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Use of Gram-Positive Grass *Bacillus* as Autonomous Repair Agent in Concrete

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ABSTRACT

Due to various reasons, crack formation may occur in the concrete structure. Crack formation increases the permeability of concrete to detrimental substances including different types of chemicals, glasses, and water, which upon contact with concrete leads to significant impairment in various properties of concrete including strength, durability, etc. In the present investigation, special microbiological growth having the ability to precipitate calcite through the process of biomineralization is induced in the concrete to evaluate the performance of the concrete. The bacteria were directly added to the concrete mix instead of encapsulating them into clay pellets. Bacteria were classified into two groups i.e. A & B. i. e. 50 & 100 g of bacteria powder were added into 1 L of water respectively. Out of the two groups A and B, 4 samples each were taken of 10 mL, 20 mL, 30 mL and 40 mL, and mixed in the concrete. The results showed that compressive strength and flexural strength increased up to 23.57% and 35% respectively more than the control specimen and the optimum capacity achieved at 30 mL bacterial concentration.

INTRODUCTION

"Concretus", which originates from the Latin language means condensed and hardened, is a versatile construction component. The first known use of cement was twelve million years ago whereas concrete-like building materials were used back in 6500 BC (Alhalabi & Dupodia 2017, Ahn 2008). However, during the Roman Empire, concrete was formed. Concrete is a globally used construction material that is diverse and so versatile that it can be used in all construction types or can be modified to be applied in specialized construction fields (Irwan et al. 2016).

Concrete is an amalgamation of water, aggregates, and cement. Cement is the most important component of concrete. Cement's job is to hold the aggregates together while also filling up the gaps between coarse and fine particles (Ahn & Kishi 2008, Binici et al. 2008). Concrete is favored as a construction material due to its high compressive strength, durability, low cost, and ability to be molded into any desired shape (Seifan et al. 2016). Concrete is the most commonly used building material across the world constitutes cement, fine aggregate, coarse aggregate, and water mixed in proper proportions. The strength and durability of concrete depend upon various factors like proportioning, mixing, and compacting of the ingredients (Topcu & Canbaz 2004, Kishi et al. 2007, Demirboga & Guil 2006).

Despite its huge popularity, the life span of concrete is reduced by the formation of cracks which also shortens the structure's life. There have been numerous studies on concrete to improve the concrete for better long life (Luhar & Gourav 2015, Isa & Turhan 2007). Self-healing of concrete is one of the outcomes of many such studies. The two main areas of research in self-healing concrete are the natural way of hydrates to seal cracks over time and the artificial way to seal cracks manually (Alhalabi & Dupodia 2017). During the studies, it has been known that some methods including the application of chemicals and polymers lead to health and environmental risks and are effective only for a short period of time. Thus, there is a huge demand for methods that are environmentally suitable and efficient (Seifan et al. 2016).

The term Self-Healing means the properties to heal itself without any external help. It means that the cracks that occur in concrete mend on their own, without the need for external assistance. When air moisture combines with the non-hydrated concrete clinker existing in the fracture, the goal of self-healing is for the fissures to fill themselves (Bang et al. 2001, Homma et al. 2009). The durability of concrete is measured in terms of resistance to wear and tear. The most common test to measure the durability of concrete is to measure its permeability by Rapid Chloride Penetration test. The addition of any mineral admixture, especially a pozzolanic mineral admixture may lead to improvement of durability and quality of concrete (Binici et al. 2009, Chindaprasirt et al. 2007). Due to the autogenous crack repair, the durability of the concrete is also enhanced. Also, the reduction in corrosion to steel reinforcement is achieved as the cracks repair themselves thereby reducing the ingress of water in concrete (Alhalabi & Dupodia 2017, Quayum et al. 2015). With respect to the autogenous method to repair cracks in concrete, the idea behind creating self-healing concrete was first created in 1994. The first technique that was adopted in creating self-healing concrete was introducing small pellets (clay encasing) in the concrete mix. This clay casing consists of bacteria that gets activated when a crack is generated in the structure and repairs the crack. This technique of producing self-healing concrete with bacteria is comparatively new and has its challenges also. The cost of production of concrete with self-healing properties is comparatively higher than conventional concrete as it requires the production of bacteria. The type of bacteria also is to be chosen carefully. There is a possibility of bacteria being dormant and dying in the concrete also due to the alkalinity of concrete (Irwan et al. 2016).

A different way of evaluating the effective properties of self-healing concrete is done using the Computational hominization tool. With this method, macro and micro scales are linked together from which multi-scale modeling can be done (Quayum et al. 2015). Bio- Concrete or self-healing concrete consists of calcium lactate ($Ca(C_3H_5O_2)_2$) and certain microbes which are planted or encased in pellets or cases that get activated or break when a crack is formed and water reaches the crack These microorganisms make limestone ($CaCO_3$) as a result of their reaction with water, which eventually fills the fissure. The rate of crack filling is determined by the percentage of microorganisms introduced to the mix as well as the amount of water in the crack (Seifan et al. 2016, Ahn & Kishi 2009).

MATERIALS AND METHODS

Review Stage

The properties of the material used and the various test conducted are described below:

Cement: OPC 43 Grade cement of Birla Ultratech Cement make was used. The experimentation is done as per the Indian Standards (IS 8112 1989, IS 4031 1996). The weight of the sample taken was 300 g. The properties are discussed in Table 1.

Fine aggregates: Fine aggregates are collected from a river that lies in grading zone III. As per IS 383 (1970), the sieve analysis was done. The results of specific gravity, fineness modulus, and water absorption of fine aggregates are discussed in Table 2.

Coarse aggregates: Locally crushed aggregate of size 20 mm were used. The tests were performed according to Indian Standards (IS 383 1970, IS 2386 1963). The results of specific gravity, water absorption, and fineness modulus are shown in Table 3.

Mix Design

After performing all the tests, a mix design as per IS 10262 (2019) was prepared. W/C ratio of 0.43 was used. Bacillus subtilis (in powder form) was mixed with water to form the bacterial solution. The solution was made with different concentrations of cells. The bacteria solution was classified into two groups as shown in the table. A varying percentage of calcium lactate was used for different bacterial concentrations. The maximum percentage used was 4% by weight of cement. An increase in the percentage of calcium lactate results in increased setting time and decreased hydration of cement which in turn results in a decrease in the strength of concrete. Calcium lactate on reacting with water forms many hydrates, among which the most common is pentahydrate when Calcium Lactate is added to the concrete mix. It combines with the water in the mix to create hydrate, resulting in a decrease in the water content of concrete. The concrete dehydrates as a result of the lower water concentration, and its strength suffers as a result. Table 4 shows the mix design proportions, whereas Fig. 1 shows the different percentages of bacteria content as well as different calcium lactate percentages.

Table 1: OPC properties.

S.No.	Properties	Values	Standard Values
1	Consistency	30%	-
2	Initial Setting Time	43 min	Not less than 30 min
3	Final Setting Time	360 min	Not greater than 600 min
4	Specific Gravity	3.12	-
5	Fineness	5%	Less than 10%

Table 2: Fine aggregate properties.

S.No.	Properties	Values Obtained
1	Specific Gravity	2.6
2	Water Absorption	1%
3	Fineness Modulus	2.3
4	Grading Zone	III

Table 3: Coarse aggregate properties.

S.No.	Properties	Values Obtained
1	Aggregate Type	Crushed
2	Specific Gravity	2.63
3	Water Absorption	0.70%
4	Fineness Modulus	6.23

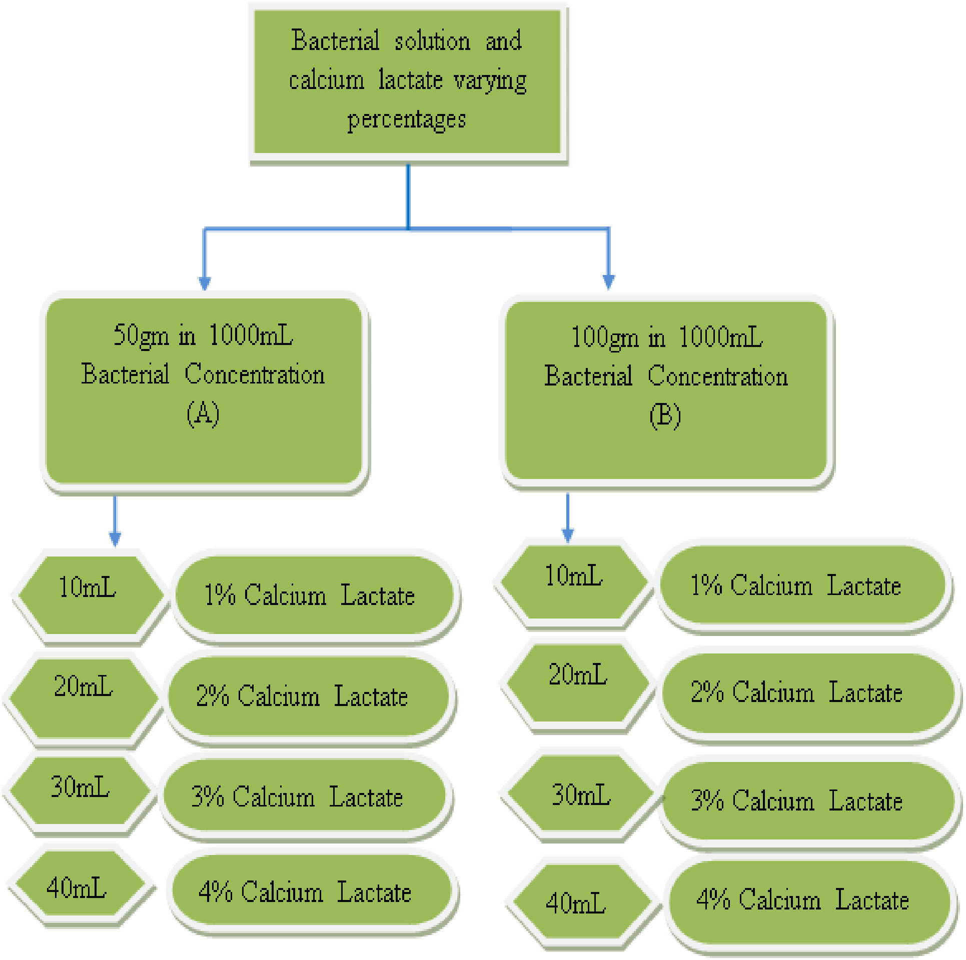

Fig. 1: Bacteria and calcium lactate dosage.

Workability Tests

The workability tests of fresh concrete were carried out to determine whether the concrete is workable or not. The tests which had been carried out to assess the workability of fresh concrete are:

Slump cone test: The slump test gives us an idea of the w/c ratio needed for concrete which is used for different works. Although it is depicted as a measure of consistency, the slump test does not assess the workability of concrete; rather, it is extremely useful in distinguishing the variations within the consistency of a given nominal percentage. The test was carried out using the IS code for Slump, which is IS 1199 (1959). The slump test apparatus consists of a mold in the shape of a frustum of a cone (Slump cone) with a height of 300 mm, bottom and top diameters of 200 mm and 100 mm, respectively, and a steel rod (tamping rod) with a diameter of 16 mm, a length of 600 mm, and one end rounded.

Table 4: Mix proportions.

Material	Quantity/Value
Grade	M30
Cement	458 kg
Fine Aggregate	591 kg
Coarse Aggregate	1130 kg
Water	197 kg
Water/Cement Ratio	0.43
Mix Proportion	1:1.29:2.46

Compaction factor test: Workability is that property of the concrete which decides the sum of work required to create full compaction. This test indicates the method for deciding the workability of concrete when the nominal maximum size of the total does not surpass 38 mm. As compared to the slump test, the compaction factor is more precise and sensitive and is specifically used in case of low workability concrete mixes. The concrete which is to be compacted by vibration may fail to slump, therefore this test is used in such concrete structures. The IS code for the compaction factor test is IS 1199 (1959) was followed to carry out the test.

Flow table test: This method entails establishing a procedure for assessing the fluidity of concrete using a flow table. This approach determines the spread of a jolted concrete pile and acts as an indicator of concrete consistency and tendency to separate. In terms of segregation, the flow table test is really useful. It can also be used to evaluate the consistency of stiff, rich, rather than cohesive combinations. This test cannot be used to determine workability since concrete with the same flow can have a wide range of workability. The IS code for flow test is IS 1199 (1959) was followed to carry out the test.

Vee-bee consistometer test: Vee-Bee Consistometer measures the workability of the mix as specified in IS 1199 (1959). The amount of time it takes to vibrate a concrete specimen into a barrel in the shape of a funnel-shaped frustum is a measure of the blend's consistency or workability.

pH Test of Water

pH is the amount of hydrogen ion concentration in solution and defined as the negative log of H+ ions concentration materials. Litmus paper was used to determine the pH value of the concrete.

Casting of Specimen

After the completion of the workability tests casting of specimens was done. The total number of specimens cast was 135 which included 81 cubes and 54 beams. 8 bacterial solution concentrations and 1 control concentration were taken into account while casting the specimens. For each given concentration 9 cubes and 6 beams were cast. The size of each cube and beam was 150*150*150 mm and 100*100*500 mm respectively. Proper lubrication of each mold was done. The molds were filled in 3 layers with subsequent tamping (25 blows) at each layer. After 24 h of casting both cubes and beams were demolded.

Curing

Effective curing maintains the hydration of concrete by preventing evaporation of water from the concrete surface. In current research work after properly demolding all the specimens, they were put in the curing tank. The pH of water used for curing was 7.3. All the specimens were distributed based on a specific curing period which includes 7, 14, 28, and 60 days.

Crack Initiation

Cracks, with the crack width in the range of 0.1 mm to 1 mm, were initiated in the specimens after 7 days of casting as shown in Fig. 2 and Fig. 3. Crack initiation was done by two methods:

By using CTM: The specimen was placed in the CTM and load was applied. The load applied was gradually increased at the rate of 0.5 $KN.s^{-1}$. The increase in load was continued until the specimen developed the crack. The maximum load applied when the specimen developed the crack was recorded. Once the crack was initiated in a specimen, it was taken out of the CTM and put in a curing tank for self-healing.

By using nails: In this method, the cracks are induced manually by the use of nails. The specimen was first wrapped in adhesive followed by manual embedding of nails of different sizes viz 3, 4, and 5 inches (to initiate cracks of different widths) into the specimen. Succeeding this, the nails were withdrawn and adhesive was removed. Then the specimens with cracks in them were put in a curing tank for self-healing.

RESULTS AND DISCUSSION

Tests were done on materials, fresh concrete, and hardened concrete.

Tests on Fresh Concrete

Slump test: Slump cone test was done. The values obtained

Fig. 2: Initiation of cracks on concrete.

Fig. 3: Initiation of cracks on concrete.

from the slump test of all the mixtures are formulated in Table 5.

As provided in Table 5, the slump values increased with an increase in bacteria content. Fig. 4 and Fig. 5 show the variation in slump values.

Compaction factor test: The result shows that the compaction factor of the control specimen was 0.79 and that of the bacterial specimen was 0.85 as shown in Table 6.

Vee-bee consistometer test: The result shows that time taken by control concrete was 10 seconds whereas by bacterial concrete was 7 seconds which is also shown in Table 7.

Test on Hardened Concrete

Compressive strength: The strength was obtained after 7, 14, and 28 days of normal water curing period. The results are tabulated in Table 8 and variations of strength are represented by Fig. 5-11.

As per the experimentation done, it is shown that if the percentage of the bacterial content is increased, it will result in an increase in the compressive strength. After 28 days of normal water curing, the strength of bacterial concrete was assessed and found to be 23.57% more when compared to the control specimen.

After 7 days of the normal water curing period, the compressive strength of Group A bacterial concrete was assessed and was found 22.09% more when compared to the control specimen.

After 14 days of the curing period, the compressive strength of Group A bacterial concrete was assessed and was found 14.89% more when compared to the control specimen.

After curing the sample for 28 days and testing in a Compressive Testing Machine for calculating the compressive strength, it was observed that the compressive strength of Group B bacterial concrete was assessed and was found 26.57% more as compared to the control specimen.

Flexural strength: The flexure (bending) strength of beam samples is obtained after 7 and 28 days of curing of samples. The results are formulated in Table 9 and varieties of strength are represented by Figs. 12-15. After 28 days of normal curing, the strength of bio concrete was evaluated and found to be 48.34% more in comparison to the control concrete specimen.

Table 5: Slump Test Results.

Mix	Bacterial Content	Slump Value
Control	0 mL	58 mm
Bacterial concrete	A-10 mL	61 mm
Bacterial concrete	A-20 mL	63 mm
Bacterial concrete	A-30 mL	66 mm
Bacterial concrete	A-40 mL	67 mm
Bacterial concrete	B-10 mL	62 mm
Bacterial concrete	B-20 mL	65 mm
Bacterial concrete	B-30 mL	68 mm
Bacterial concrete	B-40 mL	69 mm

Table 6: Compaction factor.

Mix	**Compaction Factor**
Control Specimen	0.79
Bacterial Specimen	0.85

Table 7: Vee bee consistometer.

Mix	Time in Seconds
Control concrete	10
Bacterial concrete	7

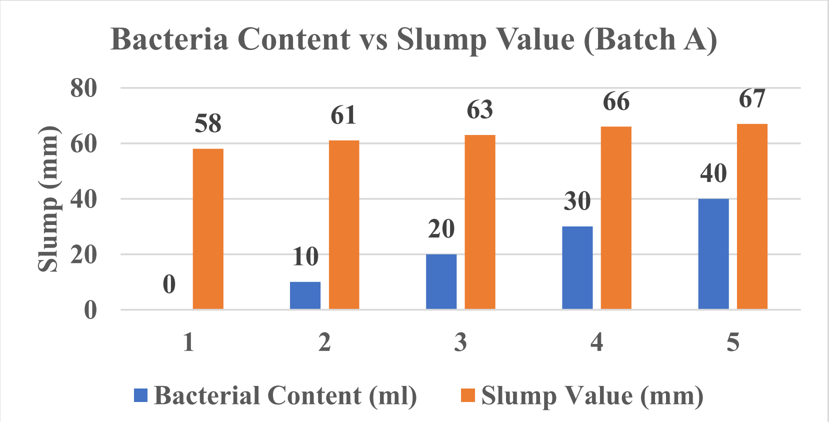

Fig. 4: Slump Values (Batch A).

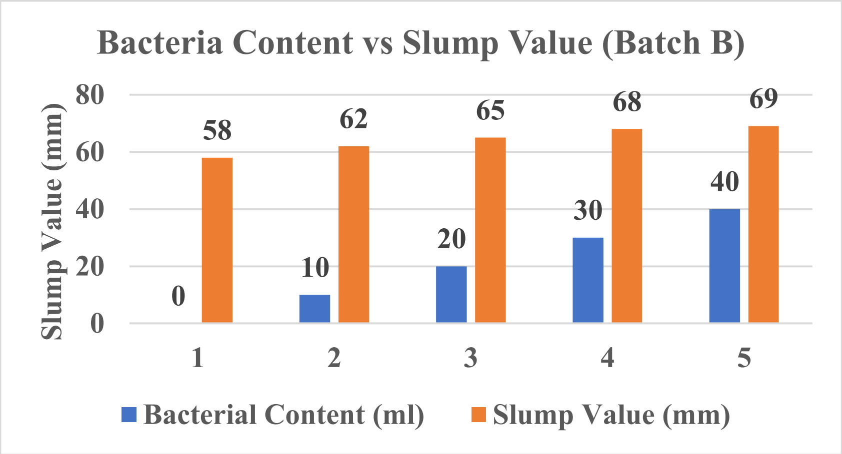

Fig. 5: Slump Values (Batch B).

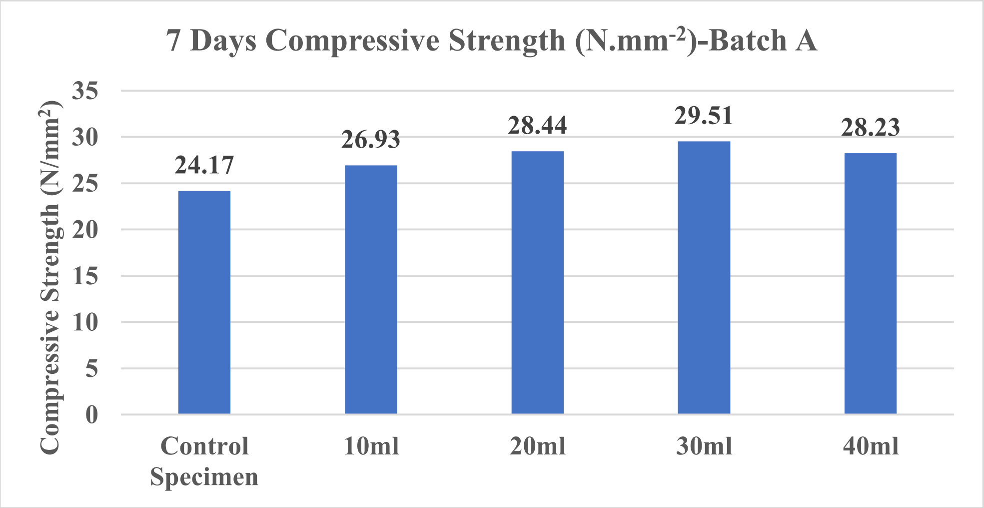

Fig. 6: 7 days compressive strength variation-Batch A.

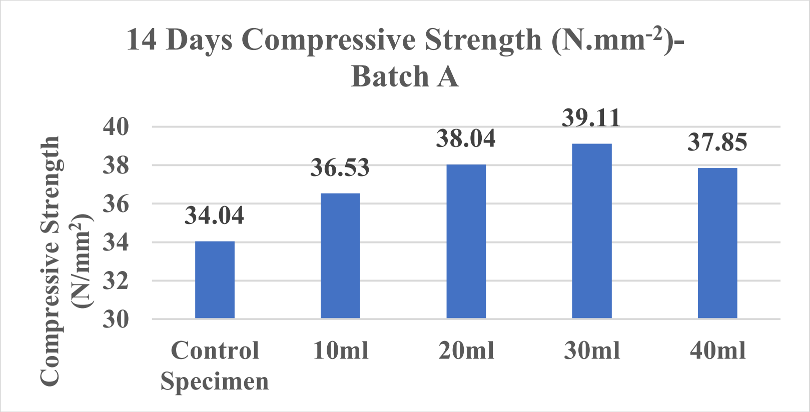

Fig. 7: 14 days compressive strength variation-Batch A.

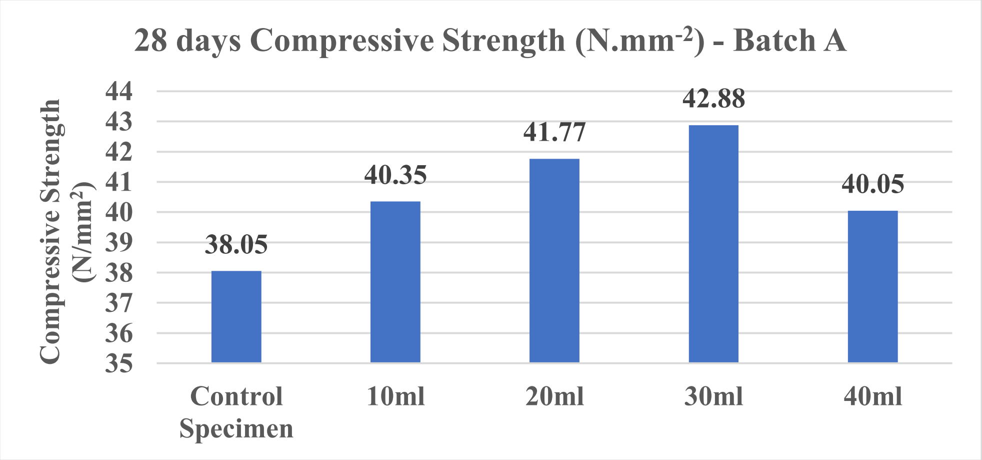

Fig. 8: 28 days compressive strength variation-Batch A.

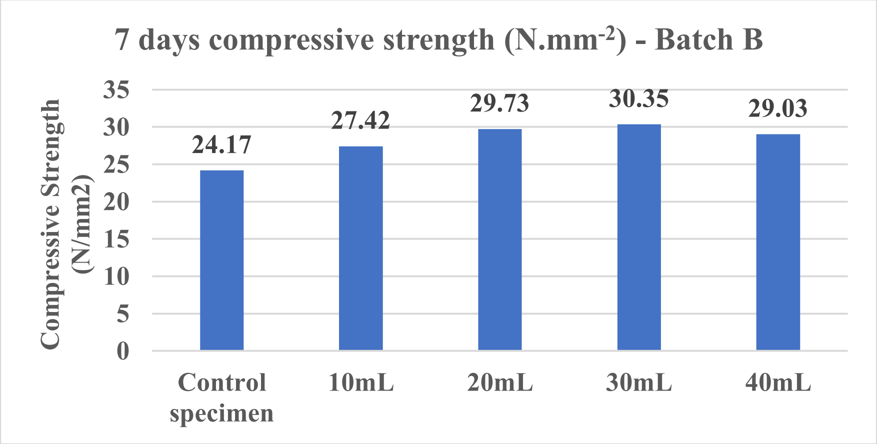

Fig. 9: 7 days compressive strength variation-Batch B.

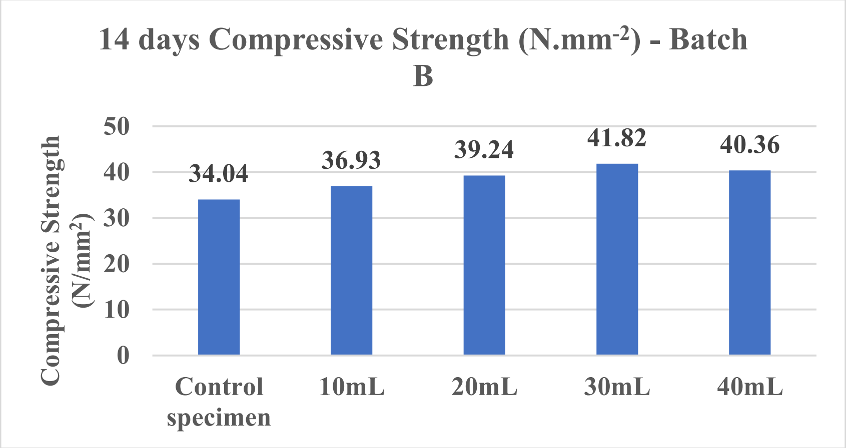

Fig. 10: 14 days compressive strength variation-Batch B.

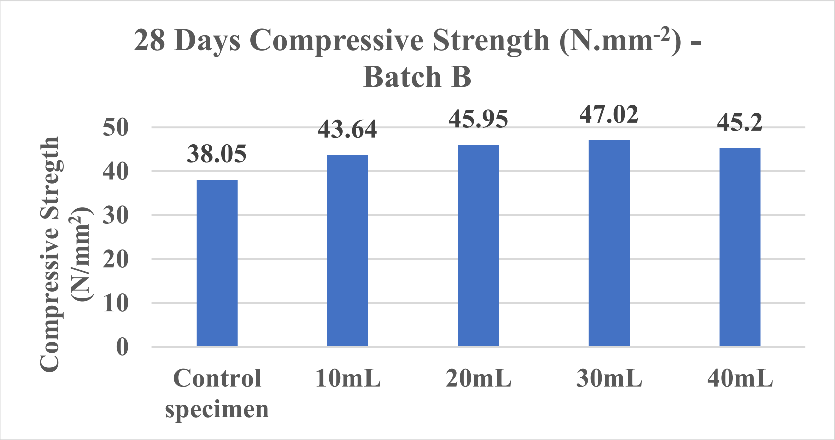

Fig. 11: 28 days compressive strength variation-Batch B.

After 7 days of the curing period, the flexural strength of Group A bacterial concrete was assessed and was found 50% more as compared to control concrete.

After 28 days of the normal curing period, the flexural (bending) strength of Group A bacterial concrete was assessed and was found 34.21% more as compared to the control concrete specimen.

After 7 days of the curing period, the flexural strength of Group B bacterial concrete was assessed and was found 95% more as compared to the control concrete specimen.

After 28 days of the curing period, the flexural strength of Group B bacterial concrete was assessed and was found 68.42% more as compared to the control concrete specimen.

Crack formation occurs frequently in concrete and results in decreased strength and hence durability of concrete. To attain and maintain the optimum durability of concrete, repair of these cracks is vital, but the costs involved in this repair are usually high. The current research focuses on the development of self-healing concrete by the use of bacteria having healing properties. The use of bacteria in concrete contributes to an increase in compressive strength, flexure strength, and hence durability of concrete. Moreover, this technology is cost-effective and eco-friendly. In the current research, Bacillus subtilis was used to heal the cracks in concrete. The bacteria were blended in different concentrations with the concrete mix while casting the specimens. Along with bacteria, calcium lactate was added to the mix which acts as a nutrient for the bacteria. Following the setting of concrete specimens, cracks were induced by two methods viz (a) By using CTM (b) By using Nails Then the specimens were put in a curing tank, and healing was assessed every 20 days up to 60 days. The specimens of group A contained 50 mg of bacteria in 1000 mL and the specimens of group B contained 100 mg of bacteria in 1000 mL. The sub concentrations for either of the groups were 10 mL, 20 mL, 30 mL, and 40 mL. After 60 days of curing, healing capacity was appraised for each concentration as shown in Fig. 16 and the following results were obtained:

- At 10 mL concentration, partial healing was acquired for both groups.
- At 20 mL concentration, specimens of group A acquired approximately 60% healing while it was approx.70% for group B specimens at the same concentration.
- At 30 mL concentration, group A specimens achieved

Table 8: Compressive strength (N.mm^{-2}).

No. of Days	Strength C.S	Group A				Group B			
		10 mL	20 mL	30 mL	40 mL	10 mL	20 mL	30 mL	40 mL
7	24.17	26.93	28.44	29.51	28.23	27.42	29.73	30.35	29.03
14	34.04	36.53	38.04	39.11	37.85	36.93	39.24	41.82	40.36
28	38.05	40.35	41.77	42.88	40.05	43.64	45.95	47.02	45.20

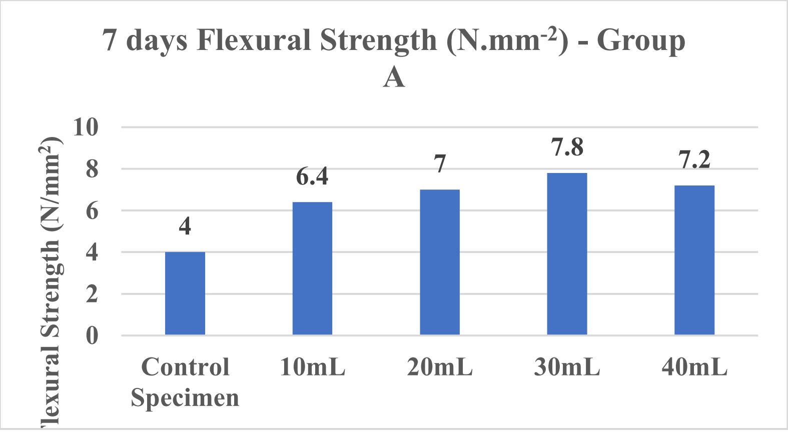

Fig. 12: 7 days flexural strength-Group A.

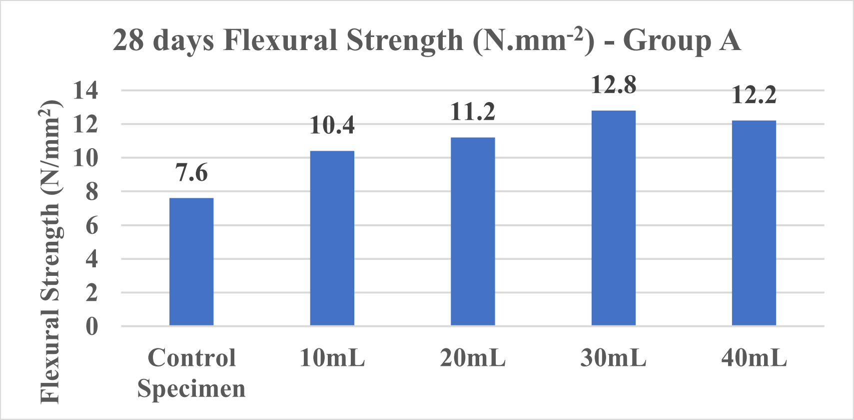

Fig. 13: 28 days flexural strength-Group A.

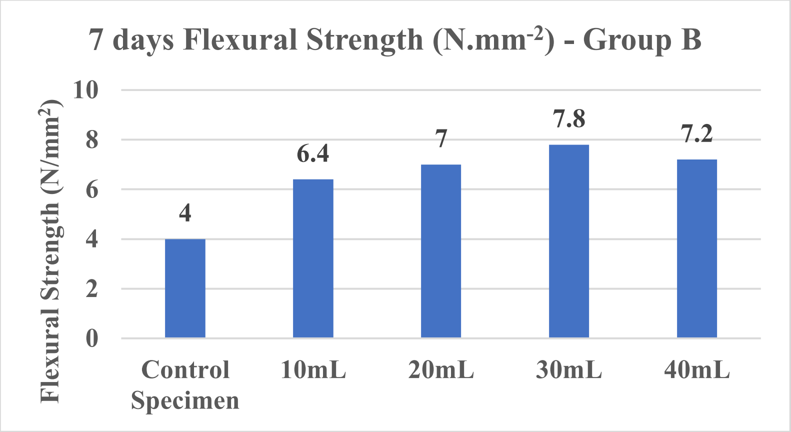

Fig. 14: 7 days flexural strength-Group B.

Table 9: Flexural strength (N.mm^{-2}).

No. of Days	Strength								
	C.S	Group A				Group B			
		10 mL	20 mL	30 mL	40 mL	10 mL	20 mL	30 mL	40 mL
7	4	5	5.4	6	5.6	6.4	7	7.8	7.2
28	7.6	8.8	9.6	10.2	9.7	10.4	11.2	12.8	12.2

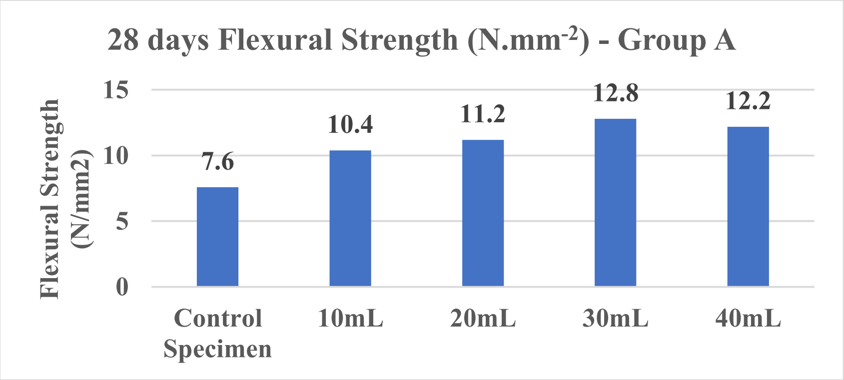

Fig. 15: 28 days flexural strength-Group B.

Fig. 16: Healing of cracks in cube and beam samples.

around 85% healing whereas specimens of group B were completely healed at the same concentration.

- At 40 mL concentration, both group A and group B specimens were completely healed.

CONCLUSION

Crack formation occurs frequently in concrete and results in decreased strength and hence durability of concrete. To attain and maintain the optimum durability of concrete, repair of these cracks is vital, but the costs involved in this repair are usually high. The current research focuses on the development of self-healing concrete by the use of bacteria having healing properties. The bacteria in concrete contribute to an increase in compressive strength, flexure strength, and hence durability of concrete.

The conclusion drawn based on current experimental investigations are as follows:

1. The alkaliphilic aerobic microorganism Bacillus subtilis can be cultured in the laboratory and is proved to be safe, non-pathogenic, and cost-effective.
2. The bacteria have the potential of healing the cracks in the concrete. It has been proved that 40 mL, as well as 30 mL bacterial concentrations significantly fill the cracks, developed, and result in an increase in the strength of concrete.
3. The compressive and flexural strength was increased till 30 mL bacterial content followed by a decrease in the respective strengths up to 40 mL bacterial content.
4. The compressive strength of bacterial concrete was increased by 25.79% as compared to control specimens at 28 days.
5. The flexural strength of bacterial concrete was increased by 68.42% as compared to control specimens at 28 days.

6. Bacterial spores are resistant to harsh environmental conditions and when the environmental conditions are favorable, they become metabolically active and utilize calcium lactate in concrete and cause hydrolysis of urea to produce ammonia and carbon dioxide resulting in the formation of calcium carbonate precipitate which fills the cracks in concrete.
7. This technology works by the process of biomineralization which results in improved strength of the concrete.
8. The most expensive ingredient in the development of self-healing concrete is nutrient i.e. calcium lactate.
9. The concentration of calcium lactate influences the setting time of concrete; therefore, it is necessary to regulate the concentration of nutrients used in concrete.
10. After exceeding the calcium lactate by 3% the initial setting time was varied by 65 min.
11. The use of bacteria in bacterial concrete is convenient and eco-friendly. Moreover, this innovative technology is cost-effective.

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