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Strength Behavior Analysis of Self-healing Concrete Using Bacteria and Silica Gel: A Comparative Study

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Abstract

Concrete cracking is a significant worry in the construction sector, and infrastructure maintenance is becoming increasingly important in the present landscape. The expenditures of inspections, repairs, and maintenance are not only unwelcome but also have negative environmental consequences. The availability of self-healing agents in self-healing concrete (SHC) may be handled in these conditions with solid integrations. Self-healing concrete has the specific benefit of detecting the emergence of fractures in SHC-made concrete pieces and initiating a self-repair process without human involvement. This paper compares two alternative concrete healing methods and offers the findings of a complete experimental examination of self-healing concrete. In this study, silica and polymer-based gels were used along with *Bacillus subtilis* bacteria in separate experiments as weight-based alternatives for cement. The mechanical properties of various concrete mixes were evaluated using the self-healing studies by silica-based polymers and bacillus bacteria. The optimum dose level has been identified for the usage of silica gel and bacillus bacteria in the concrete. These findings provide vital insights into deploying self-healing concrete and its potential to handle concrete cracking concerns more effectively.

Keywords

cracks, self-healing agent, concrete, *Bacillus subtilis*, strength properties

1 Introduction

Cracking is a kind of structural degradation that occurs naturally and threatens the lifespan of concrete structures. The limited tensile strength of concrete and external influences such as drying shrinkage, temperature changes, and chemical interactions among its components all contribute to crack development. Researchers are continuously investigating various materials and fibers as possibilities for controlling and mitigating fractures. The existence of fissures increases the possibility of hostile chemicals penetrating the concrete and compromising its long-term durability. Microcracks are unavoidable in concrete buildings, and when they become linked, they can substantially impact structural stability [1]. The continual existence of fissures offers an accessible channel for aggressive chemicals to permeate, eventually leading to reinforcing bar corrosion and structural damage. Corrosion is a recurring problem in concrete structures, reducing their strength and long-term endurance. While microcracks begin as minute defects, they can gradually link and grow into macrocracks. These cracks become corrosive in the presence of reinforcing bars. Furthermore, fissures allow liquids, gases, and possibly dangerous chemicals to get through [2]. Concrete is an adaptable material that may be designed to have self-healing cracks. This method allows concrete to autonomously mend fractures by creating healing chemicals as they emerge. Furthermore, concrete has some intrinsic self-healing potential, known as autogenous self-healing.

Cracks are generally fixed manually; however, this procedure only gives a temporary remedy. Scheduled and regular maintenance can be time-consuming, especially when access to the structure is limited, as with subterranean or towering buildings. For the concrete overlay process, cementitious composites were developed as a composite solution to rehabilitate structures. Normal concrete mix made up of water, cement and coarse aggregate has

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a capability for self-healing. To facilitate self-healing, some sections of the cement in the concrete are replaced with geomaterials [3]. The entry of corrosive compounds such as sulphate, carbonate, chloride, and others may produce vulnerable cracks in the concrete. Because of the scale or height of the structures, continual monitoring and maintenance may be impossible in such cases. As a result, it is critical to focus on the development of concrete with self-healing properties in order to counteract corrosion and deterioration of concrete buildings [4]. The purpose of this study was to look into the effect of self-healing materials on crack repair in concrete components. While crack-healing concrete is desirable, any loss of strength attributes may be unacceptable. More study is needed to discover if mineral-based healing agents or microbial cells are more successful in encouraging concrete fracture self-healing. In the context of practical applications, this conclusion might be a useful reference for picking an effective strategy from the several self-healing options that have been widely explored in research debates. The strength of concrete materials was evaluated after the healing process is the primary objective of this experimental study. Also, the silica based mineral materials and bacterial effect in the concrete surface was focused in these investigations. The efficiency of various self-healing materials was assessed in this study by employing microcapsules of silica gel and bacteria (*Bacillus subtilis*) in light weight aggregates.

1.1 Self-healing concrete (SHC)

A significant invention is self-healing concrete, which can spontaneously fix tiny fractures owing to its intrinsic qualities. According to the research conducted by Wang et al. [3], the SHC has a good life span and less maintenance compared to normal concrete, thereby reducing the overall project cost by up to 50%. The three basic processes involved in self-healing, according to Lucas et al. [5] cement paste hydration, calcium carbonate crystal production, and flow channel obstruction. Studies have shown that calcium carbonate ($CaCO_3$) crystals forming on the mineral interface within the mortar matrix have crack-sealing and permeability-reducing properties. These crystalline formations contribute to the self-healing capabilities of concrete, as they help seal cracks and reduce the permeability of the material, enhancing its durability and resilience. Self-repairing concrete is also known as self-healing concrete since it can cure itself without human involvement. Concrete self-healing mechanisms are classified into autogenous healing and autonomous healing. Autogenous self-healing may be done in concrete by introducing minerals, fibers, and internal curing chemicals to speed up hydration [6]. Fig. 1 depicts the four sequential processes of cementitious hydration after the un-hydrated stage. Calcium carbonate production within the fracture is integral to the healing process. When calcium hydroxide dissolves in water, it interacts with atmospheric carbon dioxide to form calcium carbonates. Water infiltration into fissures dissolves the calcite crystals inside the cementitious paste. This, in turn, combines with ambient carbon dioxide, eventually forming $CaCO_3$ crystals on the crack's surface and the reaction may be expressed in Eq. (1):

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O. \quad (1)$$

The admixtures, curing agents and fibers can assist the autogenic healing in concrete mix. The microbial process, vascular and capsule methods also used for self-healing process which is described by Salhi et al. [7]. Healing compounds are included in capsules comprised of materials such as glass, ceramics, and polymers. The compatibility of the cementitious media with these capsules is critical for the interface bonding strength. The binding strength between the link and the capsule should ideally be greater than the capsule's strength. Conversely, if the adhesive strength between the capsule and the interface is inadequate, the crack may propagate laterally to the boundary line in slightly nature than cracking the capsule [8]. This can hinder the release of the curative ingredient, potentially limiting the self-healing effectiveness of the material. When cracks form in the cementitious matrix, these capsules break, releasing the healing chemicals. Minerals released from these capsules and un-hydrated cementitious chemicals near the fracture surface contribute to crack healing by participating in the rehydration process. This combination of actions is responsible for preventing the spread of the crack. The main aim of this research work is to develop the capsules for releasing the ingredient at the time of break appearance in the concrete during the mixing process. The schematic representation of auto self-healing process in the concrete mix under various conditions was shown in Fig. 2.

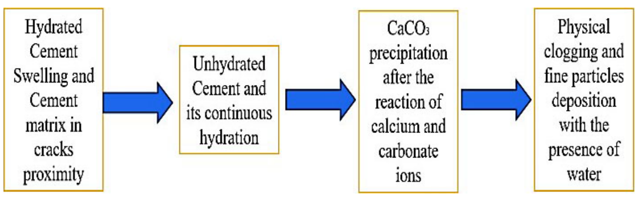

Fig. 1 Self-healing process by autogenic mode

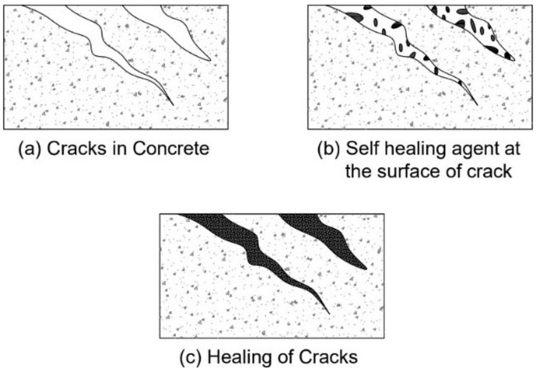

Fig. 2 Self-healing process in concrete by autonomous mode

1.2 Silica gel and its healing properties

Self-healing in structural composites is made possible by integrating encapsulated polymers into the composite matrix as the healing agent. These encapsulated polymers play a crucial role in automatically repairing and restoring the structural integrity of the composite material when it experiences damage or cracks. Essentially, self-healing polymeric materials provide cementitious blends with the capacity to reestablish load-bearing capability following structural component damage. Capillary action causes the release of the healing agent into the crack plane when the fissure breaks the microcapsules in the case of structural fractures [9]. Polymerization occurs when the healing agent comes into contact with the catalyst.

This process connects the fracture surfaces and effectively fills the fractures in the material. Superabsorbent polymers and hydrogels have the unique capability to absorb and retain significant volumes of liquid without dissolving, which makes them particularly effective in facilitating this healing process. Nano-silica gel has a remarkable long-term healing capability in a short period. In the study conducted by Barluenga et al. [10], it was demonstrated that SHC, which incorporated microcapsules holding fluid amine in glycerol tristearate shells, proved to be an efficient method for healing concrete cracks and enhancing the overall opening assembly of the concrete. Amran et al. [11], also proved that the materials with healing capacity with polymers are more efficient than other healing methods. They looked at the microcapsule composition and its significance in restoring strength properties. Their findings revealed that increasing the concentration of microcapsules resulted in a significant increase in healing performance. However, it is critical to guarantee the homogeneous dispersion of microcapsules during the casting process to accomplish the necessary mechanical property recovery. The study's findings highlight the need for further research into creating a balance between the amount and size of microcapsules to offset possible downsides connected with microcapsule-based self-healing systems. Synthetic manufacture process of amorphous SiO_2 has very hard nature and uneven grains and the silica gel was obtained from its beads. Without creating unwanted effects/by-products, the silica gel absorbs the water from the inner pores as an essential feature [12]. The silica gel also looks like dry in form even if the process reached to the saturation level. Due to this beneficial property, this research work was aimed to repair the cracks in the concrete using self-healing agent. i.e., silica gel. To retain the physical integrity the silica gel absorbs the moisture content and it referred to non-variant indication. The color of pointer inside the gel fluctuates as it absorbs moisture, offering a visible indication of the silica gel's activity [13]. This color change is often used to signal when the silica gel needs to be replaced or regenerated due to its moisture-absorbing capacity being reached. This study aims to provide an effective and economical solution for the incorporation of self-healing capabilities in concrete structures. Fig. 3 shows the encapsulation process of silica gel into the concrete.

1.3 *Bacillus subtilis* bacteria and its self-healing properties

Numerous research investigations have looked into the usage of chemical agents to improve self-healing capacities and mend concrete fractures. Another novel method for repairing damaged structural components is to use a bacterial plugging procedure. Bacteria are essential in the metabolic processes that result in the precipitation of calcium carbonate, notably calcite. This naturally occurring process can be an alternate agent for healing concrete cracks [14]. Microbial metabolic activities promote alkalinity and aid

Fig. 3 Encapsulation of silica gels and concrete embedment

in the precipitation of calcium carbonate, a valuable mineral for lowering porosity in concrete mixtures. Several studies have been conducted to investigate incorporating bacteria into concrete to improve qualities like strength, durability, and resistance to fast chloride permeability. The healing of cracks and variations in strength of SHC has been examined using bacterial species and microbial activity by Bengzon Tan et al. [15]. For example, adding *Bacillus subtilis* to concrete mixtures has been proven to meet crack-healing criteria while reducing the permeability of water. Sucharda et al. [16] stated the process of healing incorporating microbes appear more ecologically friendly than specific alternatives. Incorporating *Bacillus subtilis* as a dispersion agent with lightweight particles has demonstrated efficient fracture healing and improvement in the strength qualities of concrete mixtures. Introducing the bacterial cells into the concrete has reduced the functional efficiency of the self-healing process, and the direct mixing may expose the cement hydration, which can reduce bacteria's survival capacity and put them under physical stress. Carriers are utilized to shield the germs from these effects. Various carrier materials (Gels of silica, polyurethane etc.), have been studied to help bacteria survive in concrete mixtures. The carriers protect the germs during mixing and cover them efficiently. Abed et al. [17], emphasized the need to evaluate the influence of fracture geometry features. According to the findings of the study, non-straight cracks suggest the use of self-healing chemicals as compared to straight cracks. Also, the light weight aggregates may act as a carrier medium for bacterial introduction into the self – healing concrete. Since the process of self-healing necessitates the widespread healing applications of chemicals within actual structures, the objective is to streamline and ease the dispersion process. The light weight aggregates of *Bacillus subtilis* with 1–4 mm of size was shown in Fig. 4.

2 Materials used and methods

The main aim of this work is to match the specified concrete strength, durability and workability with the self-healing concrete mix. As per IS 8112:2013 [18] the experimental procedure was carried out and OPC-43 (UltraTech Cement) was used for the investigations. Normal river sand was used for both control and normal mix concrete which confirms the test of IS 383:1970 [19]. The study used coarse aggregates with 10 and 20 mm diameters tested according to the IS 383:1970 [19] requirements. The first mix design experiments were carried out in line with the IS 10262:2009 [20], and the various material property are shown in Table 1. Also, the mix proportion was calculated by referring the IS 10262:2009 [20] code book standards and listed in Table 2.

This study looked at the possible benefits of utilizing smaller amounts of self-healing chemicals, as previous studies had shown. The details of various mix specifications are listed in Table 3. Under the Water/Cement (W/C) ratio of 0.45, the self-healing dosage level was adjusted from 0.1% to 0.5% of the cement weight. The experimental study in Trial I, healing agent of silica gel was used at concentrations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% by weight of cement. During the final stage of concrete mixing process, the encapsuled glasses were inserted to avoid the damage of silica gel. In the second trial of experiment, for self-healing agent *Bacillus subtilis* bacteria was used in 0.1% to 0.5% with weight of cement. It was chosen because of spore-forming solid capability and resistance to severe environmental conditions. *Bacillus subtilis* spores were isolated and then diluted with distilled water to attain

Fig. 4 Light weight aggregate and Bacillus subtilis dispersion

Table 1 Characteristics of the materials

Type of property	Results obtained
Sp. Gravity of Cement	3.51
Sp. Gravity of FA	2.14
Sp. Gravity of CA	2.62
Water Absorbance of FA	1.2%
Water Absorbance of CA	0.48%
Moisture level of FA	2.16%
Moisture level of CA	0.3%
Bulk Density (FA)	1396 kg/m^3
Sand grade	Zone II – Confirmation

CA: Coarse Aggregate, FA: Fine Aggregate

Table 2 Mix proportion

Material	Calculated amount	Level of proportion
Water	186 l/m3	0.45
Cement	394.54 kg/m3	1
FA	678.21 kg/m3	1.72
CA	1124.54 kg/m3	2.84

* The assumption made in this study was that the quality control was of a high standard, and the exposure conditions were considered severe.

Table 3 Specifications of various mixes

Details of specimen	ID number	Amount of healing agent in %
Normal mix	Control specimen	0
SGC mix	SGC A	0.1
	SGC B	0.2
	SGC C	0.3
	SGC D	0.4
	SGC E	0.5
BSC mix	BSC F	0.6
	BSC G	0.7
	BSC H	0.8
	BSC I	0.9
	BSC J	1.0

the precise quantity needed for integration with carrier materials. This measure was taken to ensure the bacteria's safety and effectiveness during the concrete mixing process. To keep the bacteria alive, the carrier elements of light weight aggregates or graphite nano-particles were used in the concrete mixture. Carrier materials are critical for the operational lifespan of microorganisms within the concrete matrix. Ayub et al. [21] showed a technique for encasing the healing agent by covering impregnated porous LWAs with cement paste. The lightweight aggregates (LWAs) stayed incorporated within the concrete matrix and performed similarly to conventional aggregates, with no noticeable flaws once the healing agent was released. Using a protective matrix for live organisms can improve the viability and efficacy of healing agents in the self-healing process. All experimental attempts using bacterial mixtures in this study involved inserting *Bacillus subtilis* into lightweight aggregates as carrier components.

Tables 4 and 5 include information on the specimens used to test mechanical strength properties. The workability of fresh concrete was evaluated using the IS 1199:1991 [22] compaction factor test, and the findings are shown in Table 6.

For medium to high workability, both the control and self-healing were revealed with the workability tests. Furthermore, because of the low self-healing agent's ratio, there were only minor differences in the workability values across the various self-healing mixtures. It is critical to handle the mixing and placing of capsules with care to guarantee uniform dispersion of the healing agents inside the cement matrix since this substantially influences the healing process's efficiency.

Table 4 Test specifications of silica gel-based materials

Amount of silica gel in %	Test specimen (Cube)	Test specimen (Cylinder)	Test specimen (RCC beams)
0.1	3	3	1
0.2	3	3	1
0.3	3	3	1
0.4	3	3	1
0.5	3	3	1
Trial specimen	3	3	1
Total specimens	18	18	6

Table 5 Test specimen details of Bacillus subtilis

Starting level of dosage for cube in % for 3 specimens	Next level of dosage for cube in % for 3 specimens	Dosage for Cylinder in % for 3 specimens	Dosage for RCC beams in % for 1 specimen
0.1	0.6	0.6	0.6
0.2	0.7	0.7	0.7
0.3	0.8	0.8	0.8
0.4	0.9	0.9	0.9
0.5	1.0	1.0	1.0

Size of cube = 150 × 150 × 150 mm
Size of cylinder = 150 × 300 mm
Size of RCC beam = 150 × 200 × 210 mm

Table 6 Results for workability of concrete

Details of the specimen	ID number	Dosage level in %	Compaction factor value
SGC mix	SGC A	0.1	0.92
	SGC B	0.2	0.92
	SGC C	0.3	0.94
	SGC D	0.4	0.94
	SGC E	0.5	0.95
BSC mix	BSC F	0.1	0.91
	BSC G	0.2	0.91
	BSC H	0.3	0.92
	BSC I	0.4	0.93
	BSC J	0.5	0.93

*Normal mix compaction factor value is 0.91

3 Experimental investigations for harden concrete

The mechanical characterization of normal concrete mix and silica gel-based healing concrete with *Bacillus subtilis* was evaluated as per the Indian Standards (IS 516:2004) [23]. The following experimental studies were conducted to check the various properties of the concrete mixes.

3.1 Compressive strength of concrete

The typical concrete elements were properly mixed to preserve the mixture's water-cement ratio. Special care was taken to ensure the silica gel capsules were distributed evenly throughout the mixture. The mixture was poured into the moulds in 5 cm deep layers. The cube moulds were kept at room temperature for 24 hours before being moulded and immersed up to 28 days for curing. To avoid the pre-cracking, the cured concrete specimens were dried for 24 hours. The concrete specimens were placed into the compression testing equipment with a loading rate of 140 kg/cm^2/min, ensuring an even distribution of weight across the opposing faces of the cube, consistent with their initial formation. Loading proceeded until a slight fracture could be seen with the naked eye. The maximum load of failure and the healing agent's ability were evaluated by submitting the specimens to the compression testing machine after seven days of exposure to the environment.

3.2 Split tensile strength of concrete

As per IS 516:2004 [23], the split tensile strength of the concrete was calculated using the cylindrical specimens with the size of 150 mm × 300 mm. The tests complied with the IS 5816:1999 [24] requirements. The top and bottom plates on the compression testing machine was aligned and the specimen was centered between the loading surfaces. Thin sheets were placed at top and bottom sides of the specimen and loading patterns to ensure uniform load distribution and prevent the development of significant compressive stresses around the points of load application. This measure was taken to maintain consistent and reliable testing conditions. Gradual loading rate of 1.4 N/mm^2/min was applied into the entire cylinder length without any abnormal impact. The application of load has been continued until a noticeable crack formation on the concrete surface. After 7 days of ambient exposure, the load was applied into the specimens and the failure load was obtained. Because of the indirect tensile stress, the specimens were split in half along its vertical axis and this was developed due to the Poisson's effect.

The splitting tensile strength of a specimen was estimated as follows:

$$\text{Split tensile strength} = \left(0.64\ P\right)\big/DL\left(N/\text{mm}^2\right), \qquad (2)$$

where:

- P is denoted by compressive load in N,
- L is denoted by length of cylinder in mm,
- D is denoted by diameter of cylinder in mm.

3.3 Flexural strength of concrete

The flexural strength and self-healing capabilities of reinforced concrete beams were also investigated. Fig. 5 shows the specifics of the reinforcement employed in these beams. The reinforced concrete beams have dimensions of 2,100 × 200 × 150 mm. After 24 hours, the beams were demolded and stored in water for 28 days to cure. The following approach was used to assess flexural strength: IS 516:2004 [23]. The specimens should be cured under standard conditions, usually in water, for a specified curing period, which is often 28 days. Once the curing period is complete, the test specimens are placed horizontally on two symmetrical supports. These supports should be placed such that they are at a specific distance apart from each other, which is often four times the depth of the specimen. A load is applied at the midpoint of the specimen, using a loading machine, in a vertical plane. The load is gradually increased at a specified rate (usually 50 N/mm^2 per minute) until the specimen fails (cracks or breaks). During the test, you measure the maximum load at which the specimen fails and the corresponding mid-span deflection. The results of the test help in assessing the quality of the concrete and its ability to withstand bending stresses, which is important in structural applications like beams and slabs. It's essential to follow the standard procedures and conditions carefully to ensure accurate and consistent results in the flexural strength test of concrete.

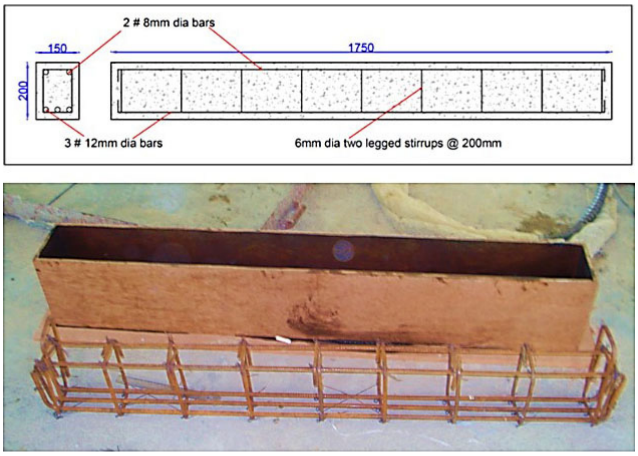

Fig. 5 Details of reinforcement for planned flexural member

3.4 Modulus of elasticity of concrete

The modulus of elasticity, also known as Young's modulus, is a measure of a material's stiffness and its ability to withstand deformation under an applied load. In concrete, this parameter is important in structural design because it indicates how much a concrete element will deform under various loads. As per the IS 516:2004 [23], the specimens with the size of 150 mm × 300 mm cylindrical shape were used to examine the elasticity modulus of concrete mix.

These specimens should be of the same concrete mix that you are testing. These specimens are often made from the same concrete used for cubes and cylinders in other tests. The compress meter was placed on the test specimens and fitted with a universal testing machine. The dial gauge on the compresso-meter is set to zero. The specimen is subjected to a compressive load in the UTM at the rate of 140 kg/cm^2/min. The load is applied until the average stress on the specimen reaches $(C + 5)$ kg/cm^2 and the extensometer reading are recorded at common intervals after the load reached to the average stress. These readings capture the deformation or strain in the concrete specimen as the load is applied and removed. The modulus of elasticity (E) is calculated by plotting the load versus the deformation data obtained from the extensometer readings. The slope of the resulting stress-strain curve within the elastic range (usually linear) is used to determine the modulus of elasticity. The modulus of elasticity is expressed in units of stress, such as N/mm^2 or MPa. It represents how much stress or load the concrete can endure for a given amount of deformation and is essential for structural analysis and design. By following the procedures outlined in IS 516:2004 [23], we can accurately assess the modulus of elasticity of the concrete under investigation.

4 Results and discussion

4.1 Compressive strength

It is an essential criterion in determining the quality of concrete. It assesses the capacity of concrete to bear axial loads, such as those found in buildings and other structures. The compressive strength test findings for SHC finished with different doses of self-healing agent are interpreted as follows. According to Table 7 and Fig. 6, the self-healing concrete with different doses self-healing material (SGC) revealed a 30% drop in strength compared to the control concrete. The presence of capsules with gels of silica are responsible for the drop in strength. The goal of such self-healing concrete is not to surpass the original strength of the control concrete but to recover some of the strength lost due to cracks [25]. In this case, the self-healing process was able to recover approximately 70% of the strength reduction caused by the initial crack. The findings suggest that the inclusion healing agent into the concrete, represented as SGC specimens, had a notable impact on the strength of the concrete. Compared to the control concrete, the SGC specimens initially showed a 30% drop in strength. The existence of capsules and fracture development may temporarily weaken the concrete, which is usual when self-healing processes are involved [26]. The SGC specimens showed a considerable improvement in strength after allowing the self-healing mechanism to occur throughout the curing phase. The strength of the concrete improved by 21% compared to the control concrete. This implies that utilizing healing agent not only mitigated the effects of concrete cracks but also considerably enhanced the compressive strength of the concrete.

Table 7 Self healing concrete (Silica gel) compressive strength values

Specimen	Silica Gel dose in %	Compressive strength – 28 days before the healing period in N/mm^2	Compressive strength – 7 days after the healing period in N/mm^2
SGC A	0.1	28.75	40.61
SGC B	0.2	26.58	45.42
SGC C	0.3	26.12	50.28
SGC D	0.4	21.83	48.38
SGC E	0.5	27.94	39.86

*Normal mix – compressive strength = 36.89 N/mm^2

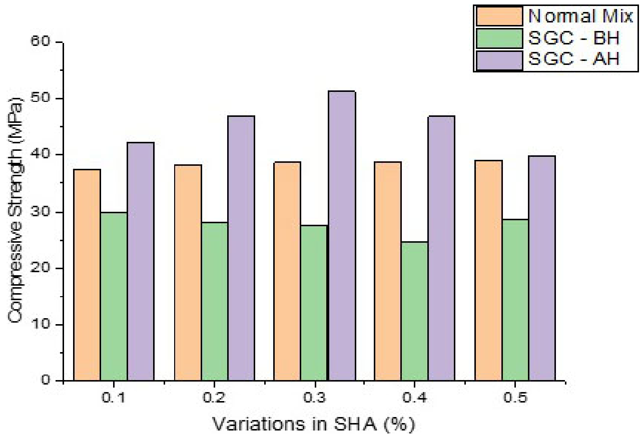

Fig. 6 Observations of variations in compressive strength by varying silica gel from 0.1–0.5% (BH: Before Healing and AH: After Healing)

According to the findings of Jena et al. [27], using 0.3% healing agent gives with deliberately created cracks in concrete resulted in the complete restoration of the material's maximal strength. A 70% increase in compressive strength was noticed for self-healed concrete specimens compared with non-healed concrete specimens. This significant increase may be due to the polymerization process promoted by silica gel, which is the fundamental mechanism responsible for the healing of concrete fractures and, as a result, improving its strength qualities [28]. Its use not only helps to heal cracks but also significantly increases the overall strength of the concrete. The study's findings strongly support the use of silica gel to improve the durability and performance of concrete buildings. More than 50%

of the strength was recovered while using the Polyurethane encapsulated in capsules as a self-healing material. The process of self-healing was increased due to the excess amount of self-healing hydration and its cementing and crystallization characteristics. The healing agents have some unreacted components found within the cracks, and these repairs the cracks continuously for an extended time. The concentration of silica gel goes more than 0.3%; the strength was decreased, showing that the 0.3% silica gel SHC specimen appears to be the ideal concentration. Exceeding this optimal level is detrimental and reduces the strength qualities of cementitious composites. The self-healing with *Bacillus subtilis* bacterial concrete specimen's compressive strength were found and listed in Table 8.

The original *Bacillus subtilis* microbe dose varied from 0.1% to 0.5%, similar to the strategy employed in silica gel self-healing concrete. The results show that self-healing concrete (BSC) based on *Bacillus subtilis* has advantageous self-healing capabilities; nevertheless, the gain in strength was negligible. Compared to control concrete, self-healing concrete mixtures based on *Bacillus subtilis* had lower strength throughout both observation times, before and after healing. While concrete fractures were effectively repaired, a significant strength enhancement is critical for assuring structural parts' lifespan [29]. Due to this reason the amount of microbes has been increased (*Bacillus subtilis*) from 0.6 to 1.0% in the concrete mix. The results obtained by varying the level of self-healing agent was shown in Fig. 7 and Table 9 respectively. Compared to first stage of concrete mix, the second stage of self-healing concrete with *Bacillus subtilis* has improved average strength by 20%. A comparison between SHC holding silica gel with and without microbes was shown in Fig. 8. The increase in compressive strength after the second set of SHC with microbes (*Bacillus subtilis*) mixes appear small associated to the control specimens, it is nevertheless much better than first set of BSC concrete mixes. It's worth noting that SHC with microbes typically shows a minor progress in

Table 8 *Bacillus subtilis* compressive strength values

Specimen	Silica gel dose in %	Compressive strength – 28 days before the healing period in N/mm^2	Compressive strength – 7 days after the healing period in N/mm^2
BSC F	0.1	22.45	28.64
BSC G	0.2	22.08	29.57
BSC H	0.3	22.55	30.08
BSC I	0.4	24.83	30.54
BSC J	0.5	25.64	31.15

*Normal mix – compressive strength = 17.54 N/mm^2

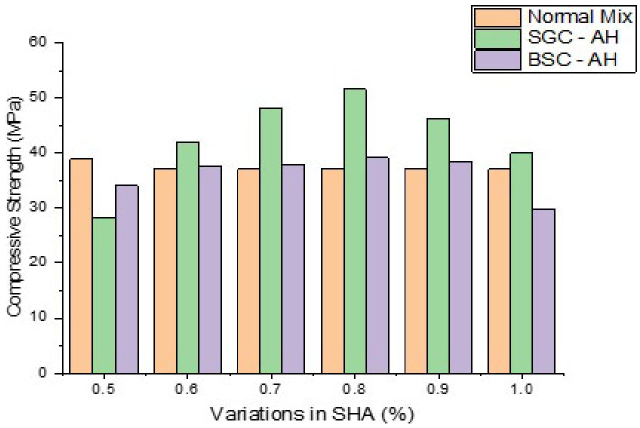

Fig. 7 Observations of variations in compressive strength by varying microbes (*Bacillus subtilis*) from 0.1–0.5% (BH: Before Healing and AH: After Healing)

Table 9 *Bacillus subtilis* compressive strength values

Specimen	Silica gel dose in %	Compressive strength – 28 days before the healing period in N/mm^2	Compressive strength – 7 days after the healing period in N/mm^2
BSC F	0.6	31.24	36.11
BSC G	0.7	31.68	36.54
BSC H	0.8	33.81	39.26
BSC I	0.9	32.04	36.29
BSC J	1.0	29.54	30.05

*Normal mix – compressive strength = 36.14 N/mm^2

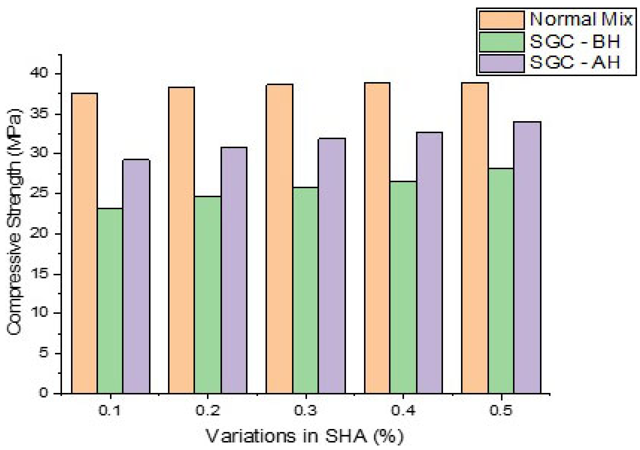

Fig. 8 Observations of variations in compressive strength by varying microbes (*Bacillus subtilis*) from 0.5–1.0% (BH: Before Healing and AH: After Healing)

compressive strength than control concrete. Furthermore, studies have indicated that the strength of microbial SHC may decrease after 28 days of curing.

4.2 Split tensile strength

The specimens were broken using compression testing equipment in both cases and following a week of self-healing in ambient atmospheric conditions, they were examined again to determine strength recovery. The spilt tensile curve for self-healing concrete with *Bacillus subtilis* was shown in Fig. 9 and the self-healed concrete has a 15.4% improvement in strength over the pre-healed concrete. Compared to the first series of *Bacillus subtilis* concrete mixes, the second series of mixes has 30.8% increase on average, indicating the extraordinary performance of self-healing concrete. The study findings are consistent with those of Sangadji et al. [29], who showed a 15% or more increase in average strength in *Bacillus subtilis*-based concrete. This increase in strength can be due to the more significant proportion of $CaCO_3$ deposition enabled by microorganism cell surfaces inside the concrete mortar matrix [30].

According to the experimental findings, the silica gel, *Bacillus subtilis* and silica gel agents can improve the strength and durability of concrete via their self-healing processes. However, compared to the BSC series of mixes, the efficacy of SHC is rather excellent. Indeed, the polymerization action of self-healing agent revealed improved durability performance when compared to *Bacillus subtilis*-induced $CaCO_3$ precipitation in concrete. Research suggests that bio-organism-based concrete faces certain challenges, primarily because of the compassion of the microbes and the types of subsidiary chemicals used in the mixture. These factors can affect the effectiveness and reliability of bio-organism-based self-healing concrete.

4.3 Modulus of elasticity

Fig. 10 shows the graphical representation of silica gel-based concrete and Table 10 represents the modulus of elasticity values obtained by referring IS 516:2004 [23].

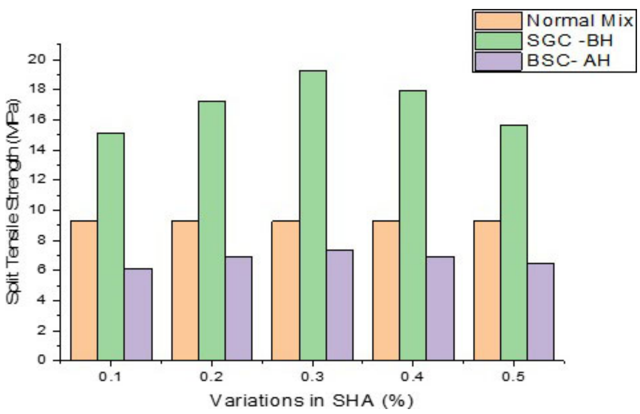

Fig. 9 Observations of variations in split tensile strength by varying microbes (*Bacillus subtilis*) and silica gel from 0.1–0.5% (BH: Before Healing and AH: After Healing)

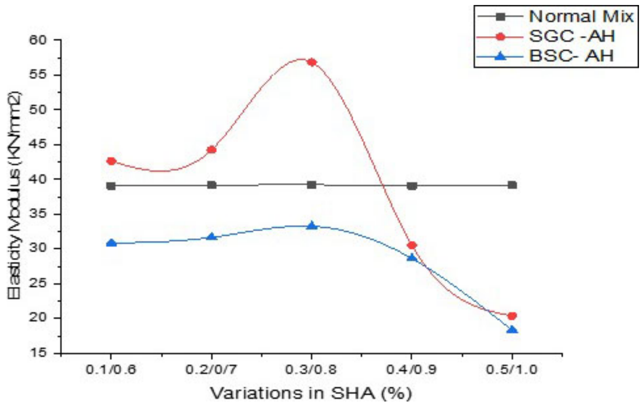

Fig. 10 Relationship of silica gel vs. *Bacillus subtilis* microbe concrete in elasticity modulus observations (AH: After Healing)

Table 10 Test results of concrete mix – Modulus of elasticity

Details of the specimen	ID number	Dosage amount in %	Modulus of elasticity (kN/mm^2)
	SGC A	0.1	41.2
	SGC B	0.2	43.6
SGC mix	SGC C	0.3	55.1
	SGC D	0.4	32.4
	SGC E	0.5	21.8
	BSC F	0.6	29.6
	BSC G	0.7	31.2
BSC mix	BSC H	0.8	33.4
	BSC I	0.9	28.2
	BSC J	1.0	19.7

*Normal mix concrete – Modulus of elasticity = 38.2 N/mm^2

Compared to the normal mix, 0.3% of silica gel-based concrete has 36% in modulus of elasticity. This silica gel % outperformed others in terms of self-healing and strength enhancement. Polymer-based self-healing materials, in general, have the intrinsic potential to regain load-carrying properties after damage. Polymeric materials' cross-linked ion bonds fill the fractures and connect, critical in restoring the original structural strength throughout the healing process [31]. Lower modulus values were detected in concrete mixes where *Bacillus subtilis* was utilized as the healing agent throughout all substitution ranges compared to control specimens. This shows that microbial organisms' ability to cure themselves is strongly reliant on metabolic alterations that result in the development of critical calcite precipitates. Although these changes are not substantial enough to significantly affect the modulus of concrete, they do have an effect on the strength qualities of the concrete mixes [32]. It's worth mentioning that several studies have found that lower permeability caused by fracture healing is a vital part of improving the durability of concrete mixtures.

4.4 Flexural strength of concrete

Fig. 3 shows the beam specimens made by concrete mix that were casted during the initial period and underwent four weeks (28 days) of curing process. They were then subjected to pressure using a testing frame, resulting in the development of the initial crack. Subsequently, they were permitted to cure in natural ambient air for a period of one week. The specimens were then exposed to another round of testing, and the flexural strength test results were obtained. The data of load vs deflection for healing agent of silica gel with RCC beams was shown in Fig. 11 (a) to Fig. 11 (e). Similarly, the data of load vs deflection for RCC beams with *Bacillus subtilis* bacteria was shown in Fig. 12 (a) to Fig. 12 (e). The results show that the flexural strength of the self-healed specimens that employed silica gel increased significantly when compared to their state before the formation of cracks. By substituting 0.3% of healing agent in the flexural members, the most notable strength gain in self-healing concrete was roughly twice as great as that in regular concrete beams. Around 70% of the average flexural strength gain was observed compared with control mix and specimens with silica gel-based mix. Concrete beams containing *Bacillus subtilis* recovered from fractures as well, albeit the strength achieved by these *Bacillus subtilis*-based concrete (BSC) specimens was marginal in comparison to the control specimens. This gap might be attributable to fluctuations in $CaCO_3$ precipitation levels promoted by living organisms throughout the healing process. The sodium silicate was used as a self-healing agent, and no adverse effect on the mechanical characteristics of concrete was observed [32]. They observed around 50% of rise in flexural strength was observed compared to the normal mix concrete. Furthermore, the study reported that, in addition to improvements in crack-healing performance, there were gains in strength and durability in structures that utilized healing agents. The study also found that the self-healing mechanism could mend cracks with widths of approximately 1 mm. This improvement in concrete technology could boost structural efficiency and lengthen infrastructure service life. For preventing corrosion, capsule-based self-healing technology is recommended, particularly in maritime constructions. Also, the mechanical property of concrete mix was improved with the constant application of silica gel in the specimens.

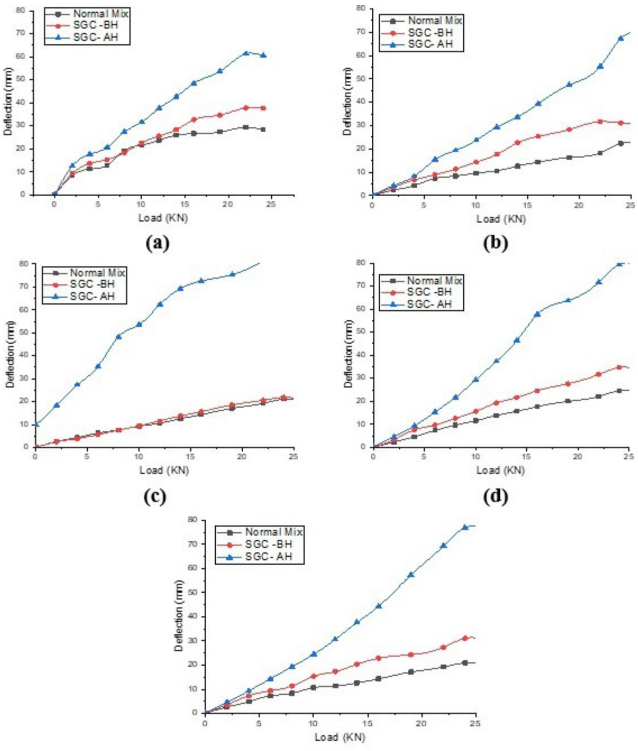

Fig. 11 Flexural strength of concrete specimens with silica gel replacement of (a) 0.1%, (b) 0.2%, (c) 0.3%, (d) 0.4% and (e) 0.5% with weight of cement respectively

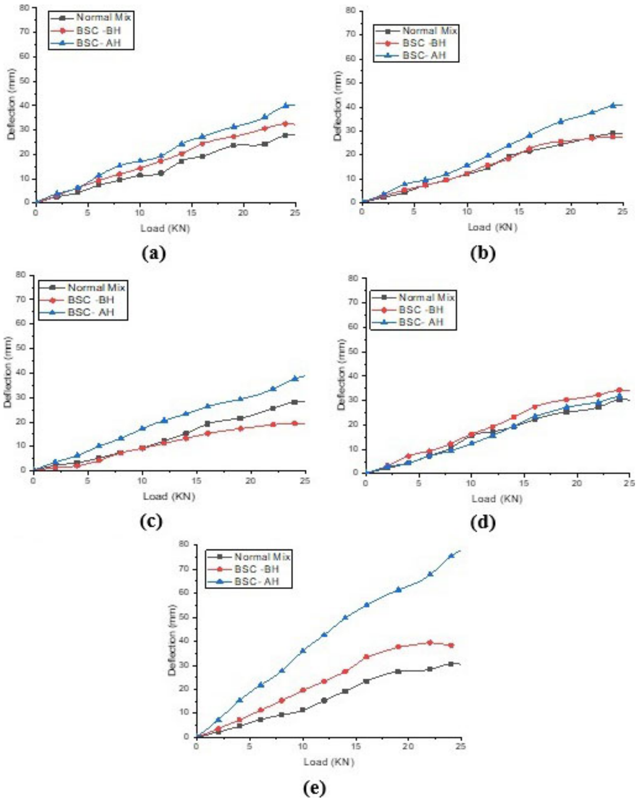

Fig. 12 Flexural strength of concrete specimens with *Bacillus subtilis* replacement of (a) 0.6%, (b) 0.7%, (c) 0.8%, (d) 0.9% and (e) 1.0% with weight of cement respectively

The RCC beams with self-healing agent (Silica gel) not only increases the strength of the concrete but also enables the self-repair of fractures that may form over the service life of structures. As per the study, bacterial concrete represents a multidisciplinary subject, and it is essential to promote interdisciplinary research to assess the hands-on experience of SHC created on microbial agents. This approach aims to explore the real-world implications and challenges of utilizing microbial agents for self-healing concrete. This strategy seeks to capitalize on the potential of self-healing concrete in real-world applications while addressing the barriers to general implementation. This experimental study aims to assess the distinct characteristics of self-healing agents, including their effectiveness, optimal dosage, and their ability to reestablish the strength of various structures during the healing process. By making such comparisons, we may get vital insights into the practical uses and limits of these self-healing materials, which will help to advance the area of self-healing concrete technology.

4.5 Micro-structural analysis

The investigations of the bacterial concrete and normal concrete mix by SEM are shown in Fig. 13 (a) and (b) respectively. Fig. 13 (a) shows the many free surfaces and the normal concrete mix to allow the particles to settle down on its top surface. Furthermore, the Tetrahedron and pyramid formations are seen in Fig. 13 (b), to specify the presence of calcite in bacterial concrete. It indicates that calcite has been deposited into the pores in the concrete mix, increasing the material's strength and longevity [33]. The EDX spectrum of the normal and bacterial concrete mix was seen in Fig. 13 (c) and (d) respectively. Referring to Fig. 13 (d), the bacterial concrete yields a greater quantity of calcium than control concrete. The elemental analysis verifies that the bacterial concrete contains a greater concentration of calcium. $CaCO_3$ is confirmed to be present in bacterial concrete by SEM and EDX investigations. This strengthens and extends the life of concrete by plugging pores and small spaces in the material. After the fissures had healed, an XRD study was performed on the material that had been deposited there. The normal concrete mix and bacterial concrete mix and its XRD analysis is displayed in Fig. 13 (e) and (f) respectively. Compared to the normal mix, the crystalline peaks are seen to be present at angles (2θ) of 28.4°, 33.5°, 40°, and 48.2°. The material's calcite content is shown by these peaks. After the cracks are healed, bacteria produce calcite, which gives concrete its increased strength and longevity.

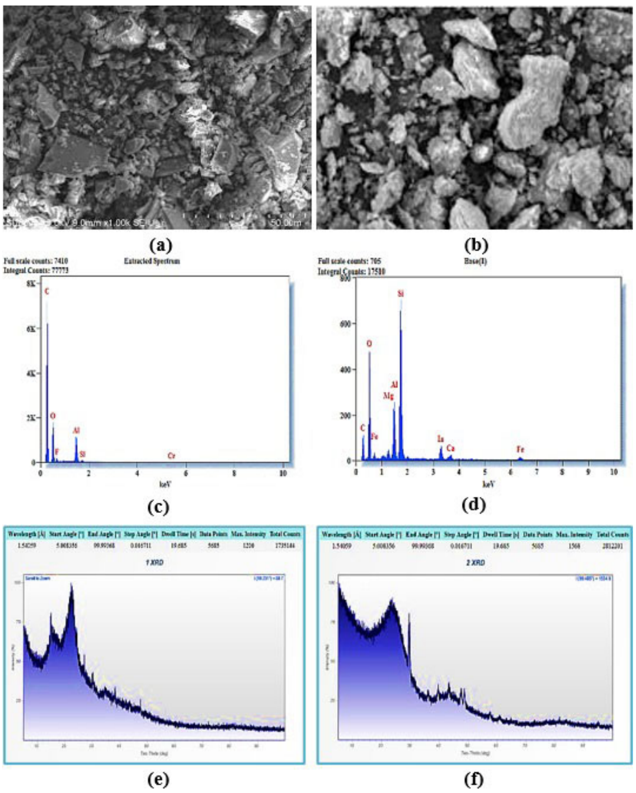

Fig. 13 Microstructure analysis of self-healing concrete by (a) Normal mix and (b) Bacterial Concrete, by EDX for (c) Normal mix and (d) Bacterial Concrete and by XRD for (e) Normal mix and (f) Bacterial concrete respectively

5 Conclusions

Self-healing agents, notably capsules in micro level from silica and microbes (*Bacillus subtilis*) were present in the concrete specimens utilized in this study at quantities ranging from 0.1% to 0.5%. The self-healing abilities of these agents, as well as their impact on concrete strength parameters, were thoroughly investigated. When silica gel was replaced at 0.3%, the concrete mixes displayed favorable strength. The concrete's self-healing capacity was remarkably effective at this dose. Within the required dose range, the concrete mixes displayed good self-healing capacity in *Bacillus subtilis*. However, the increase in strength in these concrete mixtures was slight. These findings contribute to creating more robust and durable concrete buildings by providing significant insights into the ideal dose of self-healing agents in concrete mixes to achieve the necessary balance of self-healing capabilities and strength characteristics. A comparison investigation revealed that the altered dosage of self-healing bacteria resulted in a considerable improvement in strength. Fluosilicate curing material within the microcapsules contributed to the strengthening effect, which was especially noticeable. For example, as compared to the specimen's pre-healing condition, the crushing power of the SHC specimen with

0.3% silica gel improved by an impressive 70%. The average strength enhancement for concrete mixtures, including *Bacillus subtilis* (BSC), was around 20%, consistent with earlier research. Crucially, both formulations of self-healing concrete succeeded in restoring split tensile strength. The microbial (*Bacillus subtilis*) concrete has very lower split tensile strength compared to the self-healing concrete produced with silica gel. The strength qualities of concrete have been improved based on the experimental findings of the usage of various self-healing agents. Around 36% improvement in modulus of elasticity was observed using the silica gel-based concrete mix related with the normal concrete mix. However, when the modulus of healed specimens was compared to the control concrete following induced cracks, there was no significant increase in values. This shows that microbial cell precipitation of $CaCO_3$ is insufficient to increase the modulus of elasticity. In addition, the healing performance of 2.1 m long RCC beams was examined by flexural rigidity process. Approximately 50–70% of the cracks were healed in the specimens and these beams exhibited a remarkable strength enhancement compared to their condition before the healing process. This highlights the potential of self-healing concrete to significantly improve the strength and durability of concrete structures when subjected to cracks. These findings emphasize self-healing concrete's significant potential for improving the modulus and strength characteristics of concrete structures, particularly in the context of induced fractures. When the strength of concrete specimens after healing was compared to the identical specimens before healing, it was discovered that the concrete mix containing 0.3% silica gel produced the most significant strength gain, around 67.8%. These increases in mechanical strength qualities are consistent with prior study findings. More than 50% of strength improvement was identified in self-healing mechanisms compared to normal mix based on this research work. *Bacillus subtilis* showed efficacy in repairing fractures inside concrete components, consistent with earlier study findings. These findings highlight the potential of self-healing chemicals, particularly silica gel, to significantly improve the strength of concrete buildings with cracks. Self-healing concrete has two key advantages: improved structural performance and increased structural resilience. While the significant purpose of SHC is to repair fractures, the strength of the repaired buildings must also be significantly increased. Based on the findings of this research, silica gel proves to be a highly effective self-healing agent in concrete mixes, consistently enhancing the mechanical properties across all the parameters investigated. This study highlights the ability of self-healing agent (Silica gel) and its capable of not only fixing fractures but also significantly boosting the strength and longevity of concrete buildings. As a result, it is advised that concrete constructions prioritize both strength increase and crack-healing performance. The above experimental study concludes and recommended the *Bacillus subtilis* self-healing agent can be extensively used for constructions where less maintenance is required and crack self-healing process. This is owing to its constant efficacy in repairing cracks and improving structural strength.

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