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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Repairing of Flexural Cracks on Reinforced Self-Healing Concrete Beam using Bacillus Subtillis Bacteria

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DOI: https://doi.org/10.30880/ijie.2020.12.04029
Received 26 December 2019; Accepted 30 March 2020; Available online 13 May 2020

Abstract: This paper will discuss the phenomenon of cracks in concrete beams due to flexural loads and methods of repair using bacteria which are often called self-healing concrete. Concrete is very good in resisting compressive forces but is weak in resisting tensile forces, so that concrete is often combined with steel reinforcement known as reinforced concrete. One interesting phenomenon is that there is damage to the concrete beam which is characterized by the occurrence of small cracks that affect the entry of oxygen into the concrete which causes corrosion of the steel reinforcement in it. To overcome this problem, the research was carried out by injecting a mixture of bacteria in the concrete, so that cracks that occur can be covered by bacteria that react with air. In this study, we will observe the flexural strength of concrete that has been repaired by using Bacillus subtillis which are injected into the concrete. Test specimens made in the form of beams measuring 150x150x600 mm as many as 8 samples will be tested for flexural strength using static loads in the center of the beam before and after bacterial injection. Flexural tests were carried out on normal concrete beams aged 7, 14, 21 and 28 days. Compressive strength is tested at 28 days with a 30 MPa strength plan. In addition, the process of closing cracks by bacteria is also carried out. From the results of the observation showed that the bacterium Bacillus subtillis could be used as an ingredient to repair concrete because the flexural strength produced after the repair is categorized as very good.

Keywords: Self-healing, bacteria, bacillus subtillis, flexural strength

1. Introduction

Concrete is a composite material consisting of a constituent material in the form of aggregate, cement and water. This construction material is one of the most desirable materials in the world and can be combined with other materials such as steel, aluminum, wood and plastic [1]. Concrete is very important and extensively used as building materials in construction work, the main reason for using concrete is its strength and good durability [2]. Concrete has very strong properties in resisting compressive forces and is quite easy in its production process, but concrete is very limited in resisting tensile forces so that concrete is often combined with reinforcing steel so that this material combination will work optimally [2].

The performance of the strength and durability of concrete is certainly influenced by several factors, one of the main factors is the occurrence of cracks. Cracks in concrete can reduce strength and durability, large cracks will result

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in reduced structural performance while small cracks can reduce durability, increase permeability and provide opportunities for corrosion in steel reinforcement [2], [3]. Self-healing is defined as the ability of a material to be able to repair damage automatically without assistance from external parties including humans [4]. Self-healing concrete is produced so that the cracked concrete can improve itself, especially for small cracks so that it can avoid the entry of water in the component [5].

Since the last few years, many types of bacteria have been used to repair cracks in concrete, although it is still a record that not all bac-teria have a good effect on repairing concrete [6]. Research on the use of bacteria that have been carried out includes Sporosarcina Pasteurii ATCC 11859 [4], Alkaliphilic bacteria [4], [7], Bacillus megaterium, Bacillus Subtillis and Bacillus Aerius [7], [8], and Bacillus sphaericus LMG 22557 [9].

Research that has been done on self-healing concrete, among others, repairs to new cracks in concrete [7], repair of concrete beams [6], [10], [11], self-healing concrete application in the field, comparing methods of repairing cracks in concrete beams [1], and numerical analysis of structural performance using self-healing methods for concrete [5], [12].

This paper will discuss the results of the performance of the type of Bacillus subtilis bacteria as an injection material for repair of cracks in concrete blocks. The specimens were made in the form of blocks with a size of 150 x 150 x 600 mm using 4-D6 flexural reinforcement and D4-145 mm shear reinforcement as many as 8 samples tested at the age of 7, 14, 21 and 28 days. The compressive strength of concrete was also tested by making cylindrical samples measuring 150 mm in diameter and 300 mm in height which was tested for com-pressive strength at 7, 14 and 28 days of treatment. This study aims to determine the performance of Bacillus subtillis bacteria in repairing flexural cracks in concrete beams so that the self-healing method is expected to help simplify the method of re-pairing cracks in concrete beams.

2. Test Method and Materials

2.1 Materials

In general, constituent materials consist of cement, water and aggregates and steel reinforcement when making reinforced concrete. In this study using Portland Pozzolan Cement type cement from Gresik from East Java Province, Indonesia with a specific gravity of 3.15. While the water used came from the Civil Engineering Construction Structure and Materials Laboratory, Universitas Muhammadiyah Yogyakarta. The aggregates used in this study consisted of coarse aggregates and fine aggregates originating from Kulon Progo Regency, Special Province of Yogyakarta, Indonesia. The testing of each aggregate property refers to the standard [1].

Table 1 describes the results of testing of fine aggregates in the form of water content test, unit weight, sludge content, and specific gravity and grain gradation test. The results of water content testing showed the results of 1.75% which included the category of very dry so that most likely will absorb a lot of water during the mixing process. Testing of mud content shows the results of 1.39%; it can be concluded that the sediment content that settles in the sand still meets the normal limit of less than 5%. The resulting specific gravity and unit weight is also quite good and can be used as a normal concrete constituent.

Table 1 - Fine aggregate properties

Test Item	Result
Water Content (%)	1.75
Unit Weight (gr/cm3)	1.26
Mud Content (%)	1.39
Specific Gravity	2.39

Test of coarse aggregate properties is shown in Table 2 in the form of testing water content, unit weight, sludge, specific gravity, and roughness. The test results show that the resulting water content is 1.33%, this is good enough to be used as a constituent of concrete. In addition, the specific gravity produced is 2.72, this is also categorized as a good aggregate as a constituent of concrete. The most important thing when using coarse aggregate is the roughness of the aggregate not more than 40%, but this aggregate still produces a roughness level of 39.32%, very close to the maximum allowable limit. From both types of coarse aggregates and fine aggregates, it can be concluded that all of these materials can be used as constituent materials for concrete.

In making this concrete beam using steel reinforcement as flexural reinforcement and shear reinforcement. In flexural reinforcement using deform steel with a diameter of 6mm while in shear reinforcement using reinforcement with a size of 4 mm. Fig. 1 is the result of the relationship of stress and strain of all steel reinforcement specimens where each reinforcement diameter was taken 3 samples with each test object 500 mm in length, and its tensile strength was tested. Based on the ultimate stress test results of steel with a diameter of 4 mm of 570.64 MPa while the D6 reinforcing steel obtained an ultimate voltage of 437.58 MPa.

Table 2 - Course aggregate test result

Test Item	Result
Water Content (%)	1.33
Unit Weight (gr/cm^3)	1.29
Mud Content (%)	3.83
Specific Gravity	2.72
Roughness Value (%)	39.32

There is some limitation about a tensile test of rebar steel. It is the machine cannot record the data when yield condition. The first data that have recorded when the strain is 1%. Theoretically, the yield strain of steel is around 0.2%.

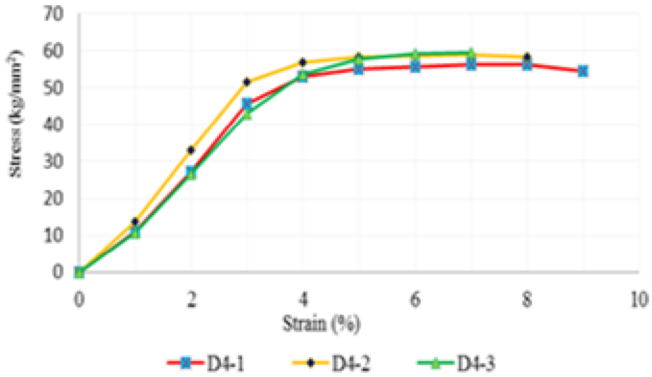


Fig 1. - Relationship of stress and strain of D4 steel tensile test

2.2 Bacillus Subtillis

Bacillus subtillis bacteria are positive rod-shaped bacteria commonly found in the soil. These bacteria are able to form strong self-defence by forming endospore that can be held in extreme environ-mental conditions [12]. Bacillus subtillis bacteria can grow with temperatures around 25 - 35 ºC and have evolved so that they can live even under very dry conditions and get faster protection against situations such as low pH conditions [13]. This type of bacteria is a bacterium that is used as self-healing concrete with an adhesive material called Bacilla Filla. How this bacteria work by producing oxalic acid and oxygen. When the water starts to enter through the gap in the concrete, the bacteria will grow and eventually become limestone. The limestone will harden on cracks on the concrete surface so that the cracks are closed [14]. The bacterial content injected into the concrete crack is 10^5 cells/ml. Injection of Bacillus subtilis bacteria was carried out during the curing process. Bacillus Subtilis bacteria can be seen in Fig. 2.

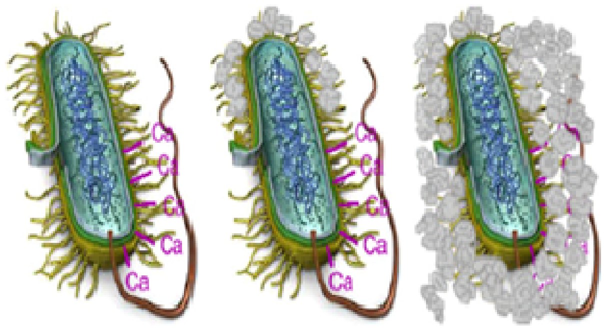


Fig 2. - Calcium carbonates formation on bacterial cell wall [1]

Self-healing material is one of the most popular topics recently because it has the ability to repair damage to concrete automatically. This will make it easier for engineers not to have to check concrete cracks. Self-healing theory was first carried out by the French Academy of Science [14], where finding calcium hydroxide in the hydration process of semen is converted to calcium carbonate on exposure to the atmosphere. The development of self-healing was first called autogenous self-healing [15] [16], and is due to the on-going hydration of cancer minerals or carbonation of calcium hydroxide [17].

2.3 Mix Design

In this study planned to use concrete with fc quality = 30 MPa at the age of 28 days, where the concrete quality is suitable for construction commonly used in Indonesia. Mix designs that are used using standards commonly used in Indonesia [14]. As well as the planned slump value of 10 ± 2 cm. The results of the mix design of the concrete constituent materials in this study can be seen in Table 3. The percentage of the concrete mixture can be seen in Fig. 3; it can be seen that the cement content is 19%, 9% water, 26% fine aggregate, and 46% coarse aggregate. This composition is used to obtain concrete with a compressive strength of 30 MPa.

Table 3: Concrete Mixture Composition for 1 m^3

Constituent materials	Composition
Water (liter)	204.9
Cement (kg)	435.96
Fine Aggregate (kg)	614.93
Coarse Aggregate (kg)	1093.21
Total Weight (kg)	2349
Cement / Water Ratio	0.47

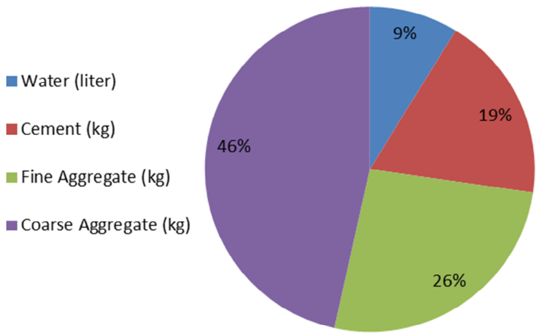


Fig 3. - Concrete mixture composition

2.4 Flexural Strength and Compressive Strength

Flexural strength is the ability of concrete placed in two places to hold the force in the direction perpendicular to the axis of the test object until the beam has broken [4]. To determine the flexural strength of a beam with a centered loading point where the fracture plane located in the central region can use the following Eq. (1).

$$Flexural\ strength = (P \times L) / (b \times h^2) \quad (1)$$

where P is loading (kg); L is the length of the beam (m); b is width section of the beam (m), and h is height section of the beam (m). A beam with a test that if the fracture is outside the centre (1/3 of the middle of the span), the flexural strength can be calculated using the following equation 1. With the h value, the average distance between the broken latitude and the nearest outer support is measured at four places at the angle of the span.

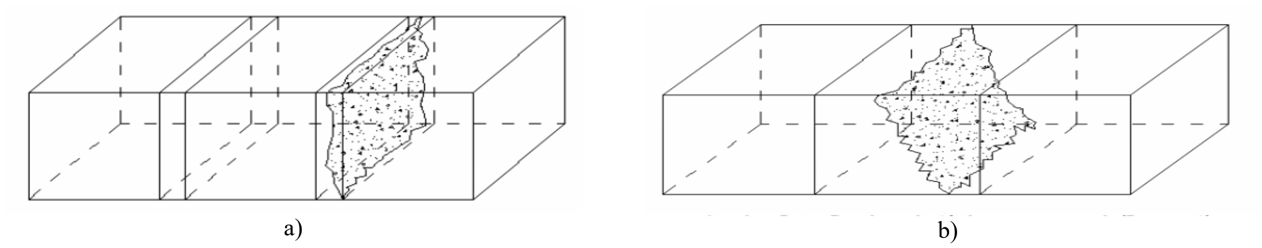


Fig 4. – (a) Beam with faults in the middle of the span; (b) Beam with faults outside the center of the span [14]

In general, there are several types of collapse on the beam, which are as follows [6]: (i) Flexural cracks are vertical cracks extending from the tensile side of the beam and pointing up until the neutral axis is shown in Fig. 5(a); Diagonal cracks due to sliding occur in reinforced concrete beams either free cracks or flexural crack extensions. This occurs in cross sections with large and thin flanges as in Fig. 5(b).

Fig. 5 - (a) Crack pattern due to bending force, (b) Crack patterns due to shear force

The compressive strength of concrete in the ability of concrete to accept compressive forces per unit area. The compressive strength of the concrete can be carried out using compressive test equipment and cylindrical test objects. The compressive strength of concrete was carried out to determine the compressive strength of concrete at 28 days. To determine the compressive strength can be calculated using the following Eq. (2).

$$\text{Compressive strength} = P / A \tag{2}$$

where P is axial load (kg), and A is an area of cylinder concrete (mm^2).

2.5 Test Method

Testing of concrete beam bending refers to applicable standards [14] where the load position is centred in the middle. The stage of making concrete beams and cylinders is first checked for slump values; then fresh concrete is inserted into each mould that has been provided. After the beam was curing 28 days, it was inputted the loading crack (Pcrack). Pcrack of 2000 kg represents as axial loading that causes of the first crack on the beam. Then, bacteria Bacillus subtilis were injected into the crack during the curing of the beam such as 7, 14, 21, and 28 days. Sample curing was done by covering the sample with wet burlap sacks. The form of testing can be seen in Fig. 6.

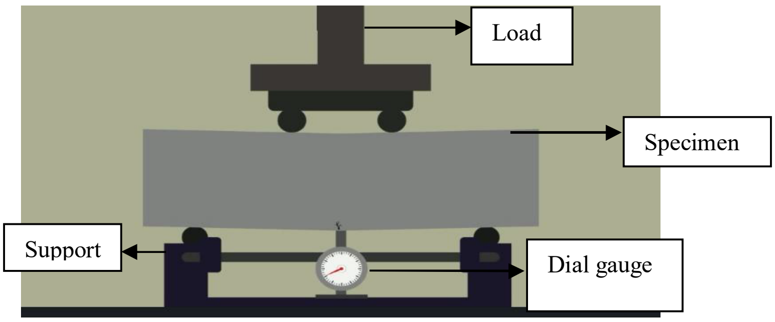


Fig. 6 - Setting up form for flexural testing

The reinforcement structure in this study can be seen as in Fig. 7 where using flexural reinforcement measuring 6 mm with yield strength 437.58 MPa in diameter as many as 4 bars and using shear reinforcement with a steel size of 4 mm diameter at a distance of 145 mm with yield strength 570.64 MPa.

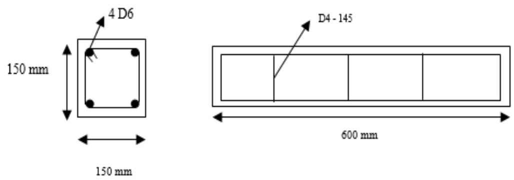


Fig. 7 - Cross section and longitudinal section of specimens

The testing phase of this concrete beam was made as many as 8 samples, each of which was tested at the age of 7.14.21 and 28 days in each variation of the day as much as 2 samples. After the concrete beam has been tested to form crack cracks, flexural strength and displacement will be noted. Bacillus subtilis bacteria were injected into concrete cracks during the curing process. In the curing process, the beam was covered in the wet gunny sack which was then observed every day and tested for flexural strength.

3. Results and Discussion

3.1 Compressive Strength and Slump Flow

Testing the slump value aims to determine the workability value of the fresh concrete. If the value of the slump is very small, it is feared that the concrete will be difficult to mix up to the difficulty during the compaction process if the slump value is too high, it is also possible to segregate and excess water which can potentially reduce its compressive strength. In this study targeting a slump value of 10 ± 2 cm which is a requirement for normal concrete. The test results show that the slump value obtained is 9.71 cm. Based on these results it is categorized that the value of concrete workability meets the required specifications.

The compressive strength that is planned in this study is 30 MPa when the concrete is 28 days old. The test of compressive strength was made as many as 9 specimens tested for compressive strength at the age of 7, 14 and 28 days. Cylindrical compressive strength test specimens measuring 15 cm in diameter with a height of 30 cm. The compressive strength test results can be seen in Fig. 8. When the concrete is 7 days old, the average compressive strength of the test object is 14.20 MPa. When 14 days the compressive strength increased by 29.88% to 20.25 MPa. The compressive strength of concrete at 28 days was 29.37 MPa.

From the results of the compressive strength, it can be concluded that this concrete meets the specified mix design specifications, namely 30 MPa compressive strength plan, the test results with compressive strength plan only have a difference of 0.63 MPa or 2.1 %.

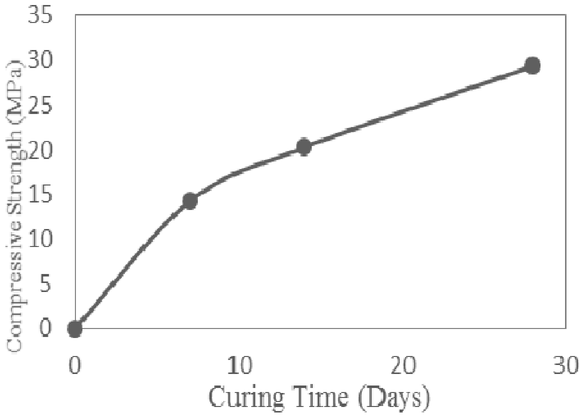


Fig 8. - The relation between compressive strength with curing time

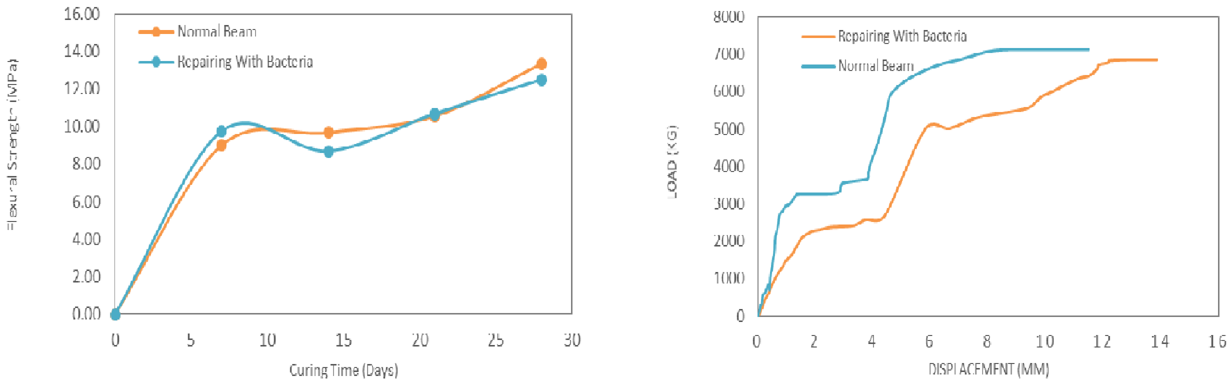
3.2 Flexural Strength

Testing of flexural strength was carried out when reinforced concrete beams were 7, 14, 21 and 28 days old. The flexural strength test results can be seen in Table 4. Meanwhile, Fig. 9(a) shows the relationship between the curing time with the flexural strength of the beam by comparing normal concrete to the concrete repaired using the Bacillus subtillis bacteria. At the age of 7 days, normal concrete has a 9 MPa flexural strength which then produces flexural cracks on the concrete pulling part, the crack is injected by bacteria and then re-tested when the 7-day-old concrete produces 9.75 MPa flexural strength, this shows that the repaired concrete using bacteria has a higher flexural strength than the initial flexural strength, this is influenced by bacteria which begin to cover cracks in the beam and very young curing time has not reached 28 days, so it is possible for the concrete to increase significant flexural strength.

Table 4: Flexural strength testing result

Age (days)	Flexural Strength (MPa)	
	Before Repair	After Repair
0	0.00	0.00
7	9.00	9.75
14	9.68	8.70
21	10.56	10.69
28	13.34	12.50

Besides that, Bacillus subtilis is bacteria exhibits urease activity which catalyzes the hydrolysis of urea ($CO(NH_2)_2$) into ammonium (NH_4^+) and carbonate (CO_3^{2-}). First, urea is hydrolyzed to carbamate and ammonia. Carbamate then hydrolyzes to form ammonia and carbonic acid additionally. These products subsequently form bicarbonate and ammonium and hydroxide ions. The ammonia is responsible for pH increase, which in turn shifts the bicarbonate equilibrium, resulting in the formation of calcium carbonate ions. Since the cell membrane of the bacteria is negatively charged, the bacteria draw cations from the environment, including Ca^{2+}, to deposit on their cell surface. The Ca^{2+} ions subsequently react with the $CO_3^{\ 2-}$ ions, leading to the precipitation of $CaCO_3$ at the cell surface that serves as a nucleation site [17]. This area helps the bacteria produce the Calcium Carbonate (Calcite). The reaction of chemist shown in Eq. (3). Therefore, calcite can cover cracking of beam.



a) b)

Fig. 9 – (a) Relation between flexural strength with curing time, (b) The relationship between load with deflection

$$\begin{array}{lcl} CO(NH_2)_2 + H_2O & \rightarrow & NH_2COOH + NH_3 \\ NH_2COOH + H_2O & \rightarrow & NH_3 + H_2CO_3 \\ 2NH_3 + 2H_2O & \leftrightarrow & 2NH^{4+} + 2OH^- \\ 2OH^- + H_2CO_3 & \leftrightarrow & CO_3^{2-} + 2H_2O \\ Ca^{2+} + Cell & \rightarrow & Cell^- Ca^{2+} \\ Cl^- + HCO_3^- + NH_3 & \rightarrow & NH_4Cl + CO_3^{2-} \\ Cell^- Ca^{2+} + CO_3^{2-} & \rightarrow & Cell^- CaCO_3 \end{array} \quad (3)$$

When the concrete beam was 14 days old, it produced a flexural strength of 9.68 MPa. This showed that the flexural strength only increased by 7.02% from flexural strength when the concrete was 7 days old. While the results of the repaired concrete only obtained a flexural strength of 8.70 MPa, this shows that the concrete that has been repaired is not better than the initial concrete before it is damaged, this is due to the optimal age of concrete, and there is no significant increase in flexural strength. Concrete beams at the age of 21 days obtained a flexural strength of 10.56 MPa; this flexural strength increased from concrete at 14 days. After being repaired at 21 days the concrete beam obtained a flexural strength of 10.69 MPa, this indicates that at the time before the décor was loaded and after being repaired using the bacterium bacillus subtillis this beam had almost the same strength.

When the concrete age is 28 days, normal concrete produces a flexural strength of 13.34 MPa, then the cracks in the concrete are repaired using the injection process of Bacillus subtillis. After 28 days, the flexural strength of this beam was tested to produce a maximum flexural strength of 12.50 MPa. It can be concluded that concrete with 28 days of age is a test object that best describes the effect of bacteria that work because the concrete is no longer affected by curing time as in the samples tested at an earlier age. At the time of this final testing phase showed that the flexural strength of concrete using repair was almost close to the results of the initial flexural strength of the concrete beam, which was 93.63% of the initial concrete compressive strength at 28 days. With a result of more than 90%, it can be concluded that this bacterium can be applied to repair concrete construction. Concrete with bacterial repair injection produces flexural strength no higher than the flexural strength of the concrete before cracking; this is influenced by several factors such as the size of the crack that is too wide so that the bacteria have not been able to cover the crack completely.

In this study, there is a limitation about the size of crack cannot control. Even though, The loading crack was same as 2000 kg. Based on the visualization crack in the sample after cracking test, There is difference cracking size in the beam sample before injection. Microcracking was found in the sample beam sample at age 7 days and 21 days, so the bacteria Bacillus subtilis is easy to recovered cracks. Therefore, the flexural strength of the slabs is increased after repair the cracks. But, At the beam sample at age 14 days and 28 days was found the macrocrack before repair causes the bacteria bacillus can not effectively repair the crack. So, we conclude that injection bacteria Bacillus subtilis are effectively in the microcrack sample. So, we can conclude that the injection of Bacillus subtilis is effectively applicated in microcracks.

Fig. 9(b) describes the results of the deflection relationship with the load during flexural testing of reinforced concrete beams for the age of 28 days. From these results, it can be explained that normal concrete has a smaller deflection value than concrete that has been repaired using bacterial injection. This is due to when testing normal concrete is not given the maximum load to collapse. At the time of the initial testing, the concrete in only loaded up to be seen there are cracks but does not damage the reinforcement in it, while at the second stage of testing after repair, the concrete beam is tested to the ultimate limit until it damages the entire reinforcement. In Fig. 10, it can be seen that the concrete beam at the time of early loading is able to receive a maximum load of up to 7,109 Tons with the largest deflection of 8.22 mm. Whereas after being repaired with subtillic bacillus bacteria, concrete beams were only able to receive a load of 6,858 Tons and the resulting deflection became larger, which was 13.0 mm.

Through the results of this study, bacteria can be used as an alternative to repairing cracks in concrete. This is caused by bacteria injected on concrete beams capable of improving the flexural strength of concrete more than 90% of the initial flexural strength. In addition, the injection method of bacteria on concrete cracks is relatively easier to carry out; the most decisive thing is the width of the cracked concrete beam and the pressure during the injection process

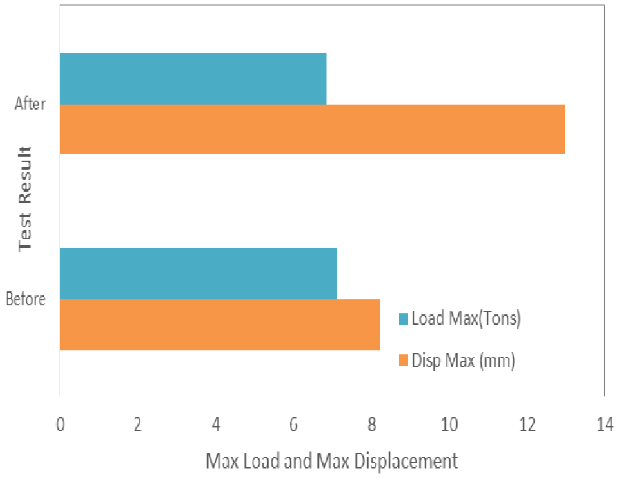


Fig 10. - Maximum load and deflection result

3.3 Failure Pattern

Fig. 11 shows the results of the concrete beam at the beginning of the 28-day age test. These beams only have cracks of concrete, but there is no damage to the steel reinforcement section. G1 beam is one sample of test specimens that are tested and observed until the age of 28 days and observed the process of closure of cracks carried out by the bacterium Bacillus subtillis. Concrete blocks in this study as a whole there is a damaged or cracked flexure at the bottom of the beam or pull section which then spreads to the press section of the beam. Cracks on the beam have no changes, only at one particular point, this is because the load used in this research is a centralized load in the middle of the span. In Fig. 11(b) is the result of the repair of concrete that has been injected by bacteria for 7 days, from the observations it can be seen that the cracks in the beam are still not closed. Crack width in the beam is still the same as before the bacteria injected. This shows that bacteria have not worked well.

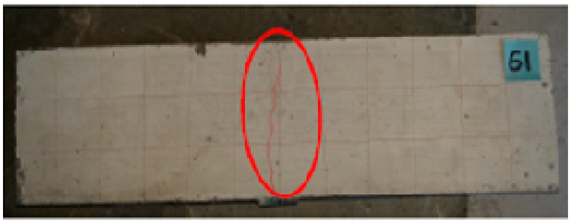
a)

b)

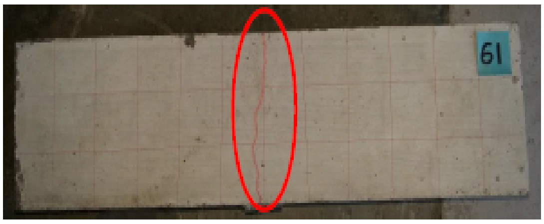
Fig. 11 – (a) Crack result during the initial testing, (b) Cracks that have been injected by bacteria for 7 days

Fig. 12(a) is the result of observations of concrete beams at the age of 14 days, cracking of concrete beams injected by bacteria has begun to shrink compared to at the time of injection at 7 days, but cracks are still very visible. From this, it can be concluded that bacteria have started working to repair cracks in concrete even though cracks have not been completely closed. Observation continued until the concrete beam was 21 days. Fig. 12(b) is the result of observing a concrete beam that has been injected for 21 days. In this observation, it can be seen that cracks that occur experience significant changes compared to the width of cracks when the concrete beam that has been injected by bacteria is 14 days old. Bacteria show good performance in repairing cracks in concrete beams.

In Fig. 12(c) is the result of observations of concrete beams that have been injected by bacteria for 28 days. In this observation, it can be seen that cracks that occur have closed to the surface of the beam even though it has not been completely closed. this shows that bacteria continue to work until the concrete beam reaches the age of 28 days. It should be necessary to observe with a long concrete age to know when the bacteria are able to cover the cracks on the beam completely. After 28 days the repaired concrete beam using the bacteria is re-tested for bending until it collapses. In Fig. 12(d) it can be seen that the position of the damage is the same as the damage to the concrete beam before it is injected with the bacteria. It can be concluded that bacteria can cover cracks that occur due to bending damage, but the load that can be resisted is not better than normal concrete beams that have not been cracked.



a)



b)

c)

d)

Fig. 12 – (a) Cracks that have been injected by bacteria for 14 days, (b) Cracks that have been injected by bacteria for 21 days, (c) Cracks that have been injected by bacteria for 28 days, (d) Flexural failure on the beam after repair

4. Conclusion

Based on the results and discussion above, some conclusions can be drawn as follows:

- The compressive strength obtained in normal concrete is 29.37 MPa with a slump value of 9.71 cm.
- The flexural strength at the beginning of the test was 28 days at 13.34 MPa while the flexural strength after repair using subtillis bacillus bacteria was 12.50 MPa.
- Using Bacillus subtilis bacteria for 28 days of concrete curing time showed that the repaired concrete reached 93.63% of the initial flexural strength of the concrete.
- Bacillus subtillis bacteria can repair microcracks that occur on the beam and restore the flexural strength of the concrete beam. But, the injection of bacteria Bacillus subtilis is cannot effectively in the macrocrack beam because It's hard to bacteria recovered the macrocrack.

Acknowledgement

Authors would like to express gratitude to Department of Civil Engineering, Faculty of Engineering, and Universitas Muhammadi-yah Yogyakarta. And would like thanks to Mr. Sumadi, Siti Afifah, and Erfandi who for helping the research project.

References

[1] Tittleboom K. V., Belie, N. D., Muynck, W. D. & Verstraete W. (2010). Use of bacteria to repair crack in concrete. Cement and Concrete Research, 40, 157-166

[2] Tittelboom K. V. & Belie N. D. (2003). Self-healing in cementitious materials - a review. Materials, 6, 2182-2217.

[3] Bashir J., Kathwarl I., Tiwary A. & Singh K. (2016). Bio concrete the self-healing concrete. Indian Journal of Science and Technology, 9, 1-5.

[4] Xu J. & Wang X. (2018). Self-healing of concrete cracks by use of bacteria containing low alkali cementitious material. Construction and Building Materials, 167, 1-14.

[5] Oucif C., Voyiadjis G. Z. & Rabczuk, T. (2018). Modelling of damage healing and nonlinear self-healing concrete behavior application to coupled and uncoupled self-healing mechanisms. Theoretical and Applied Fracture Mechanics, 96, 216-230.

[6] Heide N. T. & Schlangen H. (2017). Self-healing of early age cracks in concrete. Proceedings of the First International Conference on Self-Healing Materials. The Netherland: Spinger.

[7] Khaliq W. & Ehsan M. B. (2016). Crack healing in concrete using various bio influenced self-healing concrete techniques. Construction and Building Materials, 102, 349-357.

[8] Vijay K., Murmu, M. & Deo S. V. (2017). Bacteria based self-healing concrete a review. Construction and Building Materials, 152, 1008-1014.

[9] Wang J. Y., Tittelboom K. V., Belie N. D. & Verstraete W. (2010). Potential of applying bacteria to heal cracks in concrete. Proceedings 2nd International Conference on Sustainable Construction Materials and Technologies, Italy.

[10] Ferrara L., Krelani V. & Carsana M. (2014). A fracture testing based approach to assess crack healing of concrete with and without crystalline admixtures. Construction and Building Materials, 68, 535-551.

[11] Zhang P., Dai Y., Ding X., Zhou C., Xue X. & Zhao T. (2018). Self-healing behaviour of multiple microcracks of strain hardening cementite. Construction and building materials, 169, 705-715.

[12] Hazelwood T., Jefferson A. D., Lark R. J. & Gardner R. D. (2015). Numerical simulation of the long-term behaviour of a self-healing concrete beam vs standard reinforced concrete. Engineering Structures, 102, 176-188.

[13] Vekariya M. S. & Pitroda J. (2013). Bacterial concrete: new era for construction industry. International Journal of Engineering Trends and Technology, 4, 4128-4137.

[14] Rao M. V. S., Reddy V. S., Hafsa M., Veena P. & Anusha P. (2013). bioengineered concrete - a sustain-able self-healing construction material. Research Journal of Engineering Sciences, 2, 45-51.

[15] Hilloulin B., Grondin F., Matallah M., Loukili A. (2014). Modelling of autogenous healing in ultra-high-performance concrete. Cement Concrete Research, 61, 64-70.

[16] Yang Y., Lepech M. D., Yang E. H. & Li V. C. (2009). Autogenous healing of engineered cementitious composites under wet-dry cycles. Cement Concrete Research, 39, 382-390.

[17] Tziviloglou E., Wiktor V., Jonkers H. M. & Schlangen E. (2016). Bacteria based self-healing concrete to increase liquid tightness of cracks. Construction and Building Materials. 122, 118-125.