From observations, all beam specimens were found to have a failure pattern by developing a macroscopic crack in the shear. The crack starts with the formation of a diagonal crack that penetrates through the specimen height. As the pressure load increased, the cracks propagated vertically from the bottom of the beam specimen to indicate tensile fracture under flexure [14]. Continuous load to the beam resulted in the start of steel reinforcement yielding, causing beam failure localization to form macro-cracks [45]. In this case, the ratio between the span length and height of the concrete beam is 520/150 or 3.47, so the concrete beam is predicted to be dominated by a shear failure pattern. The concrete beam failure pattern is shown in Figures 18 through 21.

(a)

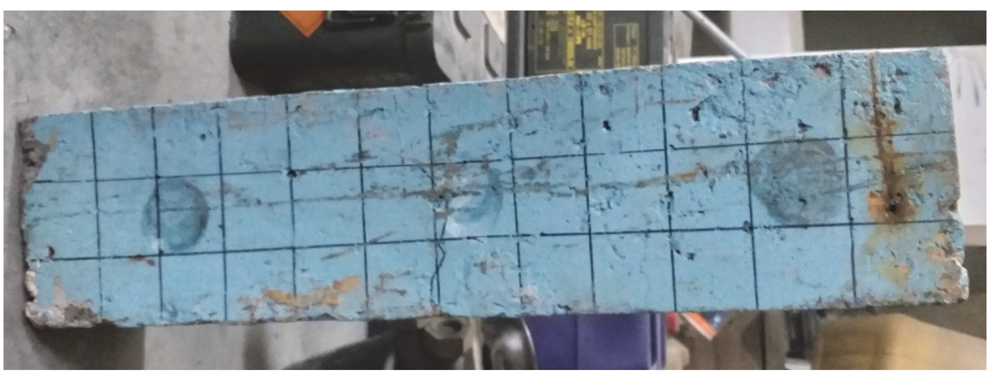


(b)

Figure 18: Failure pattern specimens (a) B1 and (b) B2.

Figure 18 shows that the crack pattern of a concrete beam with a variation of 0% bacterial encapsulation (normal concrete) shows that the concrete beam experienced shear cracks. Cracks in concrete are initiated from hairline cracks in the pure bending areas of concrete due to load application. Crack propagation continues in the concrete until a diagonal crack forms. In this case, the crack is close to the concrete beam. This indicates that the load received by the concrete beam is distributed evenly throughout the concrete, especially the reinforcement. The load the concrete beams can accept will reach its maximum point and cause cracks in the stirrups concrete area because of the existing load distribution. From the visual observations, the stirrup concrete area experienced macro cracks due to the reinforced concrete design, which would end the distribution of the overall load received by the concrete in the stirrup concrete.
Figure 19 also shows that the failure pattern of reinforced concrete beam structures with a bacterial variation of 0.1% shows more shear crack patterns due to the propagation of the load received. Macroscopic beam cracks show the result in cracks in the beam stirrup reinforcement, similar to normal concrete beam damage. The test results show that the macroscopic damage between normal concrete beams and the 0.1% bacterial encapsulation variation is not too different. This is caused by the test results for flexural strength values, which do not differ significantly. Apart from that, it is also possible that the density of concrete pores between 0% and 0.1% variations of encapsulation bacteria in concrete is not too different so that its strength in bearing loads and failure patterns can still be categorized at the same level.

(a)

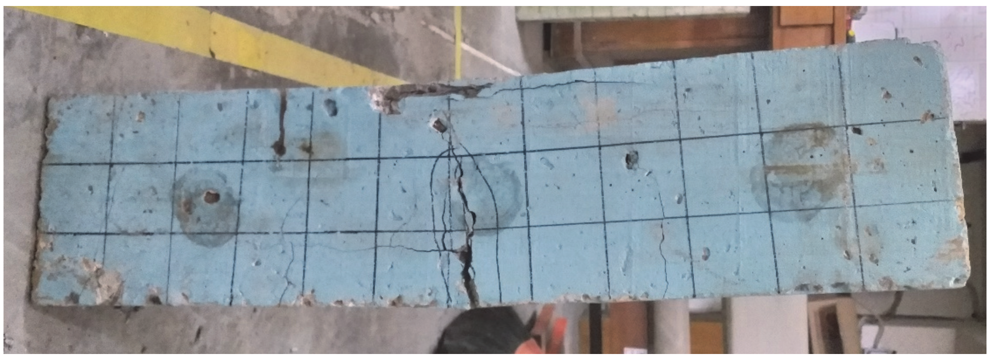


(b)

Figure 19: Failure pattern specimens (a) B3 and (b) B4.

The results of the crack pattern of concrete beams with the addition of 0.6% bacterial encapsulation variations shown in Figure 20 show that the beams experience the same type of crack pattern as concrete variations of 0% and 0.1%. The crack pattern in the concrete with a bacteria variation of 0.6% shows a shear crack pattern from the final propagation of the load on the stirrup reinforcement. However, Figure 20 (a) (beam B5) also shows parts of the concrete cover almost peeling off or experiencing delamination due to accelerated corrosion. The concrete crack pattern that previously only formed in the area around the stirrup reinforcement spread to become horizontal cracks due to the corrosion process. The appearance of these cracks can be caused by the pore density level of the 0.6% variation concrete, which is lower when compared to the 0% and 0.1% variation concrete. Although the test results for the reinforcement's corrosion level based on the reinforcement concrete's remaining mass show that the 0.6% variation has a lower corrosion level than the 0% variation, the density of the concrete pores is not as dense as the 0% concrete variation. This case is also proven by the results of the compressive strength value of 0.6% concrete, which is lower than the 0% variation concrete (normal concrete), which impacts the pore density of the concrete.

(a)



(b)

Figure 20: Failure pattern specimens (a) B5 and (b) B6.

Figure 21 shows the crack pattern experienced by concrete blocks with variations in adding 1.5% bacterial encapsulation. The crack pattern in concrete beams is generally similar to the concrete crack pattern, with a variation of 0.6%. However, when observed visually, concrete with a bacterial encapsulation variation of 1.5% had a more severe crack pattern than concrete with a variation of 0.6%. This concrete variation will also likely experience more severe damage due to corrosion, as shown in Figure 21 (b) (beam B8). Beam B8 indicated the same type of damage as beam B5, where the beam experienced initial damage in the stirrup reinforcement area, eventually spreading horizontally due to the corrosion process. However, on beam B8, damage in the form of peeling of the concrete cover or spalling has occurred. This peeling damage to the concrete blanket can also indicate that the level of concrete density due to the addition of 1.5% bacterial variation is decreasing and affecting the density of the concrete pores. As a result, concrete becomes more easily damaged or fails when under load. The reduction in concrete density due to the addition of bacterial encapsulation of 1.5% is shown in Figure 21 (b) (beam B8), which has holes from bacterial encapsulation on the surface of the concrete beams, which can result in a decrease in the compressive strength and density values of the concrete beams, especially beam B8. As previously explained, in this case, the bacterial encapsulation has the property of shrinking easily when exposed to water or liquid. Especially if the bacterial encapsulation is located on the outer part of the concrete and is in direct contact with the surrounding conditions. The encapsulated bacteria still need time to dry and harden under suitable conditions. If it is too dry, the water in the bacterial encapsulation will quickly evaporate, and the capsule will become brittle quickly.

Based on the observations on all concrete beam specimens, all concrete beams show a shear crack pattern due to the distribution of the load evenly throughout the concrete beam reinforcement until the load distribution ends at the concrete stirrup reinforcement. The deflection effect of the stirrup reinforcement propagates on the concrete cover, ultimately resulting in cracks in the concrete. Meanwhile, some other concrete, especially B5 and B8 concrete, appears to have experienced more severe damage, namely the peeling of the concrete cover due to the corrosion process due to the less dense arrangement of the pores in the concrete. From these results, it can also be seen that the addition of variations in bacterial encapsulation as a self-healing agent in concrete has not been able to drastically increase the mechanical properties of concrete, especially the compressive strength and flexural strength values. However, it has potential as a corrosion inhibitor agent in reinforced concrete because of its ability to produce calcite and act as an additional layer of protection for concrete reinforcement.

(a)

(b)

Figure 21: Failure pattern specimens (a) B7 and (b) B8.

CONCLUSIONS

Based on the experimental results and data analysis on the study of the effect of bacillus subtilis bacteria on the mechanical properties of corroded self-healing concrete, the following conclusions can be drawn:

- Adding 0.1% bacterial variation inhibited the corrosion rate in concrete compared to normal concrete. However, additional bacterial variations at 0.6% and 1.5% indicate no enhancement in the concrete corrosion rate. Thus, adding the most optimal variation of encapsulating bacteria inhibits the corrosion rate of concrete, which is equal to 0.1% by weight of sand.
- The highest compressive strength value in self-healing concrete was obtained with 0.1% encapsulated bacteria variation, with an additional value of 1.375 MPa compared to normal concrete. However, the addition of encapsulating bacteria of 0.1% could not significantly increase the compressive strength value of concrete.
- Adding 0.1% of encapsulated bacteria in concrete increases its flexural strength by 0.31 MPa compared to normal concrete. The flexural strength of concrete will decrease as the bacterial variation in concrete increases. Thus, adding the most optimal variation of encapsulating bacteria to concrete equals 0.1%.
- Adding 0.1% bacterial encapsulation to concrete is the optimum value, which can increase the ductility value of concrete by 2.22 compared to normal concrete (0% bacterial variation). However, adding more than 0.1% of bacterial variations resulted in decreased ductility due to the encapsulation nature of bacteria, which easily expands and shrinks when exposed to water.
- The most optimum increase in self-healing concrete stiffness, which is 0.85 kN/mm compared to normal concrete, is achieved by adding 0.1% bacterial encapsulation.

- The result of the compressive strength value in self-healing concrete will align with the result of the ductility, flexural strength, and stiffness of the concrete for the increasing and decreasing value for mechanical properties of self-healing concrete.
- The self-healing process in corroded concrete can still occur after the concrete has cracked. The self-healing process in concrete begins on the 14th day after cracking occurs. The self-healing process will continue as the days go by, and an accumulation of calcite will form, further closing the cracks in the concrete.
- The process of forming calcite in crack gaps can reduce the corrosion process in concrete reinforcement, but it cannot significantly affect the strength of the concrete. The percentage of its use as an additional material has an optimal limit that can influence the mechanical properties of concrete.
- All concrete beams show a shear crack pattern due to the load distribution evenly throughout the concrete beam reinforcement until the load distribution ends at the concrete stirrup reinforcement.
- The addition of variations in bacterial encapsulation as a self-healing agent in concrete has not been able to drastically increase the mechanical properties values of concrete, especially the compressive strength and flexural strength values. However, it has potential as a corrosion inhibitor agent in reinforced concrete because of its ability to produce calcite and act as an additional layer of protection for concrete reinforcement.

REFERENCES

[1] Yip, B. F., Haniffah, M. R. M., Kasiman, E. H., and Abidin, A. R. Z. (2022). Research Progress On Microbial Self-Healing Concrete, Jurnal Teknologi, 84(3), pp. 25-45. DOI: 10.11113/jurnalteknologi.v84.17895.

[2] Akhtar, J. N., Khan, R. A., Khan, R. A., Akhtar, M. N., and Nejem, J. K. (2022). Influence of Natural Zeolite and Mineral additive on Bacterial Self-healing Concrete: A Review, Civil Engineering Journal, 8(5), pp. 1069-1085. DOI: 10.28991/CEJ-2022-08-05-015.

[3] Prayuda, H., Soebandono, B., Dwi Cahyati, M., and Monika, F. (2020). Repairing of Flexural Cracks on Reinforced Self-Healing Concrete Beam using Bacillus Subtillis Bacteria, The International Journal of Integrated Engineering, 12, pp. 300-309. DOI: 10.30880/ijie.2020.12.04029.

[4] Karimi, N. and Mostofinejad, D. (2020). Bacillus subtilis bacteria used in fiber reinforced concrete and their effects on concrete penetrability, Construction and Building Materials, 230, pp. 117051-117059. DOI: 10.1016/j.conbuildmat.2019.117051.

[5] Zaki, A., Chai, H. K., Aggelis, D. G., and Alver, N. (2015). Non-Destructive Evaluation for Corrosion Monitoring in Concrete: A Review and Capability of Acoustic Emission Technique, Sensors (Basel), 15(8), pp. 19069-19101. DOI: 10.3390/s150819069.

[6] Ramón, J. E., Castillo, Á., and Martínez, I. (2021). On-site corrosion monitoring experience in concrete structures: potential improvements on the current-controlled polarization resistance method, Materiales de Construcción, 71(344), pp. 265-276. DOI: 10.3989/mc.2021.11221.

[7] Zaki, A., Megat Johari, M. A., Wan Hussin, W. M. A., and Jusman, Y. (2018). Experimental Assessment of Rebar Corrosion in Concrete Slab Using Ground Penetrating Radar (GPR), International Journal of Corrosion, pp. 1-10. DOI: 10.1155/2018/5389829.

[8] Astuti, P., Rafdinal, R. S., Yamamoto, D., Andriamisaharimanana, V., and Hamada, H. (2022). Effective Use of Sacrificial Zinc Anode as a Suitable Repair Method for Severely Damaged RC Members Due to Chloride Attack, Civil Engineering Journal, 8(7), pp. 1535-1548. DOI: 10.28991/cej-2022-08-07-015.

[9] Koleva, D. A. (2018). An Innovative Approach to Control Steel Reinforcement Corrosion by Self-Healing, Materials, 11(2), pp. 309-335. DOI: 10.3390/ma11020309.

[10] Gao, Y., Suryanto, B., Chai, H. K., and Forde, M. C. (2021). Evaluating the effect of corrosion on shear-critical RC beams by integrated NDT, Developments in the Built Environment, 7, pp. 100050-100063. DOI: 10.1016/j.dibe.2021.100050.

[11] Astuti, P., Kamarulzaman, K., and Hamada, H. (2021). Non-Destructive Investigation of a 44-Year-Old RC Structure Exposed to Actual Marine Tidal Environments Using Electrochemical Methods, International Journal of Integrated Engineering, 13(3), pp. 148-157. DOI: 10.30880/ijie.2021.13.03.018.

[12] Li, W., Wu, M., Shi, T., Yang, P., Pan, Z., Liu, W., Liu, J., and Yang, X. (2022). Experimental Investigation of the Relationship between Surface Crack of Concrete Cover and Corrosion Degree of Steel Bar Using Fractal Theory, Fractal and Fractional, 6(6), pp. 325-340. DOI: 10.3390/fractalfract6060325.

[13] Mirshahmohammad, M., Rahmani, H., Maleki-Kakelar, M., and Bahari, A. (2022). Effect of sustained service loads on the self-healing and corrosion of bacterial concretes, Construction and Building Materials, 322, pp. 126423-126438. DOI: 10.1016/j.conbuildmat.2022.126423.

[14] Zaki, A., Chai, H. K., Behnia, A., Aggelis, D. G., Tan, J. Y., and Ibrahim, Z. (2017). Monitoring fracture of steel corroded reinforced concrete members under flexure by acoustic emission technique, Construction and Building Materials, 136, pp. 609-618. DOI: 10.1016/j.conbuildmat.2016.11.079.

[15] Qian, C., Zheng, T., Zhang, X., and Su, Y. (2021). Application of microbial self-healing concrete: Case study, Construction and Building Materials, 290, pp. 123226-123239. DOI: 10.1016/j.conbuildmat.2021.123226.

[16] Tayebani, B. and Mostofinejad, D. (2019). Self-healing bacterial mortar with improved chloride permeability and electrical resistance, Construction and Building Materials, 208, pp. 75-86. DOI: 10.1016/j.conbuildmat.2019.02.172.

[17] Achal, V., Mukherjee, A., Goyal, S., and Reddy, M. S. (2012). Corrosion Prevention of Reinforced Concrete with Microbial Calcite Precipitation, ACI Materials Journal, 109(2), pp. 157-164. DOI: 10.14359/51683702.

[18] Tang, Y. and Xu, J. (2021). Application of microbial precipitation in self-healing concrete: A review on the protection strategies for bacteria, Construction and Building Materials, 306, pp. 124950-124960. DOI: 10.1016/j.conbuildmat.2021.124950.

[19] Tittelboom, K. V., Belie, N. D., Muynck, W. D., and Verstraete, W. (2010). Use of bacteria to repair cracks in concrete, Cement and Concrete Research, 40(1), pp. 157-166. DOI: 10.1016/j.cemconres.2009.08.025.

[20] Ihsani, Z. M. and Putra, H. (2021). The Utilization of Milk as a Catalyst Material in Enzyme-Mediated Calcite Precipitation (EMCP) for Crack-Healing in Concrete, Civil Engineering Dimension, 23(1), pp. 54-61. DOI: 10.9744/ced.23.1.54-61.

[21] Vijay, K., Murmu, M., and Deo, S. V. (2017). Bacteria based self healing concrete – A review, Construction and Building Materials, 152, pp. 1008-1014. DOI: 10.1016/j.conbuildmat.2017.07.040.

[22] Durga, C. S. S., Ruben, N., Chand, M. S. R., Indira, M., and Venkatesh, C. (2021). Comprehensive microbiological studies on screening bacteria for self-healing concrete, Materialia, 15, pp. 101051-101064. DOI: 10.1016/j.mtla.2021.101051.

[23] Osman, K. M., Taher, F. M., Abd El-Tawab, A., and Faried, A. S. (2021). Role of different microorganisms on the mechanical characteristics, self-healing efficiency, and corrosion protection of concrete under different curing conditions, Journal of Building Engineering, 41, pp. 102414-102433. DOI: 10.1016/j.jobe.2021.102414.

[24] Reddy, C. M. K., Ramesh, B., D, M., and reddy, K. (2020). Influence of bacteria Bacillus subtilis and its effects on flexural strength of concrete, Materials Today: Proceedings, 33, pp. 4206-4211. DOI: 10.1016/j.matpr.2020.07.225.

[25] Zhang, X., Jin, Z., Li, M., and Qian, C. (2021). Effects of carrier on the performance of bacteria-based self-healing concrete, Construction and Building Materials, 305, pp. 124771-124787. DOI: 10.1016/j.conbuildmat.2021.124771.

[26] BSN. (2012). Metode uji untuk analisis saringan agregat halus dan agregat kasar (Test method for sieve analysis of fine aggregate and coarse aggregate), Badan Standarisasi Nasioanal: Jakarta.

[27] BSN. (2008). Cara uji berat jenis dan penyerapan air agregat kasar (Specific gravity and water absorption test of coarse aggregate), Nasional, B. S., Editor, BSN: Jakarta.

[28] BSN. (2015). Semen portland (Portland cement), Badan Standarisasi Nasional: Jakarta.

[29] BSN. (2017). Baja tulangan beton (Concrete reinforcement steel), Badan Standarisasi Nasional: Jakarta.

[30] BSN. (2008). Cara uji berat jenis dan penyerapan air agregat halus (Specific gravity and water absorption test of fine aggregate), Badan Standarisasi Nasional: Jakarta.

[31] BSN. (2012). Metode uji bahan yang lebih halus dari saringan No. 200 dalam agregat mineral dengan pencucian (Test method for materials finer than No. 200 in mineral aggregate by washing), Badan Standarisasi Nasional: Jakarta.

[32] BSN. (2008). Cara uji keausan agregat dengan mesin abrasi Los Angeles (Aggregate wear test method with Los Angeles abrasion machine), Badan Standarisasi Nasional: Jakarta.

[33] ACI. (1991). Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, ACI Committe. pp. 1-38.

[34] Syarifa, R., Rizkib, I. N., Wattimenaa, R. K., and Chaerun, S. K. (2019). Selection of bacteria inducing calcium carbonate precipitation for selfhealing concrete application, Current Research on Biosciences and Biotechnology 1(1), pp. 26-30. DOI: 10.5614/crbb.2019.1.1/ZDYD8792.

[35] Xu, J., Peng, C., Wan, L., Wu, Q., and She, W. (2020). Effect of Crack Self-Healing on Concrete Diffusivity: Mesoscale Dynamics Simulation Study, Journal of Materials in Civil Engineering, 32(6). DOI: 10.1061/(asce)mt.1943-5533.0003214.

[36] Peng, C., Wua, Q., Shen, J., Mo, R., and Xu, J. (2021). Numerical study on the effect of transverse crack self-healing on the corrosion rate of steel bar in concrete, Journal of Building Engineering, 41, pp. 102767-102776.

DOI: 10.1016/j.jobe.2021.102767.
[37] Wang, H., Habibi, M., Marzouki, R., Majdi, A., Shariati, M., Denic, N., Zakic, A., Khorami, M., Khadimallah, M. A., and Ebid, A. A. K. (2022). Improving the Self-Healing of Cementitious Materials with a Hydrogel System, Gels, 8(5), pp. 278-295. 10.3390/gels8050278.
[38] BSN. (2014). Metode uji kekuatan lentur beton menggunakan balok sederhana dengan beban terpusat di tengah bentang (The concrete flexural strength test method uses a simple beam with a concentrated load in the middle of the span), Badan Standarisasi Nasional: Jakarta. pp. 1-12.
[39] BSN. (2011). Cara uji kuat lentur beton normal dengan dua titik pembebanan (How to test the flexural strength of normal concrete with two loading points), Badan Standarisasi Nasional: Jakarta. pp. 1-16.
[40] Wang, B., Yin, S., Liu, M., and Zani, G. (2021). Investigation on the Displacement Ductility Coefficient of Reinforced Concrete Columns Strengthened with Textile-Reinforced Concrete, Advances in Civil Engineering, 2021, pp. 1-12. DOI: 10.1155/2021/3152619.
[41] Han, R., Xu, S., Zhang, J., Liu, Y., and Zhou, A. (2022). Insights into the effects of microbial consortia-enhanced recycled concrete aggregates on crack self-healing in concrete, Construction and Building Materials, 343, pp. 128138-128148. DOI: 10.1016/j.conbuildmat.2022.128138.
[42] Das, S., Mansouri, I., Choudhury, S., Gandomi, A. H., and Hu, J. W. (2021). A Prediction Model for the Calculation of Effective Stiffness Ratios of Reinforced Concrete Columns, Materials, 14(7), pp. 1792-1804. DOI: 10.3390/ma14071792.
[43] Aliasghar-Mamaghani, M. and Khaloo, A. (2021). Effective Flexural Stiffness of Beams Reinforced with FRP Bars in Reinforced Concrete Moment Frames, Journal of Composites for Construction, 25(1), pp. 1-15. DOI: 10.1061/(asce)cc.1943-5614.0001101.
[44] Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., and Knutsson, S. (2020). Dam Safety: Technical Problems of Ageing Concrete Dams, Journal of Earth Sciences and Geotechnical Engineering, 10(6), pp. 241-279.
[45] Zaki, A., Putri, O., Yadi, S., and Rommel, E. (2021). Mechanical Behavior of Corroded Steel in Lightweight Concrete: A Review. in 3rd International Conference on Sustainable Infrastructure, Orlando, Florida, USA. pp 1-15. DOI: 10.1088/1755-1315/832/1/012015.