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ENHANCING PERFORMANCE OF HIGH-STRENGTH CONCRETE USING *BACILLUS MEGATERIUM* AS SELF-HEALING AGENT

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ABSTRACT: The weak tensile properties of concrete allowed micro-cracks to emerge and propagate into macro-cracks if they were left undetected. An innovation called self-healing concrete (SHC) was subsequently introduced, allowing concrete to cover micro-cracks independently without any human intervention. SHC utilizes healing agents in the form of bacteria, which react with oxygen and water when cracks occur, resulting in calcium carbonate ($CaCO_3$) compounds that play a role in the concrete repair process. The aim of this study is to determine the effects of *Bacillus megaterium* on the compressive strength, flexural strength, depth of water penetration, and velocity of the 45 MPa high-strength concrete design based on ACI 211-4r.93 guidelines, with 25% of cement substitution by fly ash and 2% of bacteria percentage of the entire water composition. A 12.662% increase in compressive strength and a 1.690% increase in flexural strength were recorded for the age of 28 days bacterial concrete compared to the control concrete. The water penetration depth of the bacterial concrete was 4.49 cm, thereby meeting the DIN 1045 standard, which is less than 5 cm. From the ultrasonic pulse velocity (UPV) test, the average velocity value for bacterial concrete was 9.483 km/sec, which is categorized as having good concrete homogeneity based on the IS 1331 standard. This research offers promising insights into the SHC field by adding innovation to the design of high-quality bacterial concrete.

Keywords: High-strength concrete, Self-healing concrete, Bacillus megaterium, Compressive strength, Flexural strength

1. INTRODUCTION

Concrete is a common component of building structures [1] whose advantages include strength against pressure, durability, ease of application, and high availability. However, it also has significant weaknesses, such as being weak in tension and having a high level of brittleness, making it susceptible to cracks. Cracks in concrete may begin from micro-cracks and subsequently spread to macro-cracks if the micro-cracks are not detected [2]. Macro-cracks allow water, chloride ions, and harmful chemicals to enter the voids in the concrete, thereby affecting the strength of the material as well as the strength and durability of concrete structures [3]. Consequently, maintenance and repair of concrete structures are necessary. In theory, crack locations are easily identified and easy to reach. In practice, however, the maintenance of concrete structures costs a lot of money and is a lengthy process [4]. Therefore, it is necessary to pay attention to cracks in concrete, especially micro-cracks, through techniques such as self-healing concrete, namely concrete that is capable of self-repair when a crack occurs [5]. In the development of asphalt production, research has been applied to increase the strength of asphalt by adding chemicals (polyphosphoric acid) [6], while in the development of concrete, there is also innovation in the form of self-healing concrete. Producing self-healing concrete with a triggering crack healing mechanism without human intervention in maintenance and increasing the service life of structures would be highly beneficial [7], [8].

Self-healing concrete is an innovation that utilizes healing agents in the form of microorganisms, namely bacteria with high alkaline properties, to survive in extreme environments such as the genus *Bacillus* [9], [10]. When cracks occur, moisture and oxygen enter the fracture zone, and active bacteria and nutrient precursors, namely calcium lactate, are dissolved from the microbial particles to form a suitable environment for spores to germinate and begin to precipitate calcium carbonate ($CaCO_3$). A portion of $CaCO_3$ is formed and fills the cracks in the concrete [11]. The self-healing characteristic is described by the following Eq. (1) [12]:

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

Self-healing concrete needs to be applied to high-strength concrete 45 MPa since it has compressive strength characteristics of more than 41.4 Mpa [13] and has stronger resistance than normal strength concrete, making it suitable for large-scale structures such as bridges and high-rise buildings. In this high-strength concrete design, fly ash is used as a partial replacement for cement to reduce cement production, which has caused environmental damage due to CO_2 emissions in the air [14].

Various studies have shown that the genus *Bacillus* positively affects the normal strength of concrete [15], [16]. Andalib [17] examined the most optimum concentration of *B. megaterium* in medium-quality and high-quality concrete mixtures. The DOE design method was used in the design without any additives, such as fly ash. Subsequently, Joy [18] conducted a study on the bacteria *Bacillus subtilis* using a 25% fly ash addition in 30 MPa concrete. As a result, bacterial concrete mixed with fly ash increased by 17.132% against the control concrete. From these studies, it is necessary to conduct a self-healing concrete study using *B. megaterium* in high-strength concrete design with the ACI 211 4r-93 method, which has not been carried out previously. Apart from that, it can be concluded that fly ash is a supporting variable that also adds durability and strength to concrete. Hasan [19] explained that fine aggregates similar to silica fumes can be used as reactive concrete powder. In this case, the use of fly ash, which has the same properties, is one of the factors that supports the presence of reactive powder in the concrete mixture, so the durability of the concrete is expected to increase.

Through this study, it is hoped that the effects of *B. megaterium* on the design of high-strength concrete 45 MPa can be identified by carrying out destructive tests in the form of compressive strength, flexural strength, and water penetration tests. In addition, non-destructive tests, UPV tests to obtain velocity values as a determinant of the importance of homogeneity of concrete, as well as analysis of self-healing observations of concrete cracks were performed. Section 3 presents the materials and methods of the research. Section 4 indicates the results of the research objectives. Finally, the conclusion is in Section 5.

2. RESEARCH SIGNIFICANCE

Self-healing concrete is a crucial topic to be studied. Many studies have been on the same issue and then developed in various variables. In this case, its application to high-strength concrete is of interest. How high-strength concrete has dense density characteristics, whether bacteria will survive in concrete, and whether, as in the study of low and medium-strength concrete, can increase the compressive strength value. Increased compressive strength values significantly affect the service life of the concrete. So, it is expected that the application of self-healing concrete will have an impact on reducing maintenance costs due to initially undetected damage, as well as the life of concrete that can last longer than conventional concrete in general.

3. MATERIALS AND METHOD

3.1 Materials

3.1.1 Bacillus megaterium

B. megaterium is more prominent than normal bacteria, measuring up to 100 times larger than *E. coli*. Bacteria of this species can also survive in extreme conditions due to their ability to form spores to protect their bodies. Bacteria are microorganisms that can produce minerals, including calcium carbonate ($CaCO_3$) or lime, and *B. megaterium* is no exception. It is capable of growing $CaCO_3$ of reliable quality to cover cracks in concrete [20].

The resistance of *B. megaterium* to extreme pH makes it suitable to be used as self-healing agent in concrete, which has a relatively high and fluctuating pH [21]. The selection of bacteria as a self-healing agent must be considered. If bacteria cannot live in a concrete environment, the bacteria can die, and the concrete self-healing process will not occur. Previous studies have proven that B. megaterium can repair concrete cracks of 0.5 mm observed within 28 days after testing [16]. In addition, research that applied *B. megaterium* to 30 MPa normal-quality concrete showed a 15.86% increase in compressive strength [22]

3.1.2 Calcium Lactate

It is necessary to have supporting nutrients to control the number of bacteria and keep the spores formed to survive. Following research on self-healing concrete with Bacillus cohnii as a self-healing agent, calcium lactate ($C_6H_{10}CaO_6$) was added to the mixture as a nutrient. The total proportion of calcium lactate used was 0.5% of the total weight of cement to enable the observation of mineralized particles measuring 20-80μm in concrete cracks [12]

The results showed that calcium lactate is capable of producing calcium ions suitable for repairing cracks. It was also observed that adding a balanced proportion of nutrients according to the number of bacteria increased the effectiveness of healing cracks in concrete. Conversely, if the addition of nutrients to the concrete was not balanced with the number of bacteria, the curing process and the quality of the concrete were affected.

3.1.3 Cement

In the concrete mixture, cement functions as a binder for aggregate and fills the voids between the aggregates to form a solid mass. The cement commonly used in concrete mixes is Portland cement. The type of cement commonly used in high-quality concrete design is cement type I, commonly known as OPC (Ordinary Portland Cement). Based on preliminary testing, the specific gravity of the cement was 3.00, which met the criteria for type I cement.

3.1.4 Fly Ash

Fly ash is obtained from the disposal of coal powder combustion from a steam power plant (SNI 6468:2000). Since the fly ash arena has no unique handling process and is often placed in open areas, it is referred to as a waste that can potentially cause environmental pollution. So, fly ash material is used as a substitute for cement that contributes 2.8 million tons of CO_2 gas annually and is then referred to as an alternative to environmentally friendly concrete[23]. The types of fly ash commonly used as a concrete mix are types F and C. This study used type F fly ash (low calcium fly ash) since it is economical, environmentally friendly, and has good flowability. and workability. In addition, the acceptable particle characteristics cause it to become impermeable and can minimize abrasion [24].

3.1.5 Aggregate

There are two types of aggregate used in the concrete mix, namely coarse aggregate and fine aggregate. Based on ASTM C 33-03, coarse aggregate is a grain retained on a 4.75 mm sieve. Meanwhile, fine aggregate is defined as a grain with a maximum size of 4.76 mm (SNI 03-6820-2002). In this study, the nominal coarse aggregate grains passed a 25-mm sieve, and the refined aggregate grains passed a 2.36-mm sieve. The specific gravity of Saturated Surface Dry (SSD) of coarse aggregate was 2.7, with water absorption of 1.72%. Meanwhile, the fine aggregate's surface dry specific gravity was 2.56, with water absorption of 6.46%. The solid content weight of the coarse aggregate was 1.53 grams/cm^3, while the solid content weight of the fine aggregate was 1.35 grams/cm^3. The passing content of 200 coarse aggregates was 0.92%, while the passing range of 200 fine aggregates was 4.08%.

3.1.6 Water

In a concrete mix, water is a substance that can react with cement to produce bonds. In addition, water also functions as a lubricant for aggregate granules.

3.1.7 Superplasticizer

The type of superplasticizer commonly used in the design of high-strength concrete mixes is type F, namely the high-range water-reducing (HRWR) type. This type of F admixture can reduce water by 12% or more. The use of this superplasticizer serves to balance the low cement water factor (w/c) with a concentration of 0.6% of the total weight of the cement proportion.

3.2 Method

3.2.1 Bio-process laboratory

Fig.1 illustrates the stages of growing 10^6 cfu/ml of *B. megaterium*, which were subsequently mixed directly into the concrete mixture as a solution medium. The culturization of *B. megaterium* bacteria referred to the approach by Andalib [17].

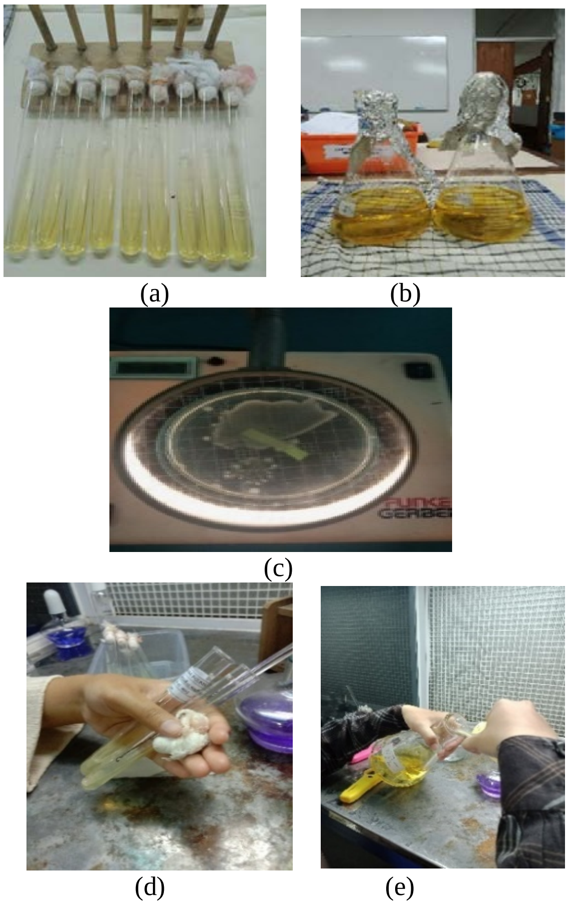


Fig.1 Culturization of *Bacillus megaterium* a,b - media creation c - calculating of bacterial concentration d,e – bacterial inoculation

a. Media creation

Two types of media were used, namely NA media (Nutrient Agar) and NB media (Nutrient Broth). Before population and concentration calculations were carried out, NA media was used for bacterial population growth. Meanwhile, NB media was used for bacterial growth after calculating the population of the parent bacteria, and NB media was the last bacterial media to be mixed directly into the concrete mixture.

b. Calculating of bacterial concentration

The calculations were carried out using the cup counting method and started with the attention of 10^{-1}-10^{-6}, mixed in a NaCl solution to ensure that bacterial conditions remain stable without contamination and serve as a solvent in diluting bacteria. The solution containing the bacteria was then transferred to a Petri dish, which was subsequently incubated so that the broodstock of the bacteria inoculated on the NA and NB media could be determined.

c. Bacterial inoculation

The bacterial inoculation process was carried out on two media, namely the NA media and NB media. The inoculation on the NA media was carried out to rejuvenate bacteria in slanting agar taken from bacterial broodstock in the Petri dishes. Meanwhile, the inoculation on the NB media was carried out to prepare bacteria to be mixed into the concrete mixture in liquid media, the amount of which had been measured. The bacteria used for the inoculation on the NB media were taken from the broodstock on the Petri dishes.

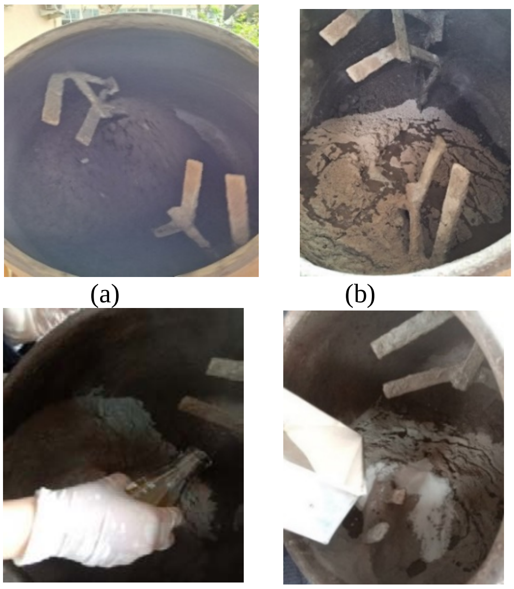
3.2.2 Materials Laboratory

a. Preliminary testing

The test was conducted as a preliminary step in ensuring that the materials used were suitable for use as a high-strength concrete mixture. Six initial tests were eventually carried out. There is, relative density and absorption, bulk density (unit weight), sieve analysis, materials finer than 75-µm (no. 200) sieve in mineral aggregates by washing, organic impurities in fine aggregate, specific gravity of cement.

b. Concrete mixing

This design applies the substitution of cement by fly ash of 25% and add admixture in the form of a superplasticizer of 0.6% of the total amount of cement and fly ash. The concrete mixing process was carried out using a method referring to the SNI 03-3976-1995 standard. The stages of material addition for concrete making are shown in Fig. 2.



(a) (b)

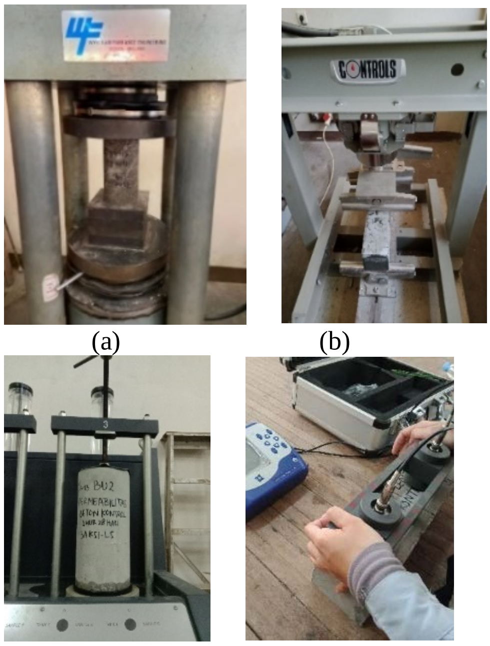
(c) (d)

Fig.2 Concrete mixing stages a – coarse and fine aggregates b – cement, fly ash, and superplasticizer c – *B. megaterium* d – calcium lactate

In control concrete, the concrete mixing was carried out by incorporating coarse and fine aggregates, and 1/3 of water composition. Cement, fly ash, water, and superplasticizer were then added and mixed with the aggregates until uniformity. A slump-flow test based on ASTM C1611M-05 was subsequently conducted to determine the workability of the concrete. In bacterial concrete, bacteria and calcium lactate were combined into the concrete mix (direct method) [10]. The *B. megaterium* in the solution and calcium lactate were added with fly ash, cement, water, and superplasticizer. A mixture was added as a solution containing bacteria as much as 2% of the water composition and calcium lactate as much as 2% of the cement.

c. Concrete testing

There were four types of tests tested on concrete (Fig. 3). First, the compressive strength test was applied to a cylindrical specimen with a diameter of 10 cm and a height of 20 cm based on ASTM C39.The second test was the flexural strength test applied to a beam test object of 10 cm x 10 cm x 50 cm based on ASTM C78. Third, the depth of water penetration was tested on a cylindrical specimen with a diameter of 15 cm and a height of 30 cm based on Standard DIN 1045-2. Fourth, the ultrasonic pulse velocity (UPV) testing was carried out using the indirect or surface transmission method with an error tolerance of 1% based on ASTM 1997 C 597 – 83 (1991) and IS 13311 part 1.



(a) (b)

(c) (d)

Fig.3 Concrete testing a - compressive strength b - flexural strength c - water penetration test d - ultrasonic pulse velocity

d. Self-healing observational analysis

The analysis of self-healing in the concrete was carried out by visual observation to detect the healing process of cracks that bacteria can repair. The tested sample was re-immersed in the curing bath and subsequently observed for a certain number of days to see the progress.

4. RESULT AND DISCUSSION

4.1 Mix Design ACI 211-4r 93 Proportion

Table 1 shows the proportion of the 45 MPa plan quality mix design that was calculated according to the ACI 211-4r 93 method. In self-healing concrete, 2% bacteria content and calcium lactate powder were added as bacterial nutrients. The design used type I cement (OPC), with a water-cement factor (w/c) of 0,38. Two types of aggregate were used, namely coarse aggregate with a specific gravity of 2,7 and fine aggregate with a specific gravity of 2,56.

Table 1 Concrete mix design Based ACI 211-4r 93 method

1m^3 Proportion	
Cement	321.62
Fly Ash (kg)	107.21
Fine Agg. (kg)	698.32
Coarse Agg. (kg)	1,155.62
Water {ℓ)	128.25
Sp 0.6% (kg)	22.57
Bacteria 2% (ℓ)	2.57
Calcium Lactate (kg)	6.43

4.2 Compressive Strength and Flexural Strength Test

The compressive strength testing displayed in Fig.4 and the flexural strength test in Fig.5 were applied on 7 days and 28 days concrete samples. In Fig.4, the compressive strength test results show a decrease at the age of 7 days; the compressive strength in the bacterial concrete is 1.719% less than the control concrete (41.178 MPa of bacteria concrete and 42.022 MPa of control concrete). However, the opposite result is indicated at 28 days of bacterial concrete, with an increase of 12.66% over the control concrete (62.199 MPa of bacterial concrete and 55.208 MPa of control concrete).

A similar trend is observed in the flexural strength test results (Fig.5). The flexural strength obtained in 7 days of age bacterial concrete is 5.433 MPa, and control concrete is 5.539 MPa, shown at 1.916% less than the control concrete. At 28 days of age, the flexural strength value increases by 1.690% against the control concrete (7.524 MPa of bacterial concrete and 7.399 MPa of control concrete).

These results show the similarity of characteristics observed in low-strength concrete in the literature [22], which offers a decrease at the 7-day test age and an increase at the 28-day test age, which reached 15,86%.

At 7 days of age, the compressive and flexural strength test results of the bacterial concrete show smaller values than those of the control concrete. This is due to the short duration of concrete treatment, causing the bacteria in the concrete to have not fully reacted, and the content produced as an enhancer of concrete strength, namely calcium carbonate ($CaCO_3$) [17] produced by bacteria, had not grown optimally. In previous research, Nain [14] and Joy [18] stated that the optimum definite strength adjustment is achieved at the age of 28 days. This proves bacterial concrete enhancement can occur according to the age of substantial requirements (ACI 21- 4r 93).

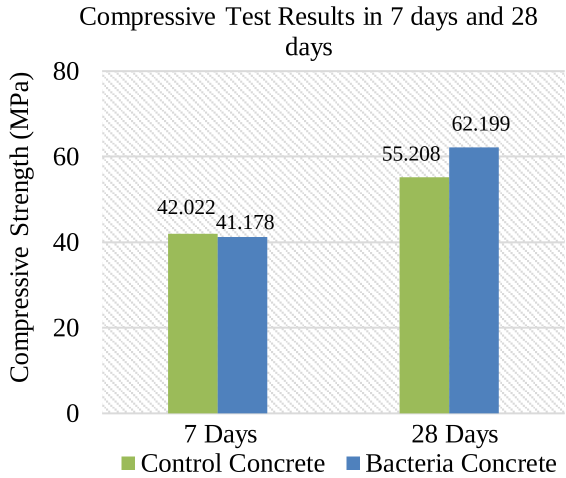


Fig.4 Value chart of compressive test

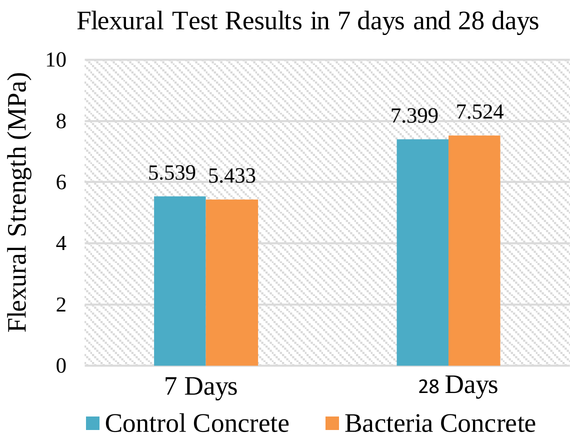


Fig.5 Value chart of flexural test

Similar research shows that *B. megaterium* is a gram-positive bacteria with a double membrane. Hence, it is slower in reacting compared to gram-negative bacteria [17]. This might also be due to the morphology of the bacteria mixed with the concrete. The round and heterogeneous shape makes the strength increase at 28 days. In addition, there would be an increase in calcium deposition [25].

Based on the test results and their comparison with previous research, it shows a typical comparison. Bacteria can function optimally after adapting to the media used; the media is concrete in this study. The quality of concrete also affects the adaptation and repair process. Although in high-strength concrete that has minimal voids and is already dense before adding bacteria, it has been proven that *B. megaterium* bacteria can still survive and work in concrete, resulting in self-healing concrete products.

4.3 Water Penetration Depth Test

Table 2 shows the penetration depth test results for 3x24 hours. The final results showed that the bacterial concrete had a greater penetration value of 25.24% than the control concrete. However, both bacterial concrete and control concrete met the DIN 1045-2 standard of less than 50 mm. In the seepage observation results, the control concrete showed less seepage than the bacterial concrete. This may occur as bacterial concrete absorbs more water due to its more organic nature than control concrete. In its life phase, bacteria need more water to form spores to balance the spore formation reaction.

Table 2 Penetration Depth Test Result

Penetration Test	Specimen Type	
	CC	BC
Day 1		
Initial Water Level (mm)	289.5	290
Penetration Depth (mm)	22.6	21.2
Day 2		
Initial Water Level (mm)	287.5	287.0
Penetration Depth (mm)	23.9	26.3
Day 3		
Initial Water Level (mm)	281.0	263.5
Penetration Depth (mm)	35.5	44.9
Final Penetration Depth (mm)	35.5	44.9

Note: CC= Control Concrete; BC= Bacterial Concrete

4.4 Ultrasonic Pulse Velocity Test

The UPV test in Table 3 was conducted on flexural specimens at 40 days of concrete age.

Table 3 Ultrasonic Pulse Velocity Test Result

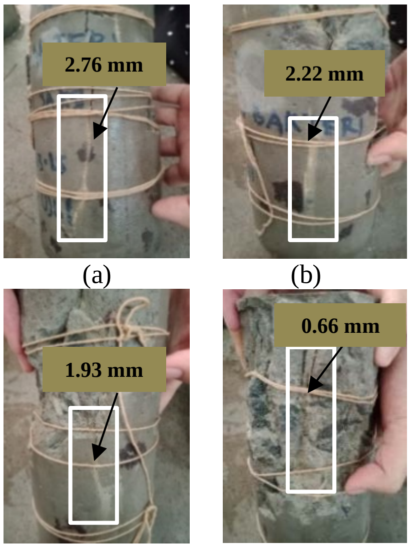
UPV Test on Specimen of Flexural Strength			
Structural Components		Beam 10x10x50 cm	
Specimen Details		CC	BC
Thickness of Specimen (mm)		100	100
Length, L (mm)		100	100
Uncracked Concrete Surface		T	T
Velocity (km/sec)	1	9.34	9.54
	2	9.51	9.49
	3	9.38	9.42
Average Velocity (km/sec)		9.41	9.48
Concrete Quality Grading		Excellent	Excellent

Note: CC= Control Concrete; BC= Bacterial Concrete

Based on the table of density properties and ultrasonic pulse velocity according to Standard IS 13311 part 1, if the velocity value is >4.5 km/sec, the homogeneity of the concrete is considered very good. In this UPV test, therefore, the concrete is deemed to be in accordance to the results of the concrete compressive strength test, in which homogeneity or density greatly affects concrete quality. This may occur since the two concrete designs (control concrete and bacterial concrete) are high-strength concrete with a good density level. By nature, high-strength concrete has low porosity and homogeneous pores. Thus, the difference in the UPV test results, which function to examine density, appears insignificant. Nevertheless, bacterial concrete has a higher value than control concrete.

4.5 Self-Healing Observation

Visual observations were made on the post-test concrete cracks until day 55 at 7 days of age sample. The Calcium Carbonate ($CaCO_3$) produced by bacteria started to cover the cracks on the 21st day. Fig. 6 shows the $CaCO_3$ covers the cracks and the width of the micro-cracks that the bacteria managed to repair during the observation until the 55th day is 0.66-2.76 mm.



(a) (b) (c) (d)

Fig.6 Self-healing observation: the $CaCO_3$ produced by bacteria has successfully covered the micro-cracks.

5. CONCLUSION

This study examined the performance of *B. megaterium* as a self-healing agent when applied to the ACI 211-4r 93 design on 45MPa high-strength concrete. The conclusions that can be drawn from the study are as follows: the addition of *B. megaterium* with a content of 2% in the concrete design increases the compressive strength by 12.66% and the flexural strength by 1.71% in bacterial concrete aged 28 days. Along with the results of the high compressive strength value of bacterial concrete, it can be proven by the velocity value in the ultrasonic pulse velocity (UPV) test of 9.45 km/sec that the concrete quality is categorized as very good according to the IS 1330 Part 1 Standard.

The results of the depth of water penetration in the permeability test obtained bacterial concrete with a value of 44.6 mm, which, according to the DIN 1045 standard, still satisfies the requirement of less than 50 mm. The performance of *B. megaterium* in high-strength concrete is considered to be able to survive and be effective in covering cracks, proven by the results that it was able to cover micro-cracks of 0.66-2.76 mm. The micro-cracks can begin to show their development on the 21st day after testing.

The results of this research offer additional insights in self-healing concrete (SHC) research based on the differences in the applied variables, which can be seen in the design composition and the tests applied to the concrete. In addition, this research can also be used to support future research on SHC. Using the results of this research, further studies can be carried out with different variables, namely differences in the percentage of bacteria, mixture composition, research time, and application to concrete in various conditions.

6. ACKNOWLEDGMENTS

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