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Analyzing Self-healing Concrete as a Remedial Measure for Repair and Maintenance of Buildings

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Abstract Crack formation in concrete is a problem that can hardly be totally prevented because of shrinkage responses of setting concrete and tensile stresses that arise in built-up structures. The integrity of a building may be compromised by larger cracks, necessitating repair work, while tiny cracks, frequently with a crack diameter of less than 0.2 mm, are typically seen as unproblematic. Even tiny, sub-millimeter-sized cracks may cause durability issues because connected cracks specifically increase matrix permeability, which erodes structural integrity similarly to bigger fissures. This is due to the fact that routine manual maintenance and repair of concrete structures are costly and occasionally even impracticable, making an autonomous self-healing repair mechanism particularly beneficial. This may result in less maintenance and longer material lifespan. The paper presents a comprehensive examination of the natural, chemical, and biological processes involved in self-healing concrete technology. The literature review has been explored through internet and secondary data from relevant published academic literature from journals articles and research papers. This paper enables an understanding of the fundamental mechanism and operation of self-healing concrete in repairing the cracks in the buildings. The paper also examines the advantages and disadvantages of self-healing concrete, which formulates the comparison criteria using this concrete technology in the building industry. Finally, a comparative cost analysis of conventional concrete and self healing concrete has been done.

Keywords Self-healing Concrete, Chemical Self-Healing, Biological Self-healing, Remedial Measure, Repair, Maintenance, Buildings

1. Introduction

The most popular building material is concrete. Concrete will eventually crack because it is brittle in tension but resilient in compression. If cracks begin to appear in concrete, its lifespan can be limited, because they provide a route for water and other potentially harmful things to enter. Concrete pores and cracks are very unfavorable because they reduce the concrete's strength and durability and cause the reinforcing to corrode. The fractures can be repaired using a variety of methods, but they are costly and time-consuming. Self-healing is a suitable concrete technology for fracture repair on its own. This bacterial remediation technology surpasses alternatives since it is bio-based, environmentally safe, effective, and long-lasting. Concrete is an alkaline substance, thus any bacteria given to it must be able to withstand the alkali environment. Most microorganisms pass away at a pH value of 10, and concrete has an alkaline pH. The addition of microorganisms with a calcium nutrition source occurs as the concrete is being blended. If the concrete has any flaws, bacteria will precipitate as calcium carbonate. The fractures will afterwards be sealed. It has been demonstrated that the precipitation of calcium carbonate (calcite) is influenced by the urease enzyme produced by urease-positive bacteria. As a result, the pH of the precipitated calcite rises. Although treating larger fractures is more difficult, when bacteria are used, cracks may close with calcite precipitation. Bacillus megaterium, Bacillus pasteurii, Bacillus sp. CT-5, Bacillus subtilis, Bacillus aerius, Sporosarcinapasteurii, AKKR5, Shewanella Species, and Bacillus flexus are a few examples of the "Urease Positive Bacteria". The bacteria-based self-healing material is designed to be able to hibernate under the concrete for up to 200 years. Concrete fissures allow bacteria to flourish when they come into contact with water and oxygen. Recently, self-healing techniques have shown promise in mending fractures that are still growing. The fissures shouldn't be deeper than 150mm for the greatest outcomes [1]. Concrete cracks larger than 0.8 mm are more difficult to fix utilizing self-healing techniques that use bacteria and a calcium nutrient source added to the concrete during mixing.

2. Process Involved in Self-healing Concrete

There are three different ways that self-healing concrete can repair itself: naturally, chemically, and biologically.

2.1. The Natural Process

This process can partially fix the cracks in concrete, and it is divided into the following four techniques:

(a) Formation of $CaCO_3$ or CaOH (calcium carbonate or calcium hydroxide)
(b) Impurities in the water's transportation cause a crack to be blocked.
(c) Hydration of the unreacted cement makes the crack much more difficult to open.
(d) The prevention of cracking is achieved by the expansion of the hydrated cementitious pattern in the crack loins (such as the lump of calcium silicate hydrate gel).

The simultaneous occurrence of several of these processes can be considered a multiple event. It's possible that the majority of these systems are unable to entirely seal off the holes of some fractures, only being able to do so partially. This will help slow the development of fractures and stop corrosive substances like acids from penetrating the structure from the inside. Calcium carbonate and calcium hydroxide configurations are the most popular and successful self-healing techniques for concrete that are inspired by natural processes [2].

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + NCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad \text{Equation (i)}$$

As a result of cement hydration and dissipation, loose calcium ions are released into concrete, and these ions are mitigated by NCO_3^- and CO_3^{2-} at cracking surfaces. As a result, calcium carbonate crystals form. Reactions (ii) and (iii) may occur only at pH values greater than or equal to 7.5. Crystals form along the surface of the fractures and eventually permeate the space [2].

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \quad \text{Equation (ii)}$$

$$Ca^2 + HCO_3^- \leftrightarrow CaCO_3 + H^+ \quad \text{Equation (iii)}$$

2.2. The Process of Chemical Self-healing

The chemical self healing is a term that refers to artificial healing which uses the chemical composites. The chemical liquid reagents (glue) are mixed with fresh concrete in small containers to create self-healing concrete. There are two different kinds of chemical reactions: Hollow pipettes and vessel networks filled with glue, and Encapsulated glue.

2.3. The Biological Process of Self-healing

Microorganisms can be found in many locations. They can be discovered in trash from industry, acidic hot springs, oil, soil, and water. Bacteria, fungi, and viruses make up the three primary categories into which microorganisms are typically divided. The genetic self-healing is made tangible with the usage of these microbes. These bacteria are employed to create the concrete because certain of them can produce specific compounds. Microorganisms can be added to the biological self-healing concrete in a variety of ways. These include the chemical process for exchanging microorganisms, which describes the direct application of microbial brew to new concrete configurations. Concrete's pH, temperature, and moisture level are often not favorable for bacterial development. As a result, rather than using fresh microbial broth, the resistant kind of bacteria (spore) is used in certain circumstances. Encapsulated microbes, on the other hand, may be used to withstand the severe conditions of concrete. Both the precipitation of calcium carbonate and the precipitation of polymorphic iron aluminium silicate fall under this group of biological processes. These procedures are often carried out by bacteria or fungus, and aside from these, two different types of microorganisms play a significant role in self-healing processes i.e. Mesophilic microorganisms and Thermophilic microorganisms, which are further divided into Aerobic and Anaerobic microorganisms [2].

3. Typologies of Self-healing Concrete

3.1. Concrete with Autogenous Self-healing

An additional binder, higher calcium hydroxide carbonation, and increased concrete hydration are all necessary for the bulk of autogenous self-healing to occur. It blocks cracks by waste and carbonation of CaOH. Both the continual hydration of clinker minerals cracks and crack flanks cause the hydrated concrete matrix to expand.

3.2. Concrete with Autonomous Self-healing

The concrete with Autonomous self-healing was fully dependent by a physical process. The phrase 'autonomous self-healing' has been used to refer to this phenomenon. There are many processes which include the vascular method; the capsule process; the bacterial process method; the electro-deposition process; the shape memory alloy process method and the microwave process.

3.3. The Environmental Impact of Self-healing Concrete

Self-healing concrete minimizes the quantity of carbon dioxide released into the atmosphere as a consequence of concrete manufacture. This is because concrete manufacture is energy demanding in several ways, especially when transportation, mining, and concrete plants are taken into account. However, industries are the primary sources of carbon dioxide emissions in India, accounting for around 8% of total emissions. To increase the lifetime of concrete as well as reducing maintenance, self-healing concrete will minimize the creation of surplus concrete, hence lowering carbon dioxide emissions in our environment [2].

3.4. Self-healing Concrete Mix Design and Composition

To understand the composition and mix design of self-healing concrete, an experiment was conducted based upon a comparative study between conventional concrete and bacterial concrete of the same grade (Table 1). The materials used were:

(a) Ordinary Portland cement of grade 53 as per IS: 12269-1987b [3].
(b) River sand was selected; it was determined to be zone-1 of IS: 383-1987a [4] and passed through a 4.75mm IS sieve. The specific gravity was measured to be 2.3.
(c) Coarse aggregate: 4.75mm IS sieves retain crushed stones up to 20 mm in size. It was found that the specific gravity was 3.13.
(d) Potable water for conventional concrete (e) Bacterial water, which contains 105 Bacillus megaterium cells per millilitre of water
(e) A thin metal sheet with a thickness of 0.3 mm is used to artificially fracture a sample of unhardened concrete to a depth of 10 mm.

Table 1. Mix design composition of M25 concrete using IS:10262-2009 and IS:456-2000 [5]

Ingredients	Cement	Fine aggregate	Coarse aggregate	Water
Quantity (Kg/m^3)	340	657.6	1335.94	171.7
Ratio	1	1.93	3.93	0.51

The design mix for conventional and bacterial concrete used was M25 grade with the ratio of 1:1.9:3.9 (cement: Fine aggregate: Coarse aggregate) having a water ratio of 0.51. For the bacterial concrete, the bacteria water substitutes an M25 concrete grade for the potable water. Now there is a need to identify a suitable bacterium that would sustain the alkali environment of concrete, hence there are certain bacteria that can be considered. They are Bacillus megaterium, Bacillus pasteurii, Bacillus sp. CT-5, Bacillus subtilis, Bacillus aerius, Sporosarcinapasteurii, AKKR5, Shewanella Species, Bacillus flexus etc. Bacillus megaterium precipitates the most calcite when compared to other urease-positive bacteria, improving compressive strength and crack-healing effectiveness the most [6].

3.5. Self-healing Concrete's Mechanism

There are 105 Bacillus megaterium cells in bacterial water per millilitre. The bacterium goes into a latent state and, when a crack occurs later, the bacteria get exposed to the air and water and begin to produce calcite crystals

The dense cell structure of these bacteria's spores permits them to survive for up to 200 years while they wait for the right conditions to germinate. Calcite precipitation is affected by bacteria decomposing urea via the bacterial urease enzyme. Urease, which catalyses the conversion of urea to ammonia and carbonate, is produced by bacteria during metabolism. Calcium carbonate is produced via the hydrolysis of these components, which also yield carbonic acid and ammonium chloride. The negatively charged, pH-neutral surface of bacteria is essential for the precipitation of calcite. The positive-charged calcium ion may mix with bacteria's surface, promoting nucleation [1]. The following chemical equations depict the formation of calcite crystals.

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (1)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \quad (2)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (3)$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^{+} + 2OH^{-} \quad (4)$$

$$HCO_3^{-} + H^{+} + 2NH_4^{+} + 2OH^{-} \leftrightarrow CO_3^{2-} + 2NH_4^{+} + 2H_2O \quad (5)$$

$$Ca^{2+} + Cell \rightarrow cell - Ca^{2+} \quad (6)$$

$$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCo_3 \quad (7)$$

4. Properties and Experimental Results

4.1. Self-healing Concrete's Compressive Strength

It was clear that bacterial concrete beat regular concrete in terms of compressive strength. It was discovered that bacterial concrete had a compressive strength that was 11.96% higher than regular concrete.

4.2. Absorption of Water

When compared to ordinary concrete, the bacterial concrete surface exhibits better water absorption due to the deposition of calcite on its surface. According to reports, there was a 0.45% drop in water absorption.

4.3. Permeability of Water

In comparison to regular concrete, the depth of water penetration in bacterial concrete is also less due to the sealing of micro pores by calcite.

4.4. Other Experimentation Results

The compressive strength of the concrete is improved compared to regular concrete by adding bacteria to it. (Table 2).

The compressive strength of conventional concrete was raised by 14.92% by adding *Bacillus subtilis* JC3. B-Sphaericus improved the compressive strength compared to conventional concrete by 30.76% after three days, 46.15% after 7 days, and 32.21% after 28 days [3].

Table 2. Comparative analysis of compressive strength of traditional and bacterial concrete

Days	Compressive strength of traditional concrete cubes, N/mm^2	Compressive strength of B-Sphaericus concrete cubes, N/mm^2	Percentage increase in strength
3	19.24	25.16	30.76
7	23.66	34.58	46.15
28	34.52	45.72	32.21

A material's ability to withstand a pulling (tensile) force is referred to as its tensile strength. As indicated in Table 3 [3], earlier studies have demonstrated that bacterial concrete has a better tensile strength than conventional concrete. The properties, experiments, and outcomes of self-healing concrete are shown in Tables 4, 5, 6, and 7.

Table 3. Comparative analysis of tensile strength of traditional concrete and bacterial concrete

Days	Compressive strength of Traditional conventional concrete cubes, N/mm^2	Compressive strength of B-Sphaericus concrete cubes, N/mm^2	Percentage increase in strength
3	3.78	4.30	13.75
7	4.62	5.28	14.28
28	4.85	5.74	18.35

Table 4. Different types of bacteria and their applications

Types of Bacteria	Application
B. pasteurtii	As a crack healer
Deleya Halophila	
Halomonasrurihalina	
Myxococcus Xanthus	
B. memgaterium	
B. sphaericus	For surface treatment
Bacillus subtilis	B. spharicus
B. spharicus	
Thiobacillus	

Table 5. Compressive strength results of different types of bacteria

Bacteria used	Bacterial concentration	Best Results
Bacillus sp. CT-5	$5x10^7 cells/mm^3$	Compressive strength is 40% more than the control concrete
Bacillus megaterium	$30x10^6 cfu/ml$	Max. The rate of strength development was 24% achieved in the highest grade of concrete 50 Mpa
Bacillus subtilis	$2.8x10^8 cells/ml$	Improvement of 12% in compressive strength as compared to controlled specimens with lightweight aggregates
Bacillus aerius	10^5 cells/ml	Increase in compressive strength by 11.8% in bacterial concrete compared to control with a 10% dosage of RHA
Sporosarcina pasteurii	$10^5 cells/ml$	Compressive strength 355 more than the control concrete
AKKRS	$10^5 cells/ml$	10% increase in compressive strength as compared to control concrete
Shewnella Species	100,000 cells/ml	25% increase in compressive strength of cement mortar compared with the control mortar

Table 6. Measured variable and self-healing methods

Methods	Width and depth of the crack
Method of Micro-encapsulation	Filling upto 35 mm depth of the crack was done
Application of Bacteria directly	Filling upto 27.2 mm depth of the crack was done
Encapsulation and Bacteria	Maximum crack width healing of 0.970 mm was reported

Table 7. Merits and Demerits of using particular methods

Techniques	Merits	Demerits
Using bacteria	Natural way through pollution free and biological activities	The measure should be taken to protect the bacteria in concrete. Many prerequisites to be meet
Using encapsulation	Discharge of healing agent, whenever required	Concrete casting is complex
	Rectifying damage measures through potential effectiveness	Problem in releasing of healing agent

5. Factors Affecting Self-healing Concrete

The five main factors that affect the self-healing concrete are:

5.1. Moisture Content

The pilot specimen is maintained in water and heals more quickly on its own.

5.2. Width of the Crack

Less than 0.3 mm wide cracks might be repaired. Larger than 0.3 mm cracks might not be mended. Cracks with a width of 0.1 mm are fully repaired after around 200 hours. Additionally, fissures between 0.2 and 0.3 mm in width mend are within 30 days. Cracks are 0.15 to 0.3 mm wide significantly close within 7 days and close completely within 33 days.

5.3. Hydration Time

Improved self-healing may be the outcome of prolonged hydration.

5.4. Application of Pressure on the Cracks

Cracks may mend more quickly if the proper amount of pressure is applied to them.

5.5. Ratio of Water and Cement

If the water-cement ratio is larger, more unreacted cement particles could be utilised for subsequent hydration to increase calcium carbonate production. Another crucial factor is the fracturing interval. Because early breaking concrete has more unreacted cement particles, it has a greater capacity for self-healing while hydration is maintained. The presence of bacteria or fungi that have been latent inside of concrete for hundreds of years and become active when exposed to water and other gases [7] as well as fibres with glue inside of them can also be found in fissures up to 1mm wide. When these fibres were added, the mechanical properties of the concrete improved, possibly because the fibres combine cracks to increase the concrete's strength and because higher self-healing increase rates were obtained when fibres were added to the concrete for bonding [7]. These last values may be further improved by an optimised combination of fibres and bacterial healing agents added to the concrete.

6. Merits of Using Self-healing Concrete

Using self-healing concrete in the construction of buildings has various benefits. The strength of the concrete is greatly increased when self-healing concrete is used. It has a lesser permeability than normal concrete. Additionally, it absorbs water more slowly than traditional concrete does. It is especially resistant to thawing and freezing-related attacks. Reinforcing corrosion has been eliminated in almost all cases. Cracks can be repaired effectively. The total cost to maintain this concrete is really minimal. Self-healing concrete can significantly reduce the need for reinforcement and enable the repair of corrosion fractures with a small to medium width. Cracks that are less than 0.3 mm broad may be fixed.

7. Demerits of Using Self-healing Concrete

Using self-healing concrete in building construction has a few drawbacks in addition to its many positives. The IS norms and any other regulations do not apply to the design of microbiological concrete. This concrete is roughly 10% to 30% more expensive than standard concrete, although it is still the same price. Bacterial germination does not occur in every bacterium. The costly study that is required to identify calcite precipitation is pricey. The use of concrete's microorganisms should be limited to construction, and when it comes to the construction of buildings, it should be preceded by a thorough investigation into any potential risks to human health over the course of the building's service life.

8. Cost Analysis of Self-healing Concrete and Conventional Concrete

The cost analysis for self-healing and conventional concrete is conducted. It is observed that the cost of conventional concrete with a binder content of 333 kg/m^3 is 2598 rupee per cubic meter. According to Dr. Henk Jonkers [8], self healing agent in concrete must not be too expensive to keep the material economically competitive. However, the cost of self-healing concrete is comparatively higher than conventional concrete, about 10-30% more [1], i.e. 2858-3377 rupees per cubic meter. Because of this, this product would only be practical in certain architectural and building constructions where the cost of concrete is high due to its superior grade, such as the linings of tunnels and maritime hydraulic constructions where safety is a top priority, or in buildings with limited access for maintenance and repair. The cost rise brought on by the use of self-healing chemicals should be manageable in these circumstances. Self-healing concrete is thought to be much less expensive if it is produced on a big scale. Even if the price of real concrete doubles, there will still be substantial long-term savings if the structure's lifespan can be increased by 30% [9].

Concrete will be substantially stronger and significantly cheaper as a result of a second self-healing chemical that is now being developed. The majority of the additional cost is made up of calcium lactate, which is currently very expensive. The procedure of incorporating the bacteria and nutrients into the pellets is particularly expensive because it makes use of vacuum technology. The cost of self-healing concrete might be reduced to Rs. 7283-7712 per cubic meter if a sugar-based dietary component is used (Table 8).

Table 8. Cost analysis of conventional concrete

Materials	Unit per	Rate in INR	Normal concrete	
			30 Mpa	
			Quantity Per 1m^3(kg)	Rate in INR
Cement	Bag	290	333.0	1931.40
20 mm	m^3	940	516.3	175.21
12 mm	m^3	871	774.4	249.84
Sand	m^3	110	754.0	31.42
Water	liter	0	0.0	0.00
HRWRA	liter	180	1.1	209.79
Total Cost				2597.66
% Savings				-

9. Conclusions

The design of self-healing concrete using natural, chemical, and biological approaches was covered by a taxonomy that was provided. Traditional methods based on chemical processes were the only ones used to produce self-healing concrete. Using bacteria that can precipitate calcite as a means of improving the development of biological self-healing concrete; this research provides an extensive assessment and discussion of the huge biological method's potential. It is evident from the analysis above that our generation needs a greener construction material that can replace conventional concrete, such as self-healing and green concrete made by combining cement with industrial waste and using crescent automated techniques. In both cases, we have seen that property-wise, whether it be compressive strength, workability, or tensile strength, conventional concrete is far out casted by Green and Self-healing concrete [10]. Although self-healing concrete is more expensive than traditional concrete, it still has more advantages than disadvantages [11]. Green concrete is ultimately the winner. Even while research is still being done to make this concrete a more significant contributor to the construction sector, it has the potential to be a game-changer in the long run, particularly for huge infrastructure development projects. Due to the use of residual waste, which lowers the embodied energy of concrete and saves landfills, both concrete and its environmental impact may be reduced [12]. They greatly reduce cement production by lengthening the life of the structure. In order to make building sites more environmentally friendly, these materials must be employed more frequently.

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