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Evaluating The Efficacy Of Bacteria-Based Self-Healing Concrete In Microcracks Using B. Coagulans

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Abstract:

Self-healing concrete is a revolutionary technology that addresses the issue of concrete cracks, which can reduce service life and lead to costly repairs, thereby revolutionizing the construction industry. This type of concrete can fix and heal itself, replenishing cracks and gaps over time without requiring external human activity. The material employs a healing agent to reactivate bacteria, enabling them to function through air and moisture exposure through cracks, initiating their metabolism. When the bacteria are activated, calcium carbonate is precipitated, which efficiently seals the cracks on their own. This paper provides an overall description of the concrete self-healing technology theory. It includes the mechanisms of the self-heal, the types of the implemented materials, and the forms of their application. The specimens with bacteria performed satisfactorily in compressive strength, surpassing traditional concrete. Self-healing concrete based on bacteria was found to be effective through experiments and observation. The study found that adding bacteria-based healing agents to concrete can be safe and eco-friendly, despite not showing improved crack healing. It suggests that Bacillus coagulans can be used to seal naturally occurring cracks, but further research is needed to make this self-healing concrete more affordable and suitable for commercial use.

Keywords **—bacillus coagulans, self-healing, cracks, bacteria-based, concrete**

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I. INTRODUCTION

Concrete is an essential and very important material widely used in residential and commercial buildings. Upon being mixed with water and put, it undergoes a chemical process known as hydration, resulting in its solidification and hardening. It is used to connect various construction components. This material, known as concrete, is extensively used in construction and is formed by blending aggregate, cement, tiny stones, sand, and water. The amalgamation of all the constituent components culminates in a material that has a resemblance to stone.[1]

One of concrete's flaws is its poor tensile strength; therefore, steel must be added to build reinforced concrete. The concrete must protect the steel from corrosion. If the concrete cracks, dangerous materials like carbon dioxide, chlorides, oxygen, and water can reach the reinforcing steel, creating rust and corrosion and destroying the concrete.

Concrete has a greater risk of developing cracks. These fissures significantly reduce the concrete's service life and need costly repair. Although it is hard to prevent cracks from occurring, there are several methods available for repairing them. Some current concrete treatment practices, such as the use of chemicals and polymers, have been shown to be hazardous to both human health and the environment. More importantly, they are just temporary fixes. As a result, there is a high need for long-term, ecologically friendly treatment methods. A microbial self-healing method stands out because it promises to fix cracks effectively, quickly, and permanently. It's also ecologically beneficial.

Consequently, an excellent demand for long-lasting, environmentally friendly treatment techniques exists. A microbial self-healing strategy stands out because it promises effective, quick, and long-lasting crack repair and is also environmentally friendly.

A new variety of concrete is self-healing concrete. It replicates how the body heals itself of wounds by the release of some substance. Some unique components (such as fibers or capsules), which include some adhesive substances, are dispensed into the concrete mix to generate self-healing concrete. When fibers or capsules break, the liquid immediately seals the crack and repairs it. Self-healing concrete, however, is still in the research stages. It will take some time before it is used in the concrete industry.

Bacteria with a calcium nutrient source are added to the concrete when mixing. When concrete cracks occur, bacteria precipitate calcium carbonate, sealing the cracks. The bacterial concrete will be stronger than regular concrete. A biotechnological technique based on calcite precipitation can be used to boost the strength and longevity of structural concrete.

Numerous Bacillus species have been investigated for their capacity to manufacture calcite (calcium carbonate), which is a spore-forming bacteria. Bacillus coagulans is one of the Bacillus species frequently discussed in bio concrete and biomineralization studies.

In that regard, this study has presented a detailed investigation of the ability of the bacteria Bacillus coagulans to seal microcracks when placed in various concrete mixtures. It focused primarily on its respective results and its level of healing capabilities. The test results were collected and assessed. The primary factors influencing whether bacterial concrete succeeds or fails were thoroughly examined in this study.

II. METHODOLOGY

A. *Collection and Preparation of Specimen/Mold Concrete*

a) To begin, the bacteria was isolated from the product, cultured, and then converted into a liquid form.
b) The next preparation is making a Class A concrete mixture with Bacillus coagulans.
c) To sum up, adding bacteria to the concrete mixture will result in three distinct curing times: seven days, fourteen days, and twenty-eight days.

B. *Extracting the Bacteria from the Sample*

a) One Opti Chocodrink product contains Bacillus coagulans. Streak-plate method was the method used in isolating the bacteria. This technique disperses individual cells by distributing them across the agar plate's surface, facilitating their growth and observation.
b) After the isolation of Bacillus coagulans from the product, it was processed for culturing.

Process of culturing:

Culturing Bacillus coagulans involves a specific set of steps to create the optimal conditions for its growth.

a. Inoculum Preparation: Begin by obtaining a pure culture of Bacillus coagulans.
b. Culture Medium Preparation: Prepare a suitable culture medium for Bacillus coagulans. Bacillus coagulans grows well in nutrient-rich media. Common cultural media include nutrient agar or nutrient broth.
c. Sterilization: To ensure sterilization of the culture medium, autoclave it at precisely 121°C and 15 psi (pounds per square inch) for approximately 15 to 20 minutes. This step ensures that the medium is free from any contaminants.
d. Inoculation: Aseptically transfer a small amount of the Bacillus coagulans culture (in freeze-dried or glycerol stock form)

to the sterilized culture medium. Ensure that you maintain sterile conditions throughout this process.

e. Incubation: Place the culture medium with the inoculated Bacillus coagulans in an incubator set at the optimal temperature for Bacillus coagulans growth, which is typically around 45-50°C.
f. Monitoring: Monitor the culture for bacterial growth. Bacillus coagulans typically forms visible colonies or turbidity in the liquid medium.
g. Harvesting: The Bacillus coagulans culture will be harvested at the desired growth stage. This may involve centrifugation, filtration, or other separation techniques.

Process in Making the Nutrient Solution

a. Creating Nutrient Solution: Create a nutrient solution with an appropriate nutrient source in a predetermined concentration, like calcium lactate. For instance, in the bacterial mixing solution,[2] utilized 200g/l of calcium lactate.
b. Spores of Bacteria: Add the 1x109 spores/mL bacteria to the nutritional solution.
c. Mix and Sterilize: To guarantee even dispersal, thoroughly combine the bacterial spores and nutritional solution. To stop contamination and to provide an ideal environment for bacterial growth, sterilize the mixture.
d. Modify Concentration: Adjust the bacterial solution's concentration in accordance with the particular needs and goals of the concrete application. The amount of bacteria in the solution can affect how well it promotes the concrete's ability to cure itself.

TABLE I

MIXED COMPOSITION FOR NUTRIENT SOLUTION

Specimen	Water (mL)	Calcium Lactate (g)	Bacterial Spores (spores/mL)
Bacterial Concrete (1)	20	4	$1x10^9$
Bacterial Concrete (2)	65	13	$1x10^9$
Traditional Concrete (1)	0	0	0

C. ***Production of Bacteria-based Self-healing Concrete***

Concrete Mixing:

The raw materials (cement, sand, gravel, and water with/without bacteria) were combined to create a standard concrete mix.

As per M. Pourfallahi's findings in 2020, the incorporation of bacterial cement amounted to 5% of the concrete's weight. Notably, uncontrolled cracks in concrete specimens were proficiently sealed to a minimum width of 39.82 micrometers. Within this framework, it is suggested that further exploration into the application of bacteria at concentrations of 2% and 7% relative to the weight of cement be undertaken.[3] This paper describes the incorporation of liquid bacteria into the concrete mix, which requires 2% and 7% modifications to the water-to-cement ratio to be taken into account.

The appropriate amount of bacterial solution to be added to the concrete mix was based on the equation below.

For 40 kg of Cement

CEMENT : V x 9.0 = *NO. OF BAGS* Equation 1
SAND: *V x 0.5 = cu. m* Equation 2
GRAVEL: *V x 1.0 = cu. m* Equation 3
WATER: *NO. OF BAGS x 40 kg/bag x 0.5 li/kg = LITERS* Equation 4

Conversion of Bags to Kilogram

1 Bag = 40 kg

Where: V = volume of the specimen in cu. M
BACTERIAL SOLUTION AMOUNT = 0.02 x Water Equation 5
BACTERIAL SOLUTION AMOUNT = 0.07 x Water Equation 6
Where: Water = amount of water in L

Concrete Design and Casting:

A prescribed mix of 0.50/1:2:4 was chosen to achieve a concrete strength of Class A. The prepared concrete mix was poured into the 15 cylindrical molds (6 x 12 in.). Five sets of three cylindrical concrete sets were used; one set served as the control for the compressive strength test. There were two sets of concrete mixed with different amounts of bacterial solution to be applied, wherein one set contained 1x spores/mL in a 20-mL bacterial solution and the other set in a 65-mL bacterial solution. Two sets were used to study the bacteria's self-healing capacity: 1x spores/mL in a 20-mL bacterial solution and the other in a 65-mL bacterial solution. After casting, cylindrical concrete was demolded and cured adequately after a day.

TABLE III
EXPERIMENTAL SAMPLE PROPORTIONS

Specimen	Cement (kg)	Sand (m3)	Gravel (m3)	Water (mL)	Bacterial Solution (mL)
Bacterial Concrete (1)	1.908	$2.65x10^{-3}$	$5.3x10^{-3}$	934	20
Bacterial Concrete (1)	1.908	$2.65x10^{-3}$	$5.3x10^{-3}$	889	65
Traditional Concrete (1)	1.908	$2.65x10^{-3}$	$5.3x10^{-3}$	954	0

Curing and Maintenance:

Properly cure the concrete to support the healing process. The 15 specimens should undergo 7-, 14-, and 28-day curing.

Intentionally Cracking of the Specimen:

For the purpose of precisely evaluating the efficacy of the bacterially mediated self-healing mechanism, a compressive stress will be applied to each specimen to intentionally produce cracking.

Activation of Self-Healing:

When cracks appear, the self-healing agent within the concrete is activated.

Healing Process:

a. *Nutrient Activation:*

- When cracks open, the self-healing agent is exposed to air and moisture.
- The nutrients of the self-healing agent combine with the water as it interacts, forming a solution that is rich in vital nutrients inside the cracks.

b. *Bacterial Activity:*

- Bacillus coagulans spores within the cracks germinate and start consuming the nutrients.
- As they metabolize the nutrients, they produce calcium carbonate as a byproduct.

c. *Calcium Carbonate Formation:*

- The produced calcium carbonate precipitates, filling the crack and effectively healing it.
- This process can continue until the crack is sealed or the available nutrients are depleted.

Quality Control:

On a weekly basis, the concrete was inspected to assess the effectiveness of the self-healing process.

D. *Testing of Bacteria-Based Self-Healing Concrete*

Compressive Strength

a. The specimen was positioned such that its axis lines up with the spherically seated bearing block's center of thrust by placing it on the lower bearing block.
b. When beginning the test, ensure that the load indicator is at zero.
c. A constant, shock-free compressive load was applied until the operator is satisfied that the maximum capacity has been reached.

$$\text{Compressive Strength} = \frac{\text{Maximum Load at Failure}}{\text{Net Area}} \quad \text{Equation7}$$

E. *Evaluation of the Sealed Cracks*

Crack sealing and filling stand as commonplace pavement preservation techniques routinely integrated into standard maintenance protocols across various states, as outlined in the handbook of practice by the Strategic Highway Research Program, crack sealing entails the insertion of materials into operational cracks, typically following routing procedures; conversely, crack filling involves the application of materials into non-functional cracks. Operational cracks are defined as those exhibiting an annual horizontal displacement of 2.5 mm (0.1 in) or greater.[4]

The examination and assessment of the effectiveness of B. coagulans-infused bacteria in addressing microcracks within concrete constituted the primary focus of this investigation. In every investigation, the test specimen's board dimensions stayed constant. Sample determination and testing were based on ASTM (American Society of Testing Materials). A specimen of 0.15 m x 0.3 m was built using 1.908 kilograms of cement, 2.65×10^{-3} m^3 of sand, 5.3×10^{-3} m^3 of gravel, 0.954 liters of water, and the B. coagulans microorganisms. The experimental setups were carried out over three different numbers of days for curing. The specimen was evaluated and observed on the 7th, 14th, and 28th days.

The evaluation of sealed cracks started with a visual inspection of the sealed fracture. Evidence of damage or discomfort was inspected, such as an enlarged crack, spalling (surface flaking), or discolouration. The breadth of the sealed fracture was measured. This was accomplished with a crack comparator.

The difference between the initial crack width and the measured crack width at various healing days is the degree of crack healing, and it is stated in Equation (8) as follows:[5]

$$\text{Compressive Strength} = \frac{C_i - C_o}{C_o} \quad \text{Equation 8}$$

Where: C_i = initial width crack
C_o = crack width after healing

III. RESULTS AND DISCUSSIONS

A. *Data Description*

The collection of findings from the group testing the variable was considered in this analysis. Every specimen's compressive test result was calculated. Conversely, the personnel of the testing laboratory quantified and verified the samples, while the proponents tabulated the results of the tests.

B. *Data Analysis and Findings*

In compliance with ASTM standard C39, the experiments were carried out on a standard-size specimen. Two 2% bacteria for the self-healing concrete and the compressive strength test, 7% bacteria for the self-healing concrete and the compressive strength test, and one traditional concrete were used in the experimental setups, which were carried out on varying amounts of bacteria and curing times (7-day curing, 14-day curing, and 28-day curing). The process's results were displayed using the following table:

C. *Compressive Strength Test*

A mechanical method called the Compressive Strength Test (TCT) finds the highest compressive stress a material could bear before failing. A gradually applied load compresses the test object between the base plate of compression-testing equipment.

TABLE III
TEST RESULT FOR COMPRESSIVE PROPERTIES OF BACTERIA-BASED CONCRETESPECIMENS THAT UNDERWENT 7-DAY CURING

Sample Identification	Actual Dimensions (mm)		Maximum Load (N)	Compressive Strength	
	Diameter	Height		psi	MPa
2% Bacteria	154.1	304.8	96,185	750	5.16
7% Bacteria	151.5	304.8	75,819	610	4.21
No Bacteria	152.3	304.8	27,074	220	1.49

After seven days of curing, the specimens were sent to the laboratory for a compressive test, which would be compared to a sample that did not include bacteria. Seeing the results in percentages and evaluating the data acquired, it was discovered that the sample with 2% of the bacteria, a diameter of 154.1 mm and a height of 304.8 mm had the maximum compressive strength (5.16 MPa). The sample with 7% bacteria in the mixture has a compressive strength of 4.21 MPa, whereas the specimen without bacteria has a compressive strength of 1.49 MPa.

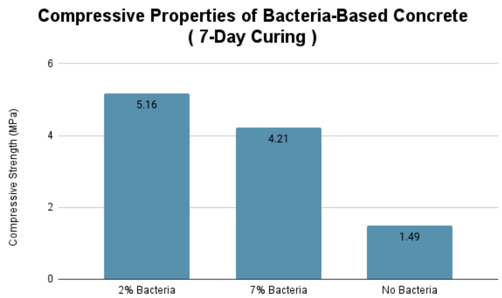


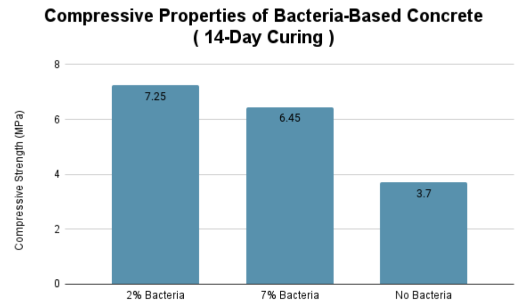
Fig. 1: Compressive Strength Test Results

For a more in-depth look at the percentage differences, the specimen with 2% bacteria in the combination has roughly 20.3% higher compressive strength than the sample with 7% of the mixture and 110.4% higher than the traditional mixture. Compared to conventional concrete, the sample with 7% bacteria is 95.4% higher.

TABLE IV
TEST RESULT FOR COMPRESSIVE PROPERTIES OF BACTERIA-BASED CONCRETESPECIMENS THAT UNDERWENT 14-DAY CURING

Sample Identification	Actual Dimensions (mm)		Maximum Load (N)	Compressive Strength	
	Diameter	Height		psi	MPa
2% Bacteria	153.5	304.8	134,221	1050	7.25
7% Bacteria	152.2	304.8	117,310	930	6.45
No Bacteria	152.6	304.8	67,732	540	3.7

After fourteen days of curing, the concrete samples undergo a compressive strength test. Table IV shows the test results of samples for the compressive properties. The 2% bacteria-based concrete sample has the highest maximum load and compressive strength among the two other samples. With a width of 153.5 mm and a height of 304.8 mm, the 2% bacteria-based concrete has a maximum load of 134,221 N and a compressive strength of 7.25 Mpa (1050 psi). On the other hand, the 7% bacteria-based concrete with a diameter of 152.2 mm and a height of 304.8 mm has higher compressive results compared with the concrete sample with no bacteria. The 7% bacteria-based concrete got a maximum load and compressive strength of 117,310 N and 6.45 Mpa (930 psi). Lastly, the sample with no bacteria with a diameter of 152.6 mm and a height of 304.8 mm got a maximum load of 67,732 N and a 3.7 MPa (540 psi) compressive strength.

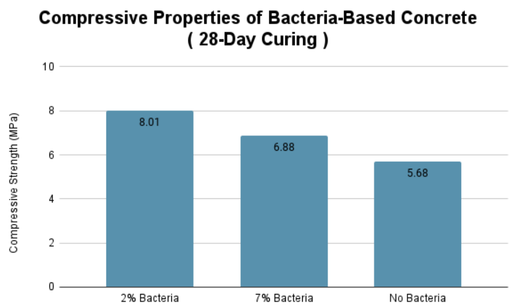


The cylinder concrete was brought to the testing center after 14 days of curing to compare the compressive strengths of samples containing 2% and 7% bacteria and the traditional concrete. The 2% bacteria sample has the highest compressive strength, followed by the 7% sample and the non-bacteria concrete. The compressive strength of the 2% bacteria sample is approximately 11.7% higher than the 7% bacteria sample. Also, the 2% bacteria sample is approximately 64.8% higher than the sample with no bacteria. This means the 7% bacteria sample is approximately 54.2% higher than the sample with no bacteria.

TABLE V
TEST RESULT FOR COMPRESSIVE PROPERTIES OF BACTERIA-BASED CONCRETESPECIMENS THAT UNDERWENT 28-DAY CURING

Sample Identification	Actual Dimensions (mm)		Maximum Load (N)	Compressive Strength	
	Diameter	Height		psi	MPa
2% Bacteria	152.1	304.8	145,513	1160	8.01
7% Bacteria	152.3	304.8	125,353	1000	6.88
No Bacteria	153.7	304.8	105,406	820	5.68

At a maximum load of 145,513 N, the concrete samples containing 2% bacteria demonstrated a compressive strength of roughly 8.01 MPa. The samples of concrete containing 7% bacteria were able to withstand a maximum load of 125,353 N and had a compressive strength of roughly 6.88 MPa. The concrete samples that were devoid of bacteria were able to withstand a maximum load of 105,406 N and showed a compressive strength of about 5.68 MPa.



After 28 days of curing, the concrete samples with added bacteria displayed changes in strength compared to those that did not have any infusion, as determined through compressive strength tests. The compressive strength of specimens containing 2% bacteria was measured at 8.01 MPa, marking a 34% increase from the strength of samples lacking bacteria, which stood at 5.68 MPa. Likewise, samples with a 7% content exhibited a strength of 6.88 MPa, showcasing a 19.1% improvement over those without inclusion. These findings highlight the influence of incorporating bacteria into concrete on its strength, with higher concentrations generally correlating with more excellent strength enhancement percentage-wise.

D. ***Visual Monitoring of Self-Healing***

The specimens that had previously cracked after seven days were collected to investigate self-healing efficacy after the healing time lasted for seven days. Figure 1 shows the observed cracks for each specimen. In the meantime, the cracking width was uncontrollable during loading, resulting in a range of crack sizes. Figure 1 shows the photos of the cracks obtained at different points during the healing process. The cracking width was measured, and the images were obtained using a handheld microscope. As seen in Figure 1, no significant crack healing was found in any specimens from their earliest age. However, after seven weeks of healing, the visible cracks showed healing signs, promoting calcium carbonate development at the fractured surface. Because the holes in the concrete keep germs alive yet dormant, they function as carriers of bacteria. When cracks and deterioration in concrete occur, they are going to cause an increase in water availability and additional oxygen.

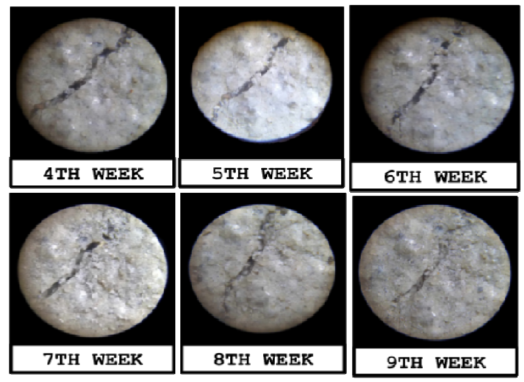


Fig. 1a. Visual observations of closure of cracks concrete with 2% bacteria

Fig. 1b. Visual observations of closure of cracks concrete with 7% bacteria

Fig. 1c. Visual observations of closure of crack, Traditional concrete

The width of the cracks that developed in concrete specimens both before and after healing is shown in

Table VI. Table VI shows that the highest percentage of crack healing was seen in the specimens with 2% bacteria. For the specimen with 2% bacteria, the crack healing percentage was roughly 0% at its initial week of observation, which is at the first week of observation, week 4, 7% at seven weeks, 14% at eight weeks, and 23% at nine weeks. This suggests that the crack was not yet closed entirely by observation. However, the specimen with 7% bacteria did not show signs of crack healing.

TABLE VI
DETAILS OF MAXIMUM CRACK WIDTH AND HEALING PERCENTAGE (7-DAY CURING)

Bacteria Amount	Initial Crack Width (mm)	Crack Healed Size (mm)					
		4th week	5th week	6th week	7th week	8th week	9th week
2%	0.08	0.08	0.08	0.08	0.075	0.07	0.065
7%	0.08	0.08	0.08	0.08	0.08	0.08	0.08
-	0.06	0.06	0.06	0.06	0.06	0.06	0.06

Bacteria Amount	Initial Crack Width (mm)	Crack Healing (%)					
		4th week	5th week	6th week	7th week	8th week	9th week
2%	0.08	0	0	0	7	14	23
7%	0.08	0	0	0	0	0	0
-	0.06	0	0	0	0	0	0

The specimens previously cracked after 14 days were collected to investigate self-healing efficacy after the healing time had lasted for 14 days. Figure 2 shows the observed cracks for each specimen. It shows photos of the cracks obtained at different points during the healing process. As seen in Figure 2, no significant crack healing was found in any specimens from their earliest age. However, after six weeks of healing, the visible cracks showed signs of closure.

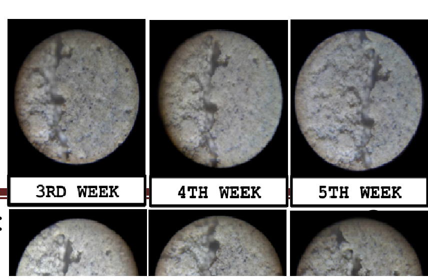


Fig. 2a. Visual observations of closure of cracks concrete with 2% bacteria

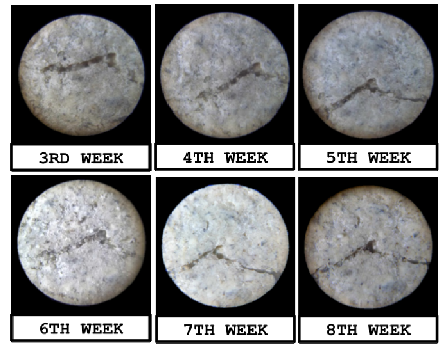


Fig. 2b. Visual observations of closure of cracks concrete with 7% bacteria

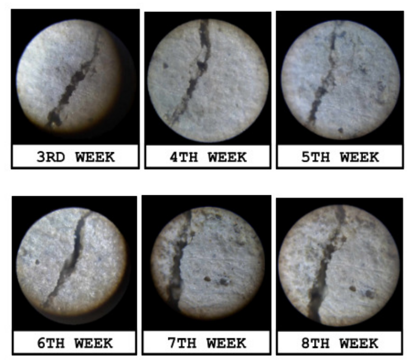


Fig. 2c. Visual observations of closure of cracks, Traditional Concrete

The width of the cracks that developed in concrete specimens both before and after healing is shown in Table VII. Table VII shows that, in contrast to the other two specimens, the highest percentage of crack healing was seen in a specimen with 7% bacteria. For the specimen with 7% bacteria, the crack healing percentage was roughly 0% at its initial week of observation, but after six weeks, the crack healed at 11%. This also suggests that the crack will be closed after week 8. Similarly, on weeks 3, 4, 5, 6, 7 and 8, the specimen with 2% bacteria showed no sign of crack healing.

TABLE VII
DETAILS OF MAXIMUM CRACK WIDTH AND HEALING PERCENTAGE (14-DAY CURING)

Bacteria Amount	Initial Crack Width (mm)	Crack Healed Size (mm)					
		3rd week	4th week	5th week	6th week	7th week	8th week
2%	0.15	0.15	0.15	0.15	0.15	0.15	0.15
7%	0.1	0.1	0.1	0.1	0.09	0.085	0.08
-	0.15	0.15	0.15	0.15	0.15	0.15	0.15

Bacteria Amount	Initial Crack Width (mm)	Crack Healing (%)					
		3rd week	4th week	5th week	6th week	7th week	8th week
2%	0.15	0	0	0	0	0	0
7%	0.1	0	0	0	11	18	25
-	0.15	0	0	0	0	0	0

The specimens that had previously cracked after 28 days were collected to investigate self-healing efficacy after the healing time had lasted for 28 days. Figure 3 shows the observed cracks for each specimen. It shows photos of the cracks obtained at different points during the healing process. As seen in Figure 3, no significant crack healing was found in any specimens from their earliest age. However, after three weeks of healing, the visible cracks showed signs of closure.

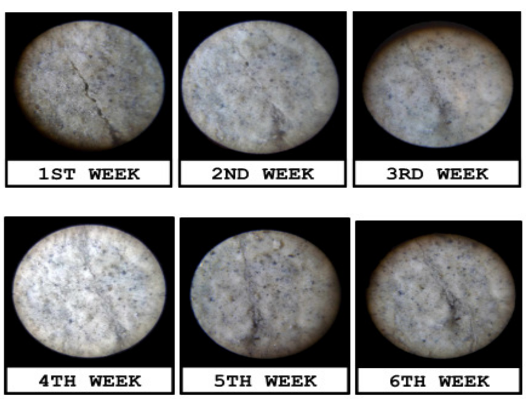


Fig. 3a. Visual observations of closure of cracks concrete with 2% bacteria

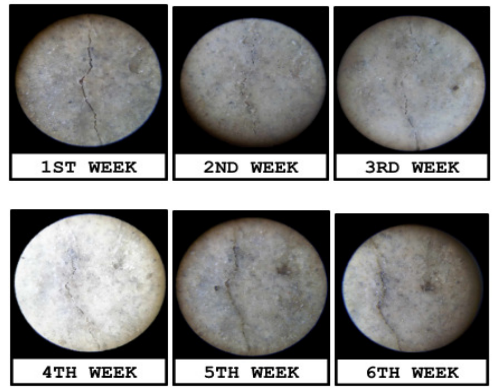


Fig. 3a. Visual observations of closure of cracks other side of concrete with 2% bacteria

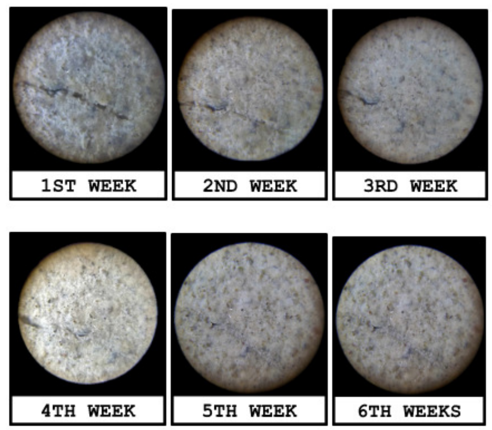


Fig. 3b. Visual observations of closure of cracks concrete with 7% bacteria

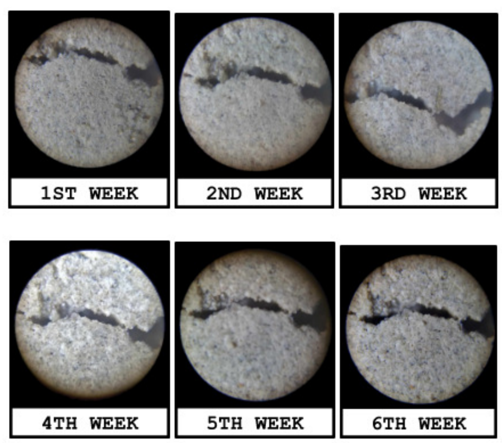


Fig. 3c. Visual observations of closure of cracks, Traditional Concrete

The width of the cracks that developed in concrete specimens before and after healing is shown in Table VIII. Table VIII makes it evident that the highest percentage of crack healing was seen in all the experimental specimens. For the specimen with 2% bacteria, the crack healing percentage was roughly 0% at its initial week of observation, which is at 1st week, 50% at two weeks, and 100% at three weeks. This suggests that the crack was closed entirely by observation and was not apparent to the naked eye. On the other part of the concrete with 2% bacteria, the crack healing percentage was roughly 0% at its initial week of observation, which was one week, 14% at two weeks, 33% at three weeks, 60% at four weeks, and 100% at five weeks. Similarly, the specimen with 7% bacteria also showed signs of crack healing; the crack healing percentage was roughly 0% at its initial week of observation, which is at one week, 20% at two weeks, 50% at three weeks, and 100% at four weeks. This suggests that the crack was closed entirely by week four and was not apparent to the naked eye.

TABLE VIII
DETAILS OF MAXIMUM CRACK WIDTH AND HEALING PERCENTAGE (28-DAY CURING)

Bacteria Amount	Initial Crack Width (mm)	Crack Healed Size (mm)					
		1st week	2nd week	3rd week	4th week	5th week	6th week
2%	0.06	0.06	0.04	0.03	-	-	-
2%	0.04	0.04	0.035	0.03	0.025	0.02	-
7%	0.03	0.03	0.025	0.02	0.015	-	-
-	0.15	0.15	0.15	0.15	0.15	0.15	0.15

Bacteria Amount	Initial Crack Width (mm)	Crack Healing (%)					
		1st week	2nd week	3rd week	4th week	5th week	6th week
2%	0.06	0	50	100	-	-	-
2%	0.04	0	14	33	60	100	-
7%	0.03	0	20	50	100	-	-
-	0.15	0	0	0	0	0	0

IV. CONCLUSIONS

The presence of microorganisms impacted the concrete's compressive strength. Thus, in the 7-day compressive sample strength, the concrete containing 2% bacteria was 110.4% greater than the control samples. Additionally, the concrete was 95.4% more than its control samples with 7% bacteria. In the 14-day compressive sample strength, the concrete containing 2% bacteria had a compressive strength of 64.8% higher than the control samples. Additionally, the concrete containing 7% bacteria was 54.2% greater than the control samples. By the 28-day, the samples of each concrete's compressive strength were 34% and 19.1% greater than their control samples. In conclusion, most samples had better compressive strength with fewer bacteria, which is 2%.

Concrete containing 2% bacteria could mend cracks up to 0.06 mm in width, whereas concrete containing 7% could do so up to 0.03 mm in width. In the control samples that had cracks of varying widths, no healing occurred. A crack can be considered a microcrack if its width is smaller than 0.03 mm. The crack is a macrocrack, if not.[6] The results proved that the bacteria was able to mend macrocracks.

The results of this study suggest that the cracks may self-heal by incorporating bacteria into the concrete mixture. The construction industry may change if we introduce a paradigm shift in how we produce our future building materials based on the self-healing approach.

REFERENCES

[1] "Concrete in Construction: Uses, Advantages, and Types," *PRO CREW SCHEDULE,* Apr. 09, 2020. https://procrewschedule.com/concrete-in-construction-uses-advantages-and-types/J. Breckling, Ed., *The Analysis of Directional Time Series: Applications to Wind Speed and Direction*, ser. Lecture Notes in Statistics. Berlin, Germany: Springer, 1989, vol. 61.

[2] J. Zhang and B. Leng, "Transition from Multiple Macro-Cracking to Multiple Micro-Cracking in Cementitious Composites," 2008. Accessed: Mar. 25, 2024. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6074184

[3] M. Pourfallahi, A. Nohegoo-Shahvari, M. Salimizadeh, *"Effect of direct addition of two different bacteria in concrete as self-healing agent,"* *Structures*, vol. 28, pp. 2646-2660, 2020, ISSN 2352-0124, doi: 10.1016/j.istruc.2020.10.070.

[4] *"Bacterial Concrete for Self-Healing Concrete,"* *The Constructor*, Available: https://theconstructor.org/concrete/bacterial-concrete-self-healing-concrete/13751/#:~:text=When%20the%20water%20comes%20in,mol

ecule%20keeps%20the%20reaction%20going., [Accessed Nov. 27, 2023]

[5] A. Sumathi, et. al., "Development of Bacterium for Crack Healing and Improving Properties of Concrete under Wet-Dry and Full-Wet Curing," *Sustainability*, vol. 12, pp. 1-20, 2020, doi: 10.3390/su122410346.

[6] J. Zhang and B. Leng, "Transition from Multiple Macro-Cracking to Multiple Micro-Cracking in Cementitious Composites," 2008. Accessed: Mar. 25, 2024. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6074184