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Effectiveness of Concrete Crack Repair Using *Bacillus subtilis* and Calcium Lactate

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ABSTRACT

Cracks facilitate aggressive substances entering the steel easily and cause corrosion of the reinforcement. There are several innovative methods for dealing with cracks in concrete, one of which is using bacteria. The purpose of using bacteria and CaL is to find out the role and effectiveness of repairing cracks in concrete. In outline, several methods and tests are carried out, including bacterial culture, test tube, concrete sample making, concrete curing, compressive strength testing, permeability testing, absorption testing, image processing testing, and microscopic testing. The test tube results showed that the highest mass of calcite was found in a solution of 2 ml of bacteria and CaL with a concentration of 65.4 g/L. The cracks appeared closed visually at 28 days of age. Through imageJ software, the crack repair rate in concrete reaches 95.94%. The effect of adding B. subtilis and CaL was proven to be able to close concrete cracks and increase the compressive strength of cracked concrete by 13.16%, reduce permeability by 53.12%, and absorption by 22.20%. This was confirmed by SEM testing and VHX-7000 observations which showed the presence of calcite crystals in the concrete pores and filled the concrete crack areas. This study elucidated that using bacillus subtilis bacteria and calcium Lactate in self-healing concrete is an effective technique to repair the concrete crack.

1. Introduction

Reinforced concrete (RC) is the most widely used construction material worldwide. Reinforced concrete (RC) is a combination of concrete and steel, which is ideal in terms of its good mechanical properties and durability [1]. Concrete has shortcomings in terms of its low tensile strength and brittle nature; therefore, it often cracks. Corrosion is one of the main problems in steel reinforcement because it can lead to destruction of the entire structure [2]. Therefore, the formation and presence of microcracks in concrete, especially in concrete skin, continues to be a global concern and challenge for civil engineers [3]. Cracks that do not significantly affect the integrity of the structure. However, cracks can facilitate the entry of aggressive substances into steel and cause corrosion of the reinforcement, thereby reducing the durability of concrete and shortening its life [4].

Large-scale maintenance and inspection efforts are costly and time-consuming, and other factors, such as unreachable damage locations, make repair efforts more difficult [5]. The self-healing characteristic of a material's ability to repair damage without human intervention is one of the most desirable properties in material science. Concrete has a natural ability to heal cracks, regain mechanical properties, and limit the ingress of aggressive substances. Many scientists aim to improve and control this ability because the successful healing of concrete cracks can result in more sustainable construction, and thus, lower maintenance costs [6].

Sustainable concrete technology, especially Self-Healing Concrete (SHC), has been the center of research in recent years [7]. The purpose of self-healing in concrete cracks is to repair and compact the concrete blanket such that the concrete becomes better in terms of durability while spending less on maintenance costs [8]. One of the most promising methods for healing cracks is to use bacteria as a self-healing medium for cement to seal concrete cracks [9].

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The most commonly used self-healing mechanism is hydrolysis of urea by ureolytic bacteria. This mechanism using bacteria produces a product called calcium carbonate, which fills the cracks in concrete and is a filler material. This type of cracking is called biocement [10]. Ureolytic Bacteria are the most widely used because of their high efficiency in calcium carbonate precipitation, but the decomposition of urea produces ammonia, which has a negative impact on the environment. The curing process must be carried out with the addition of bacteria that are harmless and not classified as pathogens. The most harmless and stable process involves consumption of organic matter through microbial respiration. The reaction that occurs is shown in Equation (1) [11].

$$Ca(C_3H_5O_3)_2+6O_2 \rightarrow CaCO_3+5CO_2+5H_2O \quad (1)$$

The SHC mechanism is activated when concrete is cracked. The presence of water vapor and oxygen activates the spores mixed in the concrete to precipitate calcite. The bacteria then return to inactivity or hibernation when the cracks are closed. Bacteria reactivate at any time when cracks occur in concrete [9]. Some types of bacteria that are widely used in the literature include *Bacillus sphaericus*, *Bacillus subtilis*, *Sporosarcina pasteurii*, and Bacillus megaterium. Bacillus species are widely used because they are resistant to alkaline environments and form spores [12]. Bacillus subtilis can produce calcite deposits at a much faster rate in media supplemented with calcium-based materials [13]. The presence of a calcium source in concrete is essential to produce calcite. Calcium lactate is one of the most widely used calcium-based foods against these bacteria. Based on this, the purpose of this research is to examine the effect of the addition of *B. subtilis* and CaL on the mechanical properties of concrete and determine their effectiveness in efforts to repair cracks in concrete. This study discusses the effectiveness of using Bacillus subtilis and calcium lactate bacteria for concrete crack repair in terms of the amount of calcium carbonate precipitate mass formed, concentration of Bacillus subtilis and calcium lactate, rate of crack repair, and its effect on mechanical properties such as compressive strength, permeability, and absorption of concrete.

2. Method

2.1 Aggregate properties testing

Aggregate property testing was first carried out to determine the characteristics of the aggregates to be used in the concrete mix so that it is known that the aggregates are suitable for use. The aggregate property testing included aggregate sieve analysis, aggregate specific gravity and absorption testing, Los Angeles testing, aggregate moisture content testing, aggregate organic content testing, aggregate durability testing, and aggregate silt content testing. The fine aggregate property test data are presented in Table 1 and the coarse aggregate property test results are presented in Table 2.

The results of the fine aggregate property test showed that the aggregates used should be treated before being used in the concrete mix. This was because the organic content and water absorption did not meet the standards. The organic content of fine aggregates is still high; therefore, it is necessary to wash the aggregates first. In addition, the coarse aggregate must also be dried to adjust its water content.

Table 1. Fine aggregate properties test results

Parameter	Res ults	Stan dart	Reference
Water content (%)	4.3	3 – 5	SNI 03-1971-1990b ([BSN], 1990)
Organic content (-)	No. 2	No. 3	ASTM C40-20 ([ASTM],2011) [14]
Agregat durability (%)	11.4	< 12	SNI 03-3407-1994 ([BSN], 2008d)[15]
Mud content (%)	0,6	< 5	SK SNI S-04-1989-F ([BSN], 1989)[16]
Specific gravity (SSD) (-)	1.8	1.6 – 3.2	SNI 1970-2008 ([BSN], 2008b)[17]
Water absorption (%)	5.8	< 3	
Fineness modulus(-)	2.3	1.5 – 3.8	ASTM C33-86 ([ASTM], 2010)[18]

Table 2. Coarse aggregate property test results

Parameters	Resu lts	Stand art	Reference
Organic content (-)	3.3	1.6 – 3.2	SNI 03-1971-1990b [19]
Agregat durability (%)	8.5	< 12	SNI 03-3407-1994
Mud content (%)	0.5	< 1	SK SNI S-04-1989-F [16]
Specific gravity (SSD) (-)	2.5	1.6 – 3.2	SNI 1969-2008 [20]
Water absorption (%)	2.2	< 3	
Fineness modulus(-)	29.0 2	< 40	SNI 2417: 2008 [21]
Organic content (-)	6.5	6.0 – 7.1	ASTM C33-86 [18]

2.2 Microorganisms and culture media

The spore-producing bacterium used in this study was Bacillus *subtilis*. The medium used was nutrient broth containing 5.0 g/L peptone, 5.0 g/L sodium chloride, 1.5 g/L beef extract, and 1.5 g/L yeast extract. Calcium lactate (CaL) is a nutrient used as a food for bacteria. The media was sterilized using an autoclave for 20 min, and then one dose of bacteria was inoculated into a 1-liter culture medium. The liquid medium and microbes were cultured at 30 °C and 125 rpm for 48 h in the laboratory. Bacterial counts were carried out using the petri dish method, where colonies formed on agar media in petri dishes were counted. The number of bacteria counted during this period was 5 × 106 cfu/ml. A test tube was used to determine the optimal composition of bacteria and nutrients (CaL). Cultured bacteria were stored in a refrigerator at 4 °C until the time of concrete mixing.

2.3 Calcite precipitation testing

Calcite precipitation testing is also known as test-tube testing. The variation in the relationship between the number of bacteria used and CaL concentration is shown in Table 3.

Table 3. Variation in the calcite precipitation test solution

Sample	Bacteria volume (ml)	Concentration CaL (g/L)
A1	1	21.80
A2	2	21.80
A3	3	21.80
B1	1	43.60
B3	2	43.60
B3	3	43.60
C1	1	65.40
C2	2	65.40
C3	3	65.40

This test was conducted to identify the amount of CaCO3 formed during bacterial reaction and precipitation. This test began by weighing the weight of each empty tube used. Bacillus subtilis bacteria in 1-liter culture media were collected according to the variation in Table 3 and then placed into each tube provided. The tubes containing the CaL variation and bacteria were placed in an incubator at 30 °C and shaken at 125 rpm for 72 h. Subsequently, the solution in each tube was filtered with filter paper that had previously been weighed. Subsequently, the oven of each tube and filter paper was weighed. The formed calcite will be obtained from the difference in the weight of the tube and the difference in the weight of the filter paper. The variation that produces the optimum calcite content is used during concrete mixing.

2.4 Precipitation of concrete samples and curing of concrete

The manufacture of concrete samples was based on the circular letter of the Minister of Public Works and Public Housing number 07/SE /2016 Concerning Guidelines for Determining the Procedure for Determining Normal Concrete Mixtures With OPC, PPC, And PCC Cement. The amounts of bacteria and calcium lactate added can be seen in the experimental conditions in Table 4.

The quality of the concrete planned in this research was K-250 concrete (20.75 MPa), which was molded with a mold made of PVC. The size of the mold was 5 × 15 cm, with a shape similar to that of a cylindrical formwork. The concrete used in this study was K-250 concrete (20.75 MPa), which was molded with a mold made of PVC. The size of the mold is 5 cm x 15 cm with a shape like a cylindrical formwork. The proportions of the concrete mixture from the mix design results based on the PUPR ministerial circular letters are listed in Table 3. Cracks in concrete are formed when the age of the concrete reaches one day. The aim is to make cracking safe and accessible because fresh concrete does not have a high compressive strength. Cracking was performed using a Universal Testing Machine (UTM). Cracks are made by cracking the sample using UTM with cracks measuring 0.3-0.5 mm hairline cracks. Bacteria and calcium nutrients were mixed into the concrete mixture at 5% instead of water [34]. The concrete samples were then placed in water-filled tanks and cured for 28 days.

Table 4. Experimental condition of concrete samples

Sample	Cement (kg)	Sand (kg)	Gravel (kg)	Water (L)	Bacte-ria (L)	Calcium Laktat (g)
Normal concrete	312	736	902	244	-	-
Concrete Bakteria + CaL	312	736	902	244	0.81	796.60
Concrete CaL	312	736	902	244	-	799.26
Normal concrete cracks	312	736	902	244	-	-
Concrete Bacteria + CaL cracks	312	736	902	244	0.81	796.60
Concrete CaL cracks	312	736	902	244	-	799.26

2.5 Image processing testing

The purpose of this test was to determine the rate of crack repair in the concrete. Observations were made to determine the healing rate of concrete and compare it with that of standard concrete or control concrete. Observations were made by taking photos of concrete samples using a cell phone camera, starting when the cracks first formed and continuing until 28 days of concrete age. Photographs were taken at the same height and shooting position. The photos were then analyzed using 'ImageJ 'software. The area repair ratio based on the number of pixel points can be calculated using Equation (2). Where A_0 is the number of pixel points of the initial crack area (before healing) and A_t is the number of pixel points of the crack area after healing at time *t* days.

$$Crack\ repair = ((A_0\text{-}A_t)/A_0) \times 100\% \quad (2)$$

2.6 Concrete compressive strength testing

The compressive strength test refers to SNI-03- 1974-2011, how tests the compressive strength of concrete with cylindrical specimens. The samples were cylindrical with a size of 50 × 100 mm; therefore, various requirements in compressive testing, including correction factors, refer to these regulations. Tests were conducted using a Universal Testing Machine (UTM) on 14-day and 28-day concrete samples.

2.7 Concrete permeability and absorption testing

Permeability testing was conducted on the 28-day concrete samples. The permeability tests were performed using the flow test method. A permeability test was conducted to determine the percentage of water passing through the concrete. Twelve samples were used for the permeability and they were tested using simple permeability test equipment, as shown in Figure 1. The permeability testing procedure was performed using the force of gravity. The water collection pipe had a height of 2 m, and the water in the water tube flowed by gravity. Water that flows gravitationally enters through the concrete matrix, and then comes out through the valve at the bottom of the pipe. The data obtained were in the form of time data and height differences. Both data sets were used to obtain the value of the concrete permeability coefficient.

The absorption test was conducted to determine the ability of the concrete to absorb water. Concrete is a porous material that can absorb water such that even without pressure, water can be absorbed into the pores of the concrete. Concrete absorption testing is quite simple and involves calculating the ratio between the weight of the submerged sample and the weight of the dry sample.

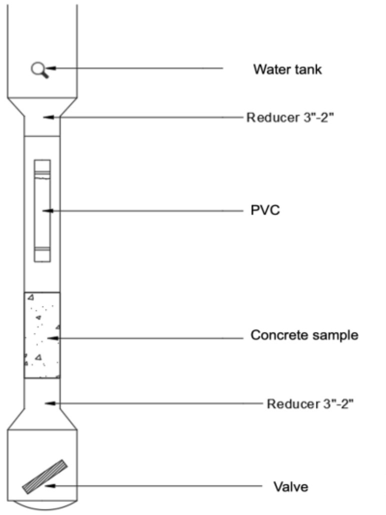


Figure 1. Concrete permeability testing scheme

2.8 Microscopic testing

Scanning electron microscopy (SEM) was used to determine the morphology or surface topology of concrete that has been repaired by calcite precipitation by bacteria; using SEM the magnification of test objects can reach 1,000,000 times with image quality that is still clear so that the morphology of concrete can be identified. SEM testing in this study was limited to the interior of concrete. Therefore, observations were made of the concrete surface in the crack area using VHX-7000.

3. Results and Discussion

3.1 Calcite formation in bacteria and CaL solution

The test-tube experiment produced results in the form of calcite formation in a solution of B. subtilis + CaL. Test tubes were used to determine the mass of calcite formed and the optimum solution, and the theoretical calcite mass obtained from chemical reactions with 100% efficiency was compared [22]. The concentrations of CaL used in this study, namely 21.8 g/L, 43.6 g/L, and 65.4 g/L, eac concentration of which added was as high as 1, 2, and 3 ml. The results of the test tube test are shown in Figure 2.

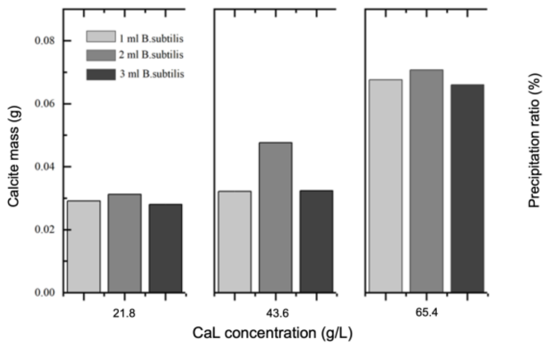


Figure 2. Test-tube results for each variation of 30 ml solution

Based on Figure 2, the solution with a CaL concentration of 65.4 g/L and 2 ml of bacteria produced a higher mass of calcite than the other solutions, with a mass of calcite formed at 0.071 g and a precipitation ratio of 7.86%. Each solution with different concentrations had the highest calcite mass when 2 ml of bacteria was added. This result shows that the addition of 2 ml is optimal. The precipitation ratio at a concentration of 65.4 g/L shows a lower value because the higher the CaL concentration, the longer it takes bacteria with the same concentration to digest all the CaL into calcite. In contrast, at low CaL concentrations, the precipitation ratio was high because the bacteria could consume a smaller amount of CaL. CaL concentration plays a major role in the self-healing process; the more CaL concentration is used, the more calcium carbonate will be produced [23]. The results of this calcite precipitation test showed that the calcite mass increased. As the CaL concentration increases, this test is proven to produce calcite, so that the optimum variation can be applied to concrete mixes. There was a decrease in a 30 ml solution containing 3 ml of Bacillus subtilis and 27 ml of calcium lactate solution. A higher concentration of bacteria should increase the amount of calcite, as reported by [23]. In fact, in the calcite precipitation test treated with 3 ml of bacteria, the amount of calcite produced decreased. This is because during the test, the solution was stored in a tube covered with cotton to avoid contamination that could interfere with the results of the test. Closure with cotton is likely to obstruct the supply of oxygen to the tube or even cut it off. Bacillus subtilis is an aerobic bacterium that requires oxygen for growth [24]. The limited oxygen in the tube is quickly depleted by the presence of bacteria; thus, the bacteria are unable to mineralize. As a result, the amount of calcite produced was reduced.

3.2 Crack Repair Rate by Image Processing

The effectiveness of the addition of bacteria + CaL solution on concrete was observed visually and with the help of ImageJ software. Photographs were taken of 10 × 20 cm cylindrical concrete samples, that is, concrete containing a mixture of bacteria and CaL, and concrete containing CaL only. This test was conducted to determine the effects of Bacillus subtilis and CaL on the healing efficiency of concrete cracks. The visual observation results are shown in Figure 3, whereas the ImageJ processing results are shown in Figure 4 and Figure 5.

Visually, at 28 d of concrete age, the cracks closed, as shown in Figure 3. The data processed by ImageJ and displayed in Figure 4 are the observation data on days 1, 10, 19, and 28. Selection was based on the clarity of the obtained images. The results of shooting on the image of the observation of day 14 and day 21 turned out to produce images that were less clear after being analyzed with ImageJ software, so it was represented by the observation data of day ten and day 19, which had a clear picture when analyzed by the software, and the results did not have a significant difference.

Figure 3. Photo of normal bacteria+CaL concrete (top) and photo of normal CaL concrete (bottom)

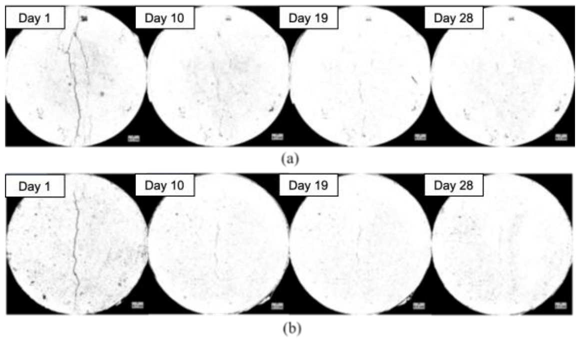


Figure 4. ImageJ processing results on normal bacteria+CaL concrete (a) and normal CaL concrete (b)

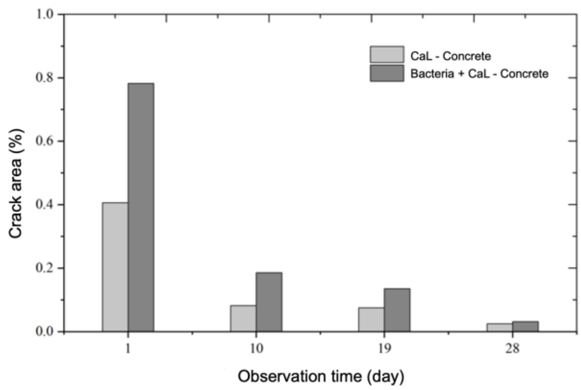


Figure 5. Graph of crack area per total area at each concrete age

The areas of the concrete cracks at each observation time are shown in Figure 5. From the cracking area in the graph, it can be observed that. The concrete containing bacteria and CaL had a larger initial cracking area than concrete containing only CaL. However, on the 28th observation day, the remaining cracking areas of the two samples were similar.

Based on the calculation of the ratio of the initial crack area to the final crack area, it was found that the repair rate ratio for concrete with bacteria + CaL was 95.94%, while that with CaL alone was 93.96%. This result shows that crack repair becomes more effective with the addition of bacteria and CaLs. It can be seen that as the age of concrete increases, the area of cracks decreases; the cause is the white powder in the form of calcium carbonate produced by bacterial induction and the advanced carbonation process in the concrete matrix covering the existing cracks [25].

3.3 Compressive Strength

The highest compressive strength at 28 days was achieved by the bacteria+CaL concrete sample with a strength of 24.41 MPa, whereas the highest compressive strength at 14 days was found in the control concrete, which was normal concrete without any additives. Bacteria + CaL concrete at the age of 14 days was lower than that of normal control concrete because of the concrete mixture. Calcium lactate affects the setting time, which slows the reaction run slowly [26]. The calcium source affects the rate and amount of calcite precipitation, allowing bacteria to increase precipitation, which is beneficial for concrete [27]. There was a 3.04% increase in strength in bacterial concrete + CaL compared to normal intact concrete at 28 days of age. The addition of calcium lactate to the concrete mix increased its compressive strength. The presence of a calcium source in the form of calcium lactate in concrete allows bacteria to produce calcium carbonate, which in its presence can increase the compressive strength [5]. The compressive strength test results for variations of concrete samples aged 14 and 28 days are shown in Figure 6.

The lowest compressive strength in 14-day-old cracked concrete was observed for normal concrete. Cracks in concrete affect the increase in compressive strength in concrete containing calcium lactate and bacteria because the presence of cracks affects the ease of concrete in contact with water or outside air; thus, the bio-mineralization process runs more effectively in cracked concrete. The o-mineralization process can precipitate calcium carbonate so that the calcium carbonate that can be produced in cracked concrete becomes six times more. Bio-mineralization occurs in bacteria + CaL concrete such that the compressive strength is greater than that of normal concrete, which only receives reinforcement from autogenous healing or from cement that has not reacted in concrete.

The cracked concrete showed remarkable improvement at 28 days, especially in the concrete containing bacteria and calcium lactate. The compressive strength value of the cracked bacterial + CaL concrete is close to that of intact normal concrete, which is 23.49 MPa, while that of intact normal concrete is 23.69 MPa. This result shows that the cracked concrete improved significantly, and its strength increased by 13.16% compared with the cracked normal concrete. The addition of bacteria and calcium lactate to the concrete covered the cracks in the concrete skin, and the addition of bacteria and calcium lactate to the concrete was also effective in increasing the compressive strength. The addition of bacteria and CaL produces more calcite, filling the pores and increasing the compressive strength [28]. The telling of concrete pores increases the compressive strength of concrete [29].

3.4 Permeability and Absorption of Concrete

The permeability value indicates the density of the material, whereas the absorption value indicates the absorbency of the material. The permeability is directly proportional to the absorbency and inversely proportional to the compressive strength. The permeability of concrete is considered to be good when it is difficult for the fluid to move within the concrete matrix, indicating that the concrete has a good density with few pores. Good concrete has a low absorbency, which indicates that the number of pores in the concrete is small. The fewer the pores in the concrete, the denser the concrete; hence, the strength is high. The permeability test results are shown in Figure 7 and the concrete absorption test results can be seen in Figure 8.

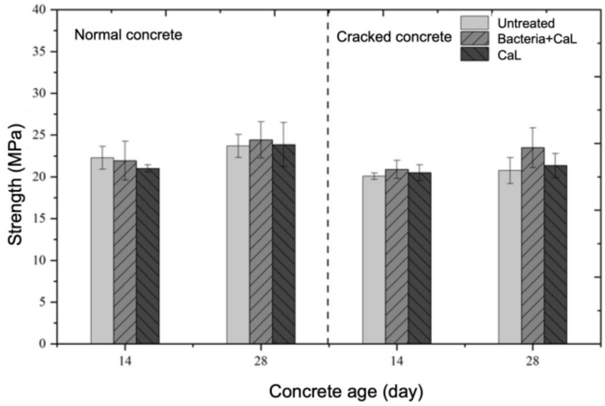


Figure 6. Compressive strength test results for variations of concrete samples aged 14 and 28 days

Based on Figure 7, normal intact concrete has the lowest permeability, which proves that intact concrete is tight, making it more difficult for the fluid to pass through. Permeability indicates the rate of fluid flow in the concrete matrix; therefore, the higher the value, the worse the quality of the concrete because it can accelerate the corrosion rate in the presence of water or corrosive substances flowing in the concrete matrix. Cracked concrete containing bacteria and calcium lactate exhibited decreased permeability. The permeability value of bacteria + CaL concrete is 7.13x10-8 cm/sec, while that of normal cracked concrete is 1.20x10-7 cm/sec. There is a 53.12% decrease in the permeability rate of normally cracked concrete. Calcium carbonate crystals filled the cracked surfaces and pores of the concrete, resulting in a reduction in the permeability of the concrete samples. Bacteria + CaL concrete has been proven to be more effective in reducing the permeability of concrete owing to the precipitation of CaCO3, which makes concrete denser [26].

Based on Figure 8, there is a decrease in absorption in concrete with bacteria and calcium lactate added, which is 22.20% compared to normal cracked concrete. This is due to the presence of bacteria that contribute to the formation of CaCO3, thus reducing the percentage of pores in the concrete [30]. Bacterial metabolism converts CaL into calcium carbonate, covering the crack pathways in the concrete, as well as the pores of the concrete, making it more difficult for the fluid to be absorbed into the concrete matrix, and a decrease in absorbency occurs [31]. Additionally, the deposition of CaCO3 in concrete increases the tightness and density of concrete pores [32].

3.5 Scanning Electron Microscope (SEM) Testing

Tests were conducted on the samples of normal concrete, bacterial concrete + CaL, and CaL concrete. The concrete samples tested were small and derived from previously crushed concrete. SEM is an electron microscope that produces images of samples by scanning the surface with a focused electron beam with magnification to a certain scale. This test looked at the inside of the concrete but not the cracks on the surface of the concrete. Based on this, observations were made using a VHX-7000 digital microscope to observe the surface of the concrete that was completely covered by calcite. The test results obtained using SEM are shown in Figure 9 and Figure 10, while the results of the VHX-7000 observations can be seen in Figure 11.

Based on Figure 9, at 2000 × magnification, calcite crystals can be seen in the concrete. Concrete is concrete containing bacteria and calcium lactate. The presence of calcite crystals in the concrete proves that calcite exists in the form of calcium carbonate produced by bacteria. The resulting calcite precipitate is used for protection against damaging materials and subsequently improves the mechanical properties of concrete [30]. Calcium carbonate precipitation results in the production of a gel that aids crack healing. SEM provides a vivid image of the inside of the material, but to confirm the precipitation of calcium carbonate and the resulting product, other tests such as EDX or XRD spectrum analysis are needed [33].

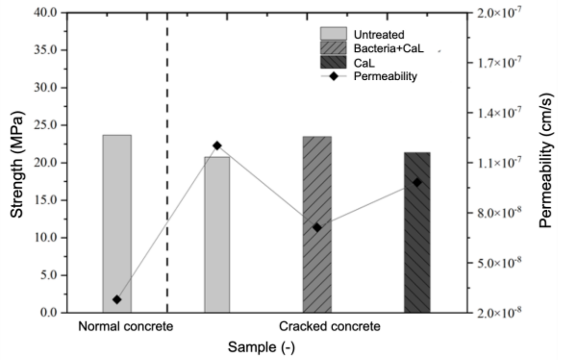


Figure 7. The relationship between compressive strength and concrete permeability

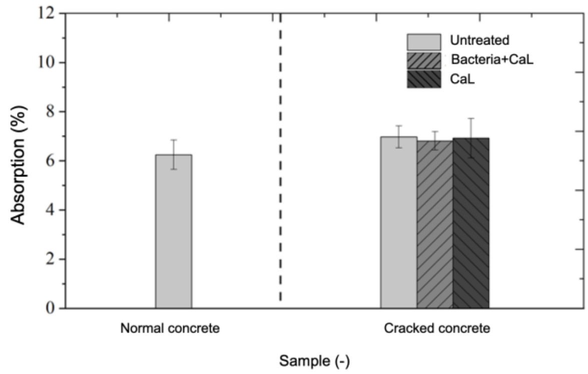


Figure 8. Concrete absorption capacity test results

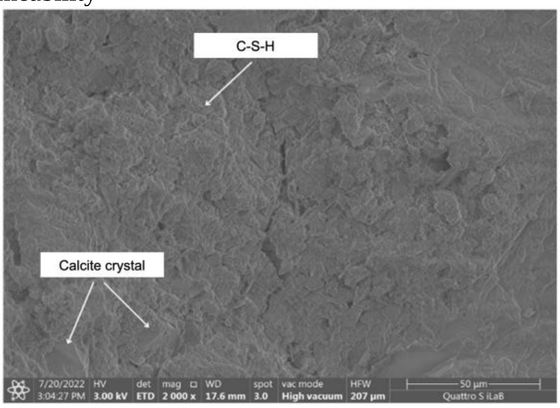
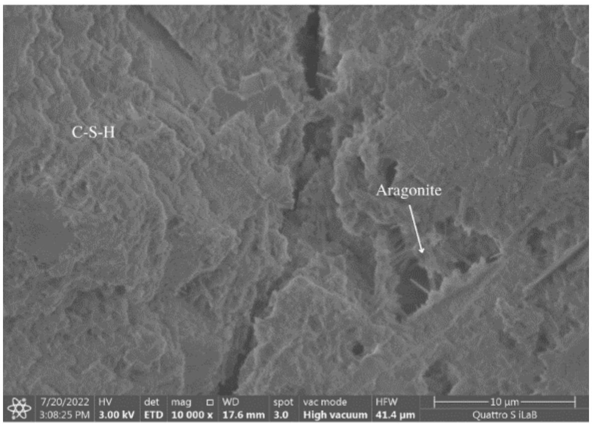
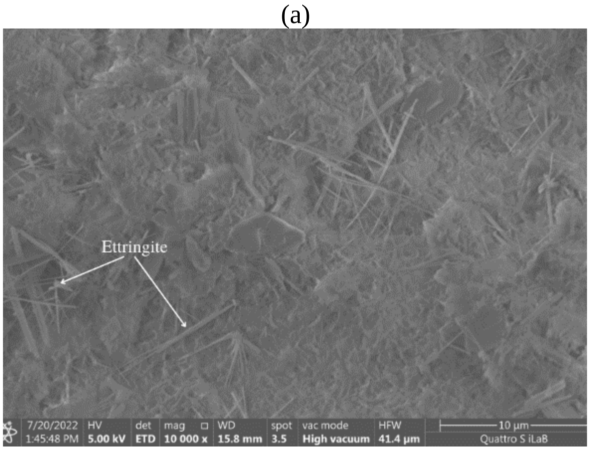


Figure 9. SEM test results on bacteria+CaL concrete with a magnification of 2,000 times



(a)



(b)

Figure 10. SEM testing on bacterial+CaL concrete (a) and normal concrete (b)

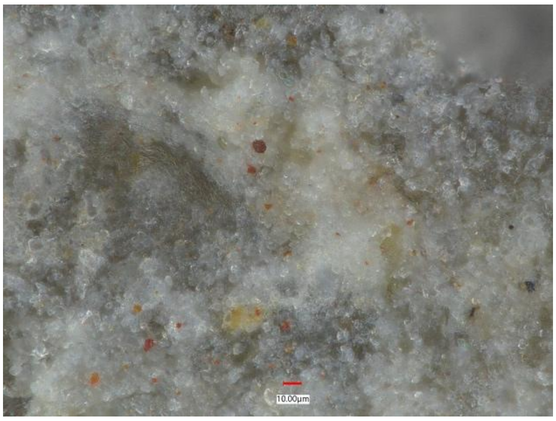


Figure 11. Observation results on the concrete surface with 1000 times magnification using VHX-7000

As shown in Figure 10, after magnification, even up to 10,000 times, no calcite crystals were found in normal concrete. A magnification of 10,000 times on bacterial concrete + CaL does not show the presence of calcite crystals, possibly because the size of calcite is too large. Instead, other forms, such as C-S-H and aragonite, were clearly visible at this magnification. The calcite crystals shown in Figure 9 indicate that the bacteria consumed a large amount of calcium lactate in the concrete to produce calcium lactate into calcium carbonate or calcite. The greater the concentration of calcium lactate and the greater the concentration of bacteria applied, the greater the amount of calcium mass identified in the concrete matrix [34].

Calcium carbonate and calcite crystals are formed by bacteria that lead to the pore filling of concrete. An increase in the number of bacteria produced more calcium carbonate and calcite crystals. Calcium silicate hydrate (CSH) and ettringite are the results of cement hydration. As shown in Figure 10, the ettringite in normal concrete has a needle-like elongated crystal shape. One of the causes of corrosion in concrete is the formation of ettringite owing to the chemical reaction between the calcium in the concrete and sulfate salts from the outside. Similar to rust on iron, ettringite causes an expansion of the concrete volume, cause the concrete mass to compress and break [35]. SEM testing confirmed the presence of calcite at an advanced CSH level in the bacterial concrete. Precipitation in the pores of concrete increases its specific gravity, which improves its mechanical properties as well [23]. Apart from filling the pores, calcite also covered the cracks on the concrete surface. This calcite covered the crack and was identified by observations using a VHX-7000 instrument. An image filled with crystals was obtained with a magnification of 1000 ×; it was then identified that the crystals were calcite deposits covering the cracks that occurred in the concrete. The improvement in the mechanical properties of concrete, such as compressive strength, permeability, and absorbency, is due to the effectiveness of microorganisms in precipitating calcium carbonate in the cracks and pores of concrete [30].

4. Conclusion

The repair of cracks in concrete can be overcome by adding B. subtilis and CaL to the concrete mixture. Besides being able to close the cracks that occur, the addition of bacteria and calcium sources to concrete improves the mechanical properties of the concrete itself so that it becomes a useful novelty, reducing the cost of concrete maintenance. The use of *B. subtilis* and calcium lactate at concentration of 65.4 g/L and 2 ml bacteria produced the optimum calcite mass. Concrete with the addition of B. subtilis + CaL had a crack repair rate of 95.94%, whereas concrete with the addition of CaL alone had a repair rate of 93.96%. The addition of B. subtilis and CaL increased the compressive strength of the cracked concrete by 13.16%. A positive effect also occurred on the permeability and absorption properties, which reduced the permeability by 53.12% and absorption by 22.20%. The increase in compressive strength and decrease in permeability and absorption is due to the presence of $CaCO_3$ deposits formed due to bacterial metabolism so that the pores are denser, and the surface cracks are closed. SEM testing showed that concrete with the addition of bacteria and calcium lactate produced calcite crystals in the concrete pores. The repair of cracks by image processing testing is reinforced by the results of observations using VHX-7000, which show that in the area of the cracks identified, many crystals are considered to be calcite crystals.

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