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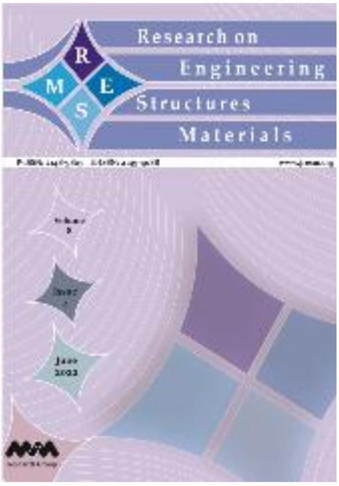

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Research Article

Crack healing and flexural behaviour of self-healing concrete influenced by different bacillus species

Chereddy Sonali Sri Durga[1,a], Chava Venkatesh*[1,b], T. Muralidhararao[1,c], Ramamohana Reddy Bellum[2,d]

[1]*Department of Civil Engineering, CVR College of Engineering, Hyderabad, India*
[2]*Department of Civil Engineering, Aditya Engineering College (Autonomous), India*

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Abstract

The main aim of this investigation is to determine the influence of Bacillus species on the crack healing ability and flexural strength of concrete. In this regard, four bacillus species, such as "*Bacillus halodurans (BH), Bacillus cereus (BC), Bacillus licheniformis (BL), and Bacillus subtilis (BS),* and two bacterial cell concentrations are selected (viz., 10^8 and 10^9 cells/ml of water), and the concrete specimens are cracked with a 65% stress level concentration. To identify the crack healing ability of selected bacillus species, three different curing conditions are adopted: calcium lactate, water, and ambient curing conditions. The ultrasonic pulse velocity test (UPV) has been conducted to identify the crack healing ability of the selected bacillus species. From the results, calcium lactate-based cured concrete specimens showed better UPV values and crack healing ability. whereas *Bacillus halodurans (BH)* effectively filled the crack with calcite precipitation, which is the reason for 90% of crack healing ability and the high flexural strength recovery compared to other selected bacillus species. There is not much difference observed between the bacteria with cell concentrations of 10^9 and 10^8; however, 10^9 has a high healing ability and recovers flexural strength.

1. Introduction

As concrete is a brittle substance, it is prone to cracking, which has major consequences for the durability of concrete structures [1-3]. Cracks will easily allow for entry of harmful substances into structures, accelerating deterioration and necessitating intensive repair and maintenance. Repair and rehabilitation of concrete structures is a difficult task nowadays because of the limited resources available to reconstruct a structure and budget required is more from an economical point of view. In the U.S, almost £40 billion are spent per year for maintenance of concrete structures in which cement plays a major role [4-5] and the reports from highway agency of England states that £80 million are used every year for the upcoming 20 years towards repair and rehabilitation of bridge works [6-7]. Moreover, for strengthening hammersmith flyover in London, nearly £70 million are spent since 2011 by its transport authority [8] and also in the U.K, it was found since from 2000, the amount spent for repair works has crossed than for new constructions [9-12]. To address the above issues, self-healing concrete was introduced for healing the cracks on the concrete surface.

Generally, animals and plants are capable of healing wounds by themselves without any external influences. For example, mammalian skin has an ability to recover from serious damage to its full extent [13]. In addition to that, a lot of organisms and natural systems

*Corresponding author: chava.venkatesh@cvr.ac.in
[a] orcid.org/0000-0003-0942-9252; [b] orcid.org/0000-0003-0028-7702; [c] orcid.org/0000-0002-7768-3298; [d] orcid.org/0000-0002-0040-5812
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are capable to heal itself; so, from these examples, the idea of healing was applied to engineering problems. This idea has come to existence through experimental work from previous decades and still it is in fantasy. Self-healing concrete is the one that heals itself when it comes into air, water and produces lime on the outer layer of the concrete. The self-healing process can be broadly classified into two types, i.e., autogenous self-healing and autonomous self-healing and the healing methods are shown in Fig 1. The healing can be done with many materials like biological agents [14-19], chemical agents, superabsorbent polymers, crystalline materials, pozzolanic materials [20-22] and mineral admixtures that are added and replaced with cement in order to arrest the cracks of concrete which shortens their production.

The bacterial agents/mediums usage for the crack healing comings under the autogenous healing method. During this process, the bacteria facilitate the precipitation of calcite (CaCO3) crystals by producing the urease enzyme. This precipitation occurs through the heterogeneous nucleation of the bacterial cell wall until supersaturation is reached. It highlights the potential of bacteria as effective self-healing agents [23]. The mechanical properties of the concrete are evaluated by using *Bacillus subtilis* bacteria and the study concluded there is an increase in mechanical properties due to the production of calcium carbonate and this is the reason for a fill of cracks [24]. Another study was done by using bacteria (*Bacillus subtilis*) and lactate derivative-based material which acts as a carbon source for crack healing. The spores of the bacteria get active and consume the nutrients, carbon source which precipitates the hydration products responsible for healing, improves the mechanical properties and water tightness enriches the durability behaviour of concrete structures [25-26].

As per the literature, several ways to carried out bacterial incorporation into the concrete for crack healing; bacterial direction injection [27], bacterial spraying on concrete cracked surface [28], bacteria encapsulation [29], and bacterial addition at time of mixing, and ect., Jonkers [30] said that addition of bacterial agents at the time of concrete mixing is better than above other methods and having optimum crack healing.

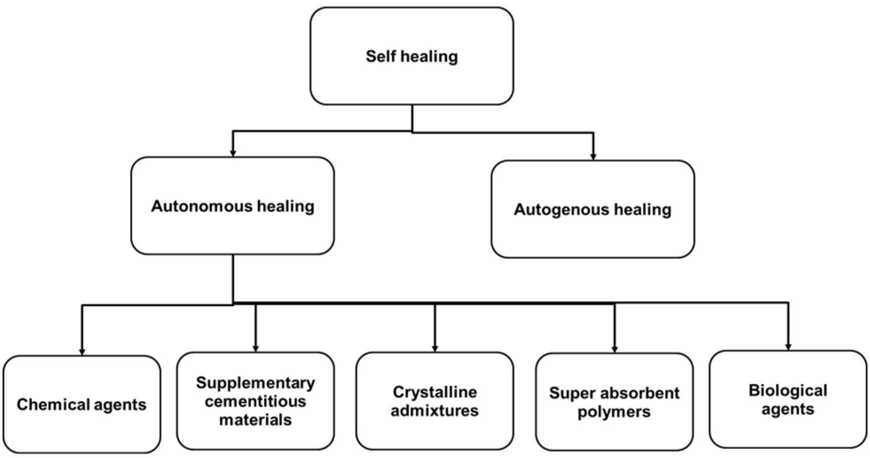

Fig. 1. Self-healing methods

The fissures underwent healing as a result of microbial precipitation induced by bacterial urealytic activity. This process of microbial precipitation is contingent upon various factors, including pH levels, the concentration of dissolved inorganic carbon, the quantity of calcium ions present, and the choice of bacterial nucleation site [31]. Many studies have mentioned that bacterial incorporation improves the mechanical strengths of concrete, especially compressive and split tensile strength. Jena [32] used Bacillus subtills (BS) with different cell concentrations ranging from 10^2 to 10^6 and investigated the mechanical properties. His study concluded that BS with 10^5 cells/ml has shown the optimum strength increments, such as a 32% increase in compressive strength, a 14.01% increase in split tensile strength, and a 29.14% increase in flexural strength. Akindahunsi [33] also mentioned that BS with 10^5 cells/ml has shown a 13% increase in compressive strength and a 15% increase in flexural strength compared to the control mix.

In the present study, four different Bacillus species, namely BH, BS, BL, and BC, with two different cell concentrations (10^8 cells/ml and 10^9 cells/ml), are selected. Additionally, three different curing conditions (calcium lactate, water, and ambient air) are identified to evaluate the potential of Bacillus species for crack healing ability and strength recovery. These parameters are considered as research gaps in the present study. The rate of crack healing is monitored daily using UPV, and the flexural strength is monitored to evaluate strength recovery.

2. Materials and Experimental Methodology

2.1 Materials

The required materials for preparing the concrete collected from local forums and its properties (i.e., physical and chemical) match the IS 12269-2013 [34], IS 383-2016 [35], and IS 456-2000 [36]. Subsequently, ordinary Portland cement contains 64.2% of CaO, 19.6% of SiO_2, 4.62% of Al_2O_3, 3.89% of Fe_2O_3, 1.86% of Na_2O_3, 0.78% of K_2O, 0.65% of TiO_2, 0.92% of MgO, and 3.48% of loss of ignition. Similarly, fine aggregates have 2.70, 1.45, and 2.56 specific gravity, bulk density, and fineness modulus, respectively. Similarly, coarse aggregates have specific gravity of 2.75, and bulk density of 1.51, respectively.

2.2 Bacteria

In the present study, the selected bacterial agents were purchased from the "National Collection of Industrial Microorganisms (NCIM), CSIR-National Chemical Laboratory (NCL), Pune, India," and cultured according to the nutrient broth medium method [18]. Based on the biological laboratory studies, all the bacterial agents exhibited a rod-like shape and were gram-positive. Furthermore, additional characteristics of the bacterial agents are listed in Table 1.

Table 1. characteristics of bacterial agents

Name of bacteria	Size, B×L (μm)	Shape	Pigmentati on	Gram staining properties	Medium	Temperature	pH
Bacillus halodurans	0.5×1.8	Rod shaped	Pink	Gram positive	Nutrient broth	37°C	7
Bacillus licheniformis	1×4.2	Rod shaped	Red	Gram positive	Nutrient	30°C	6-8
Bacillus cereus	3×4	Rod shaped	Green	Gram positive	broth	28°C	4.6
Bacillus subtilis	0.2×1.2	Rod shaped	Brown	Gram positive	Nutrient	30°C	6-9

2.3 Experimental Methodology

According to IS 10262-2009 [37], the mix calculations for 40MPa strength concrete are evaluated and listed in Table 2. Additionally, two different bacterial cell concentrations, namely 5.79×10^8 and 5.79×10^9, are used in the concrete throughout the present research work. The crack healing ability of bacterial agents and the flexural behavior of bacterial agent-induced concrete are carried out. All the prepared concrete samples are cured in normal water for 28 days before testing. The surface cracks are formed using 65% and 75% stress level concentrations [16]. To evaluate the healing ability of bacterial agents, three different curing conditions are adopted, namely water, calcium lactate, and air (i.e., ambient curing).

Table 2. Mix calculations (Kg/m^3)

Cement	Fine aggregates	Coarse aggregates	Water	Bacteria (cells/ml of water)
450	624	1220	186	(5.79×108) & (5.79×109)

2.4 Ultrasonic Pulse Velocity Test

The non-destructive studies were carried out on the hardened concrete by performing an ultrasonic pulse velocity test as per IS: 13311 (Part 1) – 1992 [38]. An Ultrasonic Pulse Velocity (UPV) test is an in-situ, non-destructive test to check the concrete quality. In this, the strength and quality of concrete are evaluated by measuring the velocity of an ultrasonic pulse passing through a concrete structure. Higher velocities indicate good quality and continuity of the material, while a lower velocity indicates concrete with many cracks or voids. The pulse velocity will be calculated by using Eq 1. The specimens (prisms) are cracked from the mean strengths as shown in Fig 2 and are placed in different curing agents such as calcium lactate, water and air in Fig 3. The experimental setup of UPV measurement to the concrete specimen is represented in Fig 4. A white precipitate was formed on the concrete specimen's surface indicating crack healing shown in Fig 5.

$$\text{Pulse velocity} = \text{Width of structure}/\text{Time taken by the pulse to go through} \tag{1}$$

Fig. 2. Setup of cracked concrete specimens

Fig.3 Concrete specimens cured at various curing agents

Fig.4 Setup of UPV measurement

Fig. 5. Crack healed specimens

2.5 Flexural Strength Test

The flexural strength is the beam or prism's capability to resist failure in bending action; it can also be termed modulus of rupture. The size of specimens adopted is 500mm×100mm×100mm to test flexural strength using a flexural testing machine with a capacity of 100KN at a loading rate of 180kg/min. As per IS 516-1959 [36] requirements, the test was carried out for the specimens cured for 28 days. The flexural strength can be calculated with the following formulae in Eq 2.

$$\text{Flexural strength } (f_b) = \frac{3PL}{2bd^2} \quad (2)$$

4. Results and Discussion

4.1 Ultra Sonic Pulse Velocity

The ultrasonic pulse velocity (UPV) values are used presently to evaluate the crack healing ability of the selected Bacillus species, namely BS, BH, BL, and BC. The bacteria-induced concrete specimens are cracked with a stress level concentration of 65% and cured in calcium lactate, water, and ambient air, respectively. Table 3 illustrates the UPV values when the cracked specimens are cured in calcium lactate. Based on Table 3, BH has a UPV value of 4.36@14 days, and its corresponding crack healing ability is 90%, which is the highest among the bacterial cell concentration 10^9 induced specimens. This effect is due to the reaction between the bacteria and calcium lactate within the concrete pores and cracks. The calcium lactate crystallizes within the cracks, leading to crack healing or sealing, thereby increasing the UPV values [39-40]. The principle of repair or crack healing involves the formation of calcium carbonate from the bacteria's spores by consuming nutrients such as calcium lactate, water, and oxygen [41-42]. The chemical agent calcium lactate has an alkaline nature, indicated by its pH value of 8, which is favorable for the concrete environment. Similarly, BC has a UPV value of 4.26@21 days, BL has 4.32@14 days, and BS has 4.11@21 days, with corresponding crack healing abilities of 87%, 88%, and 86%, respectively. A similar behavior was observed in the case of bacterial cell concentration of 10^8 induced concrete specimens.

Table 3. UPV (km/sec) crack healing after cured in calcium lactate

		Cell concentration,10^9					Cell concentration,10^8				
		NC	BC	BH	BL	BS	NC	BC	BH	BL	BS
UPV values (Km/Sec)	Before Crack	4.85	4.85	4.85	4.86	4.85	4.85	4.86	4.87	4.88	4.86
	After Crack	2.37	2.34	2.31	2.36	2.39	2.37	2.33	2.34	2.34	2.38
	Curing age (days) 3	2.65	2.85	2.62	2.68	2.98	2.65	2.61	2.48	2.54	2.66
	7	3.01	3.67	3.37	3.59	3.86	3.01	3.54	3.24	3.3	3.67
	14	3.16	3.96	**4.36**	4.32	4.11	3.16	3.82	**4.35**	4.3	3.95
	21	3.44	4.26	4.36	4.32	4.21	3.44	4.25	4.35	4.3	4.19
	28	3.86	4.26	4.36	4.32	4.21	3.86	4.25	4.35	4.3	4.19
	35	3.86	4.26	4.36	4.32	4.21	3.86	4.25	4.35	4.3	4.19
Healing ability (%)	Before Crack	100	100	100	100	100	100	100	100	100	100
	After Crack	49	48	48	49	49	49	48	48	48	49
	Curing age (days) 3	55	59	54	55	61	55	54	51	52	55
	7	62	76	69	74	80	62	73	67	68	76
	14	65	82	**90**	89	85	65	79	**89**	88	81
	21	71	88	90	89	87	71	87	89	88	86
	28	80	88	90	89	87	80	87	89	88	86
	35	80	88	90	89	87	80	87	89	88	86

Table 4 lists the UPV values and crack healing ability percentages of bacteria-induced cracked concrete specimens cured in water for their crack healing. The bacteria with a cell concentration of 10^9 induced greater healing ability than bacteria with a cell concentration of 10^8. The optimum UPV values and their corresponding healing ability percentages are as follows: NC has 3.49 @ 72% for 28 days, BC has 3.55 @ 73% for 21 days, BH has 3.65 @ 75% for 14 days, BL has 3.58 @ 74% for 14 days, and BS has 3.5 @ 72% for 21 days, respectively. The bacterial agents are capable of excreting calcite on the cracked surfaces when they react with the available moisture in their surroundings, according to [23],[43]. Similar results were observed in the bacteria with a cell concentration of 10^8 induced concrete specimens, as shown in Table 4.

The UPV values and crack healing ability percentages for bacteria-induced cracked specimens cured in ambient air are shown in Table 5. Results show that BH has the highest healing ability, i.e., 70%, which is optimum in the respective ambient air-cured concrete specimens. Whereas, BL has 68%, BS has 65%, BC has 67%, and NC has 64% in 14 days, 21 days, 21 days, and 28 days, respectively, and its corresponding optimum UPV values are 3.31 km/sec, 3.23 km/sec, 3.26 km/sec, and 3.13 km/sec, respectively. For bacteria with a cell concentration of 108, the optimum UPV values are 3.13 Km/sec for NC, 3.23 Km/sec for BC, 3.39 Km/sec for BH, 3.29 Km/sec for BL, and 3.11 Km/sec for BS, respectively, for corresponding curing ages of 28 days, 21 days, 14 days, and 21 days, as shown in Table 5. According to [44&45], the selected bacillus species are sealed with a cracked concrete surface with calcite when it reacts with surrounding ambient air, which is the reason for crack healing.

Table 4. Crack healing after cured in water

		Cell concentration, 10^9					Cell concentration, 10^8				
		NC	BC	BH	BL	BS	NC	BC	BH	BL	BS
UPV values (Km/Sec)	Before Crack	4.86	4.87	4.87	4.85	4.87	4.85	4.85	4.86	4.87	4.88
	After Crack	2.36	2.31	2.32	2.32	2.41	2.37	2.32	2.35	2.35	2.4
Curing age (days)	3	2.53	2.67	2.59	2.59	2.83	2.65	2.54	2.46	2.48	2.59
	7	2.99	3.13	3.11	3.17	3.39	3.01	3.07	3.03	3.01	3.29
	14	3.12	3.42	**3.65**	3.58	3.44	3.16	3.38	**3.62**	3.56	3.26
	21	3.4	3.55	3.65	3.58	3.5	3.44	3.51	3.62	3.56	3.48
	28	3.49	3.55	3.65	3.58	3.5	3.46	3.51	3.62	3.56	3.48
	35	3.49	3.55	3.65	3.58	3.5	3.46	3.51	3.62	3.56	3.48
Healing ability (%)	Before Crack	100	100	100	100	100	100	100	100	100	100
	After Crack	49	47	48	48	49	49	48	48	48	49
Curing age (days)	3	52	55	53	53	58	52	52	51	51	53
	7	62	64	64	65	70	62	63	62	62	67
	14	64	70	**75**	74	71	64	70	**74**	73	67
	21	70	73	75	74	72	70	72	74	73	71
	28	72	73	75	74	72	71	72	74	73	71
	35	72	73	75	74	72	71	72	74	73	71

Summary of the results: Among the selected Bacillus species, BH has shown better crack healing ability than others under the given three curing conditions, namely calcium lactate, water, and ambient air curing. Concrete specimens cured with calcium lactate effectively sealed 90% of the cracked portion in a relatively shorter time, specifically 14 days, compared to the other conditions. Similar behavior was observed in both water and ambient air curing conditions. Subsequently, BL exhibited the second-largest healing ability (89% in 14 days) among the selected Bacillus species, followed by BC and BS. The bacterial agents ideally consume calcium lactate and excrete calcite in the surrounding voids or cracks in the concrete, which is the reason for achieving high UPV (ultrasonic pulse velocity) and observed healing ability in the calcium lactate curing conditions. Similarly, bacteria can also produce calcite precipitation by reacting with moisture and air, but these healing processes require slightly more time and have lower healing ability compared to calcium lactate conditioning.

3.2 Flexural Strength Test

Fig. 6 depicts the flexural strength of bacteria with cell concentrations of 10^9 in concrete specimens before and after crack healing. In the selected bacillus species, BH has shown the greater flexural strength, i.e., 5.09 MPa, and it is considered optimum among other bacillus species. Based on biological studies, BH can survive effectively in a high alkaline environment (concrete pH > 12) compared to others and is primarily responsible for the calcium carbonate in the cracked portion of the concrete, which helps enhance the concrete's flexural strength. The calcium lactate curing-conditioned specimens have shown the highest recovery of the flexural strength, i.e., 99.61% in BH, 91.13% in BC, 96.02 in BL, 86.78 in BS, and 82.09 in NC, respectively. Similarly, BH has shown better strength recovery under water and ambient air curing conditions, i.e., 98.23% and 96.46%, respectively. From the UPV values, it was observed that the bacteria can seal the crack by observing the surrounding moisture and air, which is the reason for the recovery of strength. Similar results were observed in the case of bacteria with a cell concentration of 10^8, which are shown in Fig. 7.

Table 5. crack healing after cured in ambient air

		Cell concentration,10^9					Cell concentration,10^8				
		NC	BC	BH	BL	BS	NC	BC	BH	BL	BS
UPV values (Km/Sec)	Before Crack	4.87	4.88	4.88	4.87	4.9	4.87	4.87	4.89	4.89	4.89
	After Crack	2.35	2.32	2.34	2.3	2.42	2.35	2.3	2.32	2.33	2.39
Curing age (days)	3	2.46	2.56	2.48	2.45	2.75	2.46	2.48	2.36	2.39	2.47
	7	2.97	2.92	2.86	271	3.14	2.97	2.86	2.84	2.6	3.04
	14	3.08	3.16	**3.41**	3.31	3.18	3.08	3.09	**3.39**	3.29	3.11
	21	3.09	3.26	3.41	3.31	3.23	3.09	3.23	3.39	3.29	3.2
	28	3.13	3.26	3.41	3.31	3.23	3.13	3.23	3.39	3.29	3.2
	35	3.13	3.26	3.41	3.31	3.23	3.13	3.23	3.39	3.29	3.2
Healing ability (%)	Before Crack	100	100	100	100	100	100	100	100	100	100
	After Crack	48	48	48	47	49	48	47	47	48	49
Curing age (days)	3	51	52	51	50	56	51	51	48	49	51
	7	61	60	59	56	64	61	59	58	53	62
	14	63	65	**70**	68	65	63	63	**69**	67	64
	21	63	67	70	68	66	63	66	69	67	65
	28	64	67	70	68	66	64	66	69	67	65
	35	64	67	70	68	66	64	66	69	67	65

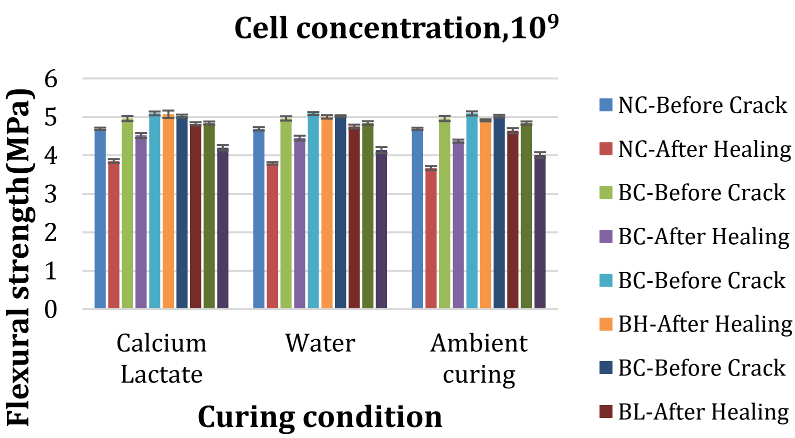

Fig. 6 Flexural strength of bacteria cell concentration of 109

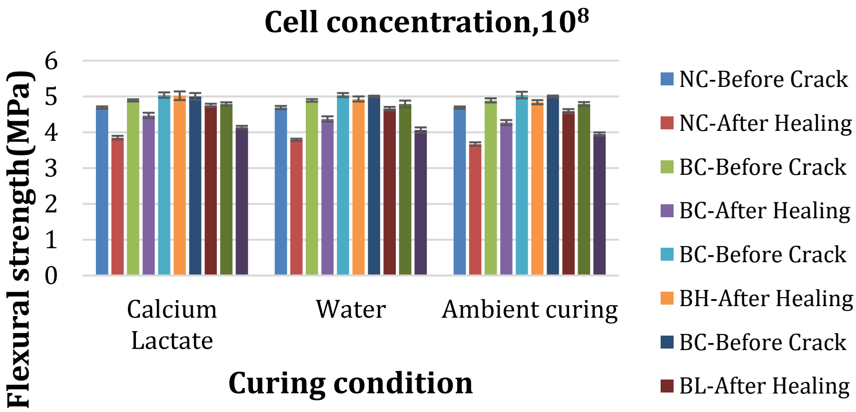

Fig. 7 Flexural strength of bacteria cell concentration of 108

5. Conclusions

In the present research study, the four bacteria (*Bacillus subtilis, Bacillus cereus, Bacillus licheniformis, and Bacillus halodurans*) were cultured, and the bio-concrete specimens were prepared using bacteria with two different cell concentrations of 10^8 and 10^9. The specimens are cured for 28 days and checked for mechanical properties (flexural strength). The specimens are cracked with stress level concentrations of 65% mean strength and were placed in various curing conditions such as calcium lactate, air, water, and bacterial solution to determine the healing rate by conducting ultrasonic pulse velocity tests. The following are the conclusions drawn from the present research work:

- Bacillus halodurans has the highest crack healing ability compared to other Bacillus species used in the present study. Particularly, calcium lactate cured BH has the optimum performance in terms of crack healing and flexural strength recovery.
- The UPV values get constant for Bacillus subtilis (4.21 km/sec) and Bacillus cereus (4.26 km/sec) concrete specimens at 21 days, Bacillus licheniformis (4.32 km/sec), and Bacillus halodurans (4.36 km/sec) concrete specimens at 14 days, illustrating no further healing.
- In all the mixes, bacterial cell concentrations in 109 concrete samples showed better healing performance in the selected curing conditions, i.e., calcium lactate, water, and ambient air.
- The crack healing of BH is 90%, 75%, and 70% in calcium lactate, water, and ambient air curing, respectively. The name Bacillus halodurans, i.e., the term halo itself, indicates alkalinity, representing that this bacterium can sustain itself easily in a concrete environment and precipitate calcium carbonate.
- Subsequently, BL has shown the second highest performance, i.e., 89%, 74%, and 68% of crack healing in calcium lactate, water, and ambient air conditions, respectively.
- The selected bacillus species has shown considerable concrete specimen crack healing and recovery of flexural strength in ambient air and water curing conditions. From the results, it was found that ambient air and water can react with bacillus species and produce calcite precipitants.
- The Bacillus halodurans exhibited the highest flexural strength, measuring 5.07 MPa, while the control samples measured 5.09 MPa. This is attributed to the

bacteria's ability to survive in a high-alkaline environment and produce calcium carbonate, which fills the cracks and enhances the flexural strength of the concrete.

- From the obtained results, the present study concludes that Bacillus halodurans can be used for concrete repairs, particularly crack healing.

Future scope and limitations of the study

- The present investigation has proven that the selected Bacillus species are ideally suitable as self-healing agents in concrete repair works. It is necessary to study the performance of these Bacillus species in structural elements such as reinforced concrete beams, columns, and slabs. Additionally, it is advisable to study the behavior of the Bacillus species in adverse environments such as acid environments and elevated temperatures.
- From the observation, it can be noted that most of the time the crack healing ability of the selected Bacillus species is limited to surface cracks.

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References

[1] Wang R, Zhang Q, Li Y. Deterioration of concrete under the coupling effects of freeze-thaw cycles and other actions: A review. Construction and Building Materials, 2022, 319, 126045. https://doi.org/10.1016/j.conbuildmat.2021.126045

[2] Mohammadi A, Ghiasvand E, Nili M. Relation between mechanical properties of concrete and alkali-silica reaction (ASR); a review. Construction and Building Materials, 2020, 258, 119567. https://doi.org/10.1016/j.conbuildmat.2020.119567

[3] Kabir H, Hooton RD, Popoff NJ. Evaluation of cement soundness using the ASTM C151 autoclave expansion test. Cement and Concrete Research, 2020, 136, 106159. https://doi.org/10.1016/j.cemconres.2020.106159

[4] Joseph C, Jefferson AD, Isaacs B, Lark R, Gardner D. Experimental investigation of adhesive-based self-healing of cementitious materials. Magazine of Concrete Research, 2010, 62(11), 831-843. https://doi.org/10.1680/macr.2010.62.11.831

[5] DTI (Department for Trade and Industry). Construction Statistics Annual Report 2006. TSO, London.

[6] Das PC, Maintenance planning for trunk road structures in England. TRB Transport Research Circular, 1999.

[7] Insaurralde CC, Rahman PK, Ramegowda M, Vemury CM. Follow-up methods for autonomic repairing process. In 2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC) (pp. 004854-004859). IEEE 2016. https://doi.org/10.1109/SMC.2016.7844997

[8] J Prynn, Hammersmith flyover needs £60m repair job after £10m emergency work two years ago. London Evening Standard.

[9] Fib (Fédération Internationale du béton). Bulletin 44: Concrete Structure Management: Guide to Ownership and Good Practice. Fib, Lausanne, Switzerland, 2008.

[10] McCarter W, Chrisp T, Starrs G, Holmes N, Basheer L, Basheer M, Nanukuttan SV. Developments in monitoring techniques for durability assessment of cover-zone concrete. Computer-Aided Design, 2010, 17(6), 294-303.

[11] McCarter WJ, Chrisp TM, Starrs G, Adamson A, Owens E, Basheer PM, Holmes N. Developments in performance monitoring of concrete exposed to extreme

environments. Journal of infrastructure systems, 2012, 18(3), 167-175. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000089
[12] Suryanto B, Wilson SA, McCarter WJ, Chrisp TM. Self-healing performance of engineered cementitious composites under natural environmental exposure. Advances in Cement Research, 2016, 28(4), 211-220. https://doi.org/10.1680/jadcr.15.00022
[13] Frei R, McWilliam R, Derrick B, Purvis A, Tiwari A, Di Marzo Serugendo G. Self-healing and self-repairing technologies. The International Journal of Advanced Manufacturing Technology, 2013, 69(5), 1033-1061. https://doi.org/10.1007/s00170-013-5070-2
[14] Durga C, Ruben N. Assessment of various self-healing materials to enhance the durability of concrete structures. Ann. Chim.-Sci. Matér, 2019, 43(2), 75-79. https://doi.org/10.18280/acsm.430202
[15] Durga CSS, Ruben N. A review of the mechanical behavior of substitution materials in self-healing concrete. Sustainable Construction and Building Materials, 2019, 135-144. https://doi.org/10.1007/978-981-13-3317-0_12
[16] Durga CSS, Ruben N, Chand MSR, Venkatesh C. Evaluation of mechanical parameters of bacterial concrete. In Annales de Chimie-Science des Matériaux, 2019, (Vol. 43, No. 6, pp. 395-399). https://doi.org/10.18280/acsm.430606
[17] Durga CSS, Ruben N, Chand MSR, Venkatesh C. Performance studies on rate of self-healing in bio concrete. Materials Today: Proceedings, 2020, 27, 158-162. https://doi.org/10.1016/j.matpr.2019.09.151
[18] Durga CSS, Ruben N, Chand MSR, Indira M, Venkatesh C. Comprehensive microbiological studies on screening bacteria for self-healing concrete. Materialia, 2021, 15, 101051. https://doi.org/10.1016/j.mtla.2021.101051
[19] Reddy S, Rao M, Aparna P, Sasikala CH. Performance of standard grade bacterial (Bacillus subtilis) concrete. Asian J Civ Eng (Build Housing), 2010, 11, 43-55.
[20] Ruben N, Venkatesh C, Durga CSS, Priyanka M, Reddy KHK. Evaluation of Flow Ability Properties of Cement Paste Incorporated with Bagasse Ash. Indian journal of ecology, 2020, Vol 47(11), 171-175.
[21] Venkatesh C, Sri Rama Chand M, Ruben N, Sonali Sri Durga C. Strength Characteristics of Red Mud and Silica Fume Based Concrete. In Smart Technologies for Sustainable Development (pp. 387-393). Springer, Singapore 2021. https://doi.org/10.1007/978-981-15-5001-0_33
[22] Venkatesh C, Ramanjaneyulu V, Reddy K, Durga C, Sathish P. A pilot strength studies on granite powder and silica fume based concrete. International Journal of Innovative Technology and Exploring Engineering, 2019, 8(7), 2278-3075.
[23] Vijay K, Murmu M. Effect of calcium lactate on compressive strength and self-healing of cracks in microbial concrete. Frontiers of Structural and Civil Engineering, 2019, 13, 515-525. https://doi.org/10.1007/s11709-018-0494-2
[24] Seifan M, Samani AK, Berenjian A. Bioconcrete: next generation of self-healing concrete. Applied microbiology and biotechnology, 2016, 100(6), 2591-2602. https://doi.org/10.1007/s00253-016-7316-z
[25] Mors RM, Jonkers HM. Feasibility of lactate derivative based agent as additive for concrete for regain of crack water tightness by bacterial metabolism. Industrial crops and products, 2017, 106, 97-104. https://doi.org/10.1016/j.indcrop.2016.10.037
[26] Rao MV, Reddy VS, Sasikala C. Performance of microbial concrete developed using bacillus subtilus JC3. Journal of The Institution of Engineers (India): Series A, 2017, 98(4), 501-510. https://doi.org/10.1007/s40030-017-0227-x
[27] Sangadji S, Wiktor VAC, Jonkers HM, Schlangen HEJG. Injecting a liquid bacteria-based repair system to make porous network conrete healed. In ICSHM 2013: Proceedings of the 4th International Conference on Self-Healing Materials, Ghent, Belgium, 16-20 June 2013. Magnel Laboratory for Concrete Research.

[28] Wiktor V, Jonkers HM. Field performance of bacteria-based repair system: Pilot study in a parking garage. Case Studies in Construction Materials, 2015, 2, 11-17. https://doi.org/10.1016/j.cscm.2014.12.004

[29] Espitia-Nery ME, Corredor-Pulido DE, Castaño-Oliveros PA, Rodríguez-Medina JA, Ordoñez-Bello QY, Pérez-Fuentes MS. Mechanisms of encapsulation of bacteria in self-healing concrete. Dyna, 2019, 86(210), 17-22. https://doi.org/10.15446/dyna.v86n210.75343

[30] Jonkers HM, Thijssen A, Muyzer G, Copuroglu O, Schlangen E. Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological engineering, 2010, 36(2), 230-235. https://doi.org/10.1016/j.ecoleng.2008.12.036

[31] Bang SS, Galinat JK, Ramakrishnan V. Calcite precipitation induced by polyurethane-immobilized Bacillus pasteurii. Enzyme and microbial technology, 2001, 28(4-5), 404-409. https://doi.org/10.1016/S0141-0229(00)00348-3

[32] Jena S, Basa B, Panda KC, Sahoo NK. Impact of Bacillus subtilis bacterium on the properties of concrete. Materials Today: Proceedings, 2020, 32, 651-656. https://doi.org/10.1016/j.matpr.2020.03.129

[33] Akindahunsi AA, Adeyemo SM, Adeoye A. The use of bacteria (Bacillus subtilis) in improving the mechanical properties of concrete. Journal of Building Pathology and Rehabilitation, 2021, 6, 1-8.. https://doi.org/10.1007/s41024-021-00112-7

[34] IS 12269-1987. Specifications for 53 grade ordinary Portland cement. Bureau of Indian Standards, New Delhi, India, 1987.

[35] IS 383-2016. Coarse and fine aggregate for concrete - specification. Bureau of Indian Standards, New Delhi, India, 2016.

[36] IS 456-2000. Plain and reinforced concrete - code of practice. Bureau of Indian Standards, New Delhi, India, 200.

[37] IS 10262-2009. Concrete mix proportioning - guidelines. Bureau of Indian Standards, New Delhi, India, 2009.

[38] IS 13311 (Part 1) - 1992. Non-destructive testing of concrete-methods of test. Bureau of Indian Standards, New Delhi, India, 1992.

[39] IS 516-1959. Methods of tests for strength of concrete. Bureau of Indian Standards, New Delhi, India, 1959.

[40] Vijay K, Murmu M. Self-repairing of concrete cracks by using bacteria and basalt fiber. SN Applied Sciences, 2019, 1(11), 1-10. https://doi.org/10.1007/s42452-019-1404-5

[41] Khaliq W, Ehsan MB. Crack healing in concrete using various bio influenced self-healing techniques. Construction and Building Materials, 2016, 102, 349-357. https://doi.org/10.1016/j.conbuildmat.2015.11.006

[42] Rao M, Reddy VS, Hafsa M, Veena P, Anusha P. Bioengineered concrete-a sustainable self-healing construction material. Res. J. Eng. Sci. ISSN, 2278, 9472, 2013.

[43] Irwan JM, Anneza LH, Othman N, Alshalif AF, Zamer MM, Teddy T. Calcium Lactate addition in Bioconcrete: Effect on Compressive strength and Water permeability. In MATEC Web of Conferences, 2016, (Vol. 78, p. 01027). EDP Sciences. https://doi.org/10.1051/matecconf/20167801027

[44] Achal V, Mukherjee A, Kumari D, Zhang Q. Biomineralization for sustainable construction-A review of processes and applications. Earth-science reviews, 2015, 148, 1-17. https://doi.org/10.1016/j.earscirev.2015.05.008

[45] Chuo SC, Mohamed SF, Mohd Setapar SH, Ahmad A, Jawaid M, Wani WA, Mohamad Ibrahim MN. Insights into the Current Trends in the Utilization of Bacteria for Microbially Induced Calcium Carbonate Precipitation. Materials, 2020, 13(21), 4993. https://doi.org/10.3390/ma13214993

[46] Seifan M, Sarmah AK, Samani AK, Ebrahiminezhad A, Ghasemi Y, Berenjian A. Mechanical properties of bio self-healing concrete containing immobilized bacteria with iron oxide nanoparticles. Applied microbiology and biotechnology, 2018, 102(10), 4489-4498. https://doi.org/10.1007/s00253-018-8913-9