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STUDY ON THE STRNGTH AND DURABILITY OF SELF HEALING CONCRETE

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Abstract

Self-healing concrete has developed as a potentially beneficial material for extending the durability and performance of infrastructure due to its ability to autonomously heal cracks and reduce repair efforts. This review compiled findings from five recent studies evaluating the performance of mechanical strength and durability of various self-healing concrete systems and the use of bacteria to heal cracks. The results consistently demonstrated that adding microorganisms, for instance, Bacillus subtilis, even when encapsulated in an expanded clay or natural fibers, results in greater compressive, tensile, and flexural strength than unmodified concrete. After cracking of the specimens, strength recovery ranged between 40-60% after 28-63 days, depending on the type of healing environment (water or air) and bacterial viability. For durability, self-healing concrete has demonstrated better than unmodified concrete: sulfate attack, freeze-thaw cycles and permeability due to the bio-mineralization of calcium carbonate that sealed microcracks. Microstructural evaluation of cured self-healing concrete specimens also identified denser, less porous matrices than unmodified concrete. These results correlate with mechanical restoration from physiological or biological micro-repair but provide inconclusive evidence that self-healing concrete improvements fully restores mechanical behavior. Nevertheless, self-healing concrete can restore mechanical strength after mechanical damage and significantly enhance durability performance, and offer sustainable and resilient engineering solutions for the future of sustainable construction.

Keyword

Self-healing concrete; Bacterial concrete; Bacillus subtilis; Strength recovery; Durability; Crack healing; Calcium carbonate precipitation; Sustainable construction; Freeze–thaw resistance; Sulfate attack.

1.Introduction

Concrete serves as the spine of our current day infrastructure or built environment and is found everywhere in concrete roads, bridges, buildings and dams because of its capability of having strength, availability and cost. The major drawback of concrete, despite its many advantages, is that it cracks. These cracks allow penetration of water, chemicals and gases into concrete - although small initially, these cracks significantly reduce the life and safety of the structure

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since the penetration of water and chemicals leads to corrosion of reinforcing steel and damage to the concrete over time, often requiring repair or maintenance that is costly and time consuming to the owner (Wang et al., 2014). Traditionally, concrete repair has been considered to involve entering the concrete and repairing, patching or sealing manually, and usually there are many temporary repairs that made in ecological sense costly (De Belie et al., 2018). These observations and outcomes have made researchers and engineers search for sustainable and autonomous options.

One of the most highly researched fields of recent years, in this regard, is self-healing concrete, which is a new cement-based material designed and capable of repairing its own cracking. Within the focus on self-healing concrete, biological self-healing concrete, which employs bacteria to precipitate calcium carbonate can heal cracks in concrete or encapsulated (Siddique et al., 2016).

Some bacteria, such as Bacillus subtilis, can survive even in hostile environments and remain dormant until present in concrete until cracks occur and moisture activates them. When active, they produce a calcite that naturally fills and seals a Sulfate attack, and water penetration (Wiktor & Jonkers of the concrete (Jonkers, 2007; Mors & Jonkers, 2012). Recent studies have shown that bacterial self-healing concrete is able recover a significant amount of its mechanical strength as well as gain resistance against environmental challenges, including freeze–thaw cycles, sulfate attack, and water penetration (Wiktor & Jonkers, 2011; Wang et al., 2020). Researchers have also tested bringing the bacteria into the concrete package and then protecting it - using materials as natural fibers, expanded clay, or synthetic carriers - of course with each varying the healing efficiency of the bacteria (Han et al., 2019; Silva et al., 2015).

2. Literature Review

A Systematic Review and Meta-Analysis of Mechanical, Durability, and Microstructure Investigations of Self-Healing Concrete. The literature identified approximately 150 contributions - most notably one by - that referenced use of bacteria for self-healing concrete design; mechanically improving self-healed concrete compressive and tensile strength improved after the concrete would undergo cracking. The self-healing was attributed to the bacteria-induced calcium carbonate precipitation that would fill micro cracks, add to durability decreasing permeability, and provide added resistance to sulfate and chloride attack. Most studies that investigated microstructure revealed a reduction in porosity and denser matrices in the self-healing concrete. The conditions in which the bacteria were grown were pivotal in determining effectiveness, especially viability, bacterial concentration, and substrates available. Althoey et al. (2023) [1] Investigating Mechanical Properties of Bacillus subtilis Self-Healing Concrete found that the experimental results showed self-healing was optimal at a microbial concentration with PVA fibers at 2.5 optical density (od). There were increases in compressive strength in the range of 10 - 15% compared to control mixes after healing. After the compressive strength, flexural strength showed increase as well. Finally, durability testing - under freeze/thaw cycles and sulfate exposure - confirmed that the bio-concrete retained strength and had less mass loss than conventional concrete. Increased bacterial concentration did not show similar improvements beyond 2.5 od. Results

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varied by the authors concerning lower strength developed from higher bacterial concentration. Tie et al. (2024) [2] Assessment of Strength and Durability of Bio-Based Composite Self-Healing Concretes in Different Exposures.

Concrete samples with Bacillus paramycoides and natural-fiber carriers healed cracks from 0.3 to 1.1 mm. Healing rates depended on exposure: ~92% healed in wet-dry cycling conditions, ~83% healed in full wet exposure. Healing was less in soil exposure conditions - ~76% healed in soil and ~42.5% healed in marine soil. After healing, there was significant recovery in compressive and tensile strengths confirming the bio-based carriers were effective under realistic environmental exposure conditions. Sorptivity tests showed less water absorption for healed specimens that aligned with higher durability. A. Rajesh et al. (2023) [3] Encapsulation of Bacteria in Expanded Clay for Self-Healing Concrete

Bacteria encapsulated in expanded clay survived and activated when cracks occurred. After 63 days of healing, compressive strength recovered approximately 40–60% compared to unmended concrete. Scanning electron microscope (SEM) images confirmed dense calcite crystals filled cracks, confirming that healing occurred. The encapsulation method protected the bacteria during the mixing and curing parts of concrete application. The encapsulation approach improved the longevity of healing capability. Belie et al. (2018) [4].

Evaluation of Engineering Characteristics and Microstructure of Bio-Concrete versus Conventional Concrete. Bacterial healing agent bio-concrete mixes demonstrated superior compressive, tensile, and flexural strength of 10–20% greater than conventional concrete following the healing process. Bio-concrete achieved better crack closure, and more rapidly, than conventional concrete. Water absorption and permeability tests indicated significantly lower values for bio-concrete mixes, supporting improved durability. Microstructural examination of bio-concrete mixes showed denser matrices, lower levels of porosity, which support improved strength and durability. Han et al. (2019) [5]

3. Research Gap

Current research indicates that bacterial self-healing concrete can enhance strength and durability compared to conventional concrete; however, several critical gaps limit its broader application and scientific understanding. First, although many studies report partial mechanical recovery, it remains unclear whether self-healing systems can consistently restore compressive, tensile, and flexural strength to pre-damage levels across different crack widths, loading conditions, and concrete mixes. This lack of clarity highlights the need for more comprehensive mechanical analyses and long-term monitoring. Second, most available findings are based on short-term laboratory studies, leaving a significant gap in understanding the long-term performance of self-healing concrete under real environmental exposures such as fluctuating temperatures, continuous wet–dry cycles, combined chemical attacks, and repeated cracking over an extended service life. Third, the effectiveness of bacterial healing is strongly dependent on bacterial viability, but studies vary widely in encapsulation techniques, nutrient delivery methods, and environmental conditions, creating uncertainty about how well bacteria survive, activate, and re-heal cracks in practical scenarios.

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Finally, despite claims of sustainability, comprehensive life-cycle assessments, cost analyses, and evaluations of environmental impact are still scarce, raising questions about the economic and ecological feasibility of implementing self-healing concrete in full-scale infrastructure projects. Collectively, these gaps highlight the need for more holistic, standardized, and real-world research to fully validate the performance and practicality of bacterial self-healing concrete.

4. Implementation

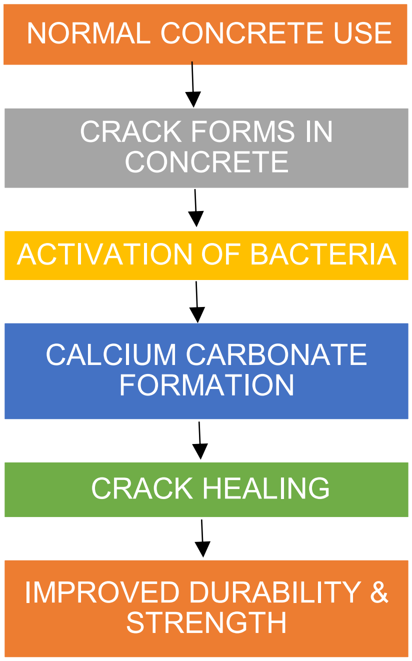
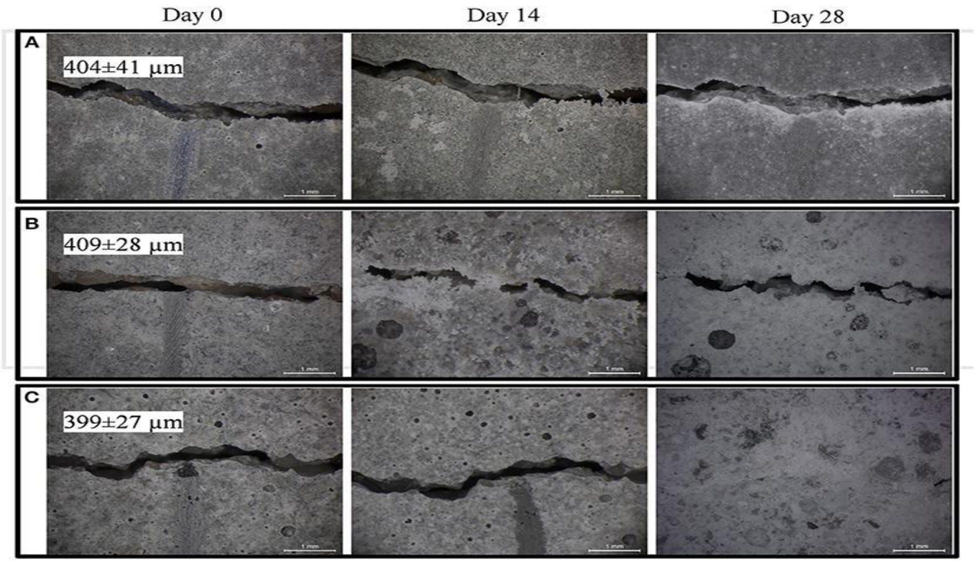


Fig 1:Flow chart for self healing concrete

3.1. Establishing Goals & Context

Prior to starting the project, it is necessary to be very clear about what your expectations are in utilizing self-healing concrete. Do you want to regain lost strength after cracking, or mainly provide added durability (reduced permeability, reinforcement protection, prevent chemical ingress)? What will be the exposure environment of the structure? (wet vs dry cycles, freeze-thaw, sulfate/chloride exposure, marine). What crack widths do you expect to see? (how wide, how often, what types: micro vs macro). In general, wide cracks will almost never heal themselves completely unless purposely designed. All of these factors will inform what self-healing systems and mixes may apply.



Source: From Frontiers in Built Environment — paper:

Fig: 2 "Volume Fraction, Thickness, and Permeability of the Sealing Layer in Microbial Self-Healing Concrete Containing Biogranules."

3.2. Selecting the Self-Healing Method

From the literature, there are some current options to choose from, but you can make a selection depending on your situation:

Biological healing (bacterial-based): either Bacillus subtilis, Bacillus paramycoides, or any other strain of bacteria that has shown environmental durability, triggers the production of calcium carbonate to fill cracks where moisture or water has penetrated the crack.

A carrier or protective medium for the bacteria: natural fibers (e.g. coir, jute, flax); expanded perlite or expanded clay; or synthetic or polymeric fibers. The protective carrier will keep the bacteria alive through the mixing/casting process and until moisture penetrates one of the cracks and initiates the bacteria. Encapsulation: adding the bacteria (and nutrients) into small capsules or some porous particles (e.g. expanded clay) that is viable once mixed and until activated.

From reading your supplementary papers: In particular, both studies found that either using encapsulated expanded clay as a harvesting carrier, or using a bacterial carrier, significantly improved recovery in strength and durability compared to specimens under severe conditions.

3.3. Preparing the Concrete Mix

Choose an appropriate concrete mix strength class (e.g. C30, or higher if required by loads). Incorporate the bacteria + carrier at optimal levels. For example, one study indicated that Bacillus Subtilis at a concentration of 2.5 od with PVA fibres produces a good balance between strength and durability. Provide the nutrient sources (if required) to

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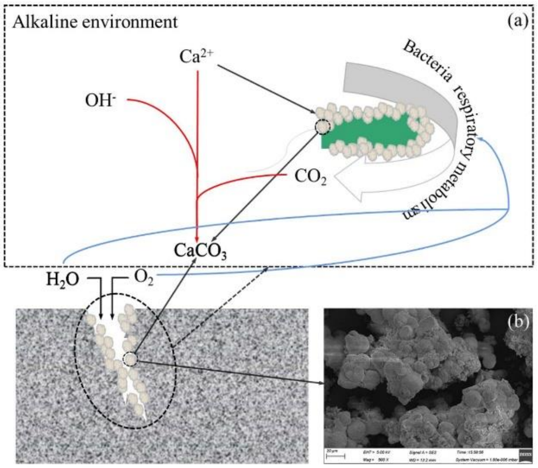
provide the bacteria with something to feed on as they are activated. For example, some bacteria require a specific calcium (Ca) (calcium source or other, such as urea, calcium lactate) nutrient source. Make sure to monitor w/c ratio, as lower w/c usually yields denser concrete, but will also often lead to a decreased mobility activation of the bacteria unless moisture is provided. Add supplementary materials if needed (fly ash, silica fume, etc.) to improve microstructure and durability.



Source: From Crystals — article:

Fig: 3“Application of Carrier Materials in Self-Healing Cement-Based Materials Based on Microbial-Induced Mineralization.”

3.4. Encapsulation / Protection Strategy

If you are using natural fibers, use durable natural fibers that are resistant to an alkaline cement environment, again without sacrificing the strength of the composite. Flax, jute, and coir have been tested. As soon as you add expanded clay to your bacteria, the bacteria will be protected from hydration heat and oxidative stress for a transient time (with good mixing of the expanded clay) immediately at the start and throughout initiation. It is essential that the expanded clay is well-mixed, but also has the right porosity and release mechanism when the cracks happen in parallel with some hydration. If synthetic fibers (such as PVA) are used, keep in mind that, in addition to porosity and distribution/spread of fibers in respect to the bacteria, the orientation and interaction of the fibers with the bacteria need to be thought about (as some fibers are stimulating crack formation and propagation).

3.5. Crack Prevention and Healing Potential

Design to minimize crack width. Much of the research suggests healing is best for microcracks (i.e. < ~0.5 - 1 mm). Bigger cracks may not even heal to completion. Provide suitable curing conditions. Moisture is often the main instigator of bacteria. Wet/dry cycles, immersion, and sustained humidity will lead to activation of the bacteria. Keep in mind the repeated cracking of the material: materials should either be designed to heal multiple times, or be durable enough to withstand at least a second or third crack (if this is advantageous long-term).

3.6. Evaluation & Monitoring

All five papers that have been tested indicate that these tests are useful, so you should use these in your implementation plan:

Strength tests: compressive, tensile, and flexural strength of healed versus control specimens; how much was the initial strength (before damage) & after cracking & healing, document this.

Durability tests: Freeze-thaw cycle tests, Sulfate/chloride attack tests, Water permeability / sorptivity tests, Microstructure (SEM, XRD) to check for calcite precipitation, check the porosity, check for crack closure.Healing speed and efficiency: how much of the strength / durability is being recovered and in what time (ie. 7, 28, 56, 63 days etc.).

Field Trials: small scale panels or slabs that are situated outside and exposed in the actual environment will give you plausible issues that are not seen in lab tests (temperature fluctuations, moisture variation, loading).

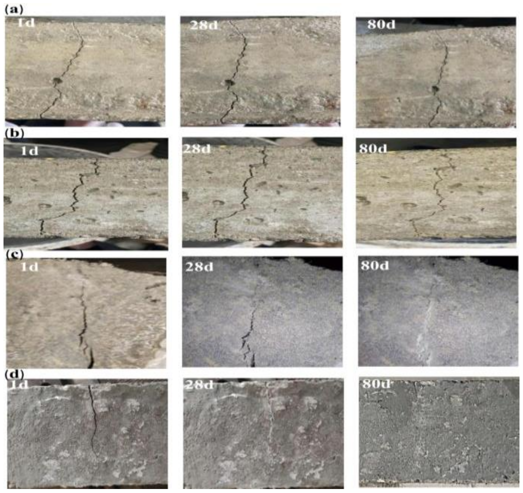
3.7. Practical Considerations Regarding the Construction Site

Training of staff on the site: Staff should be trained on how to appropriately handle bacterial agents, carriers (if used), encapsulation (if used), mixing, curing, and moisture control.

Quality Control: Verifying that bacteria are viable (if checking viability of spores through storage conditions), the carriers remain intact when mixed (this may include identifying if it is a liquid or solid carrier), and assurance that the cement concrete batching/mixing and placement does not segregate the healing agents.

Curing protocol: Assurance that moisture is continually present during the curing process. Options for moisture during curing could include wet curing, moisture membranes, or controlled environments.

Budget and cost effectiveness: self-healing concrete has a greater upfront cost (bacterial cultures, carriers, encapsulation, and possibly more complex mixing/curing processes) but the payoff will be an increased life, reduced



Source: From Scientific Reports

Fig: 4"Characteristics of bacteria-based self-healing rubberized concrete for sustainable and durable construction."

4. Conclusion

The collaborative research of multiple investigations (e.g., Althoey et al., 2023; Tie et al., 2024; Rajesh et al., 2023; etc.) supports and shows enhancements in mechanical properties and long-term durability of self-healing concrete technology. There is consensus among these studies that the addition of bacteria, specifically Bacillus subtilis and Bacillus paramycoides, improve mechanical properties and durability of concrete. Althoey et al. (2023) present a methodical review that explains that the durability of self-healing concrete comes down to maintaining viability of the bacteria and properly incorporating into the concrete matrix. Furthermore, Althoey et al. (2023) describe various changes in the microstructure that were observed, such as calcite precipitation, which aided in sealing the crack face, ultimately, reducing the porosity of the concrete which would be tied directly to improvements in the compressive strength and chemical ingress resistance. Tie et al. (2024) demonstrated through experimental investigation that the bacterial carrier material and initial concentration of bacteria both have a significant effect on the mechanical properties of the bio-concrete. Tie et al. (2024) discovered that with PVA fibers and the 2.5 OD bacteria solution, the bio-concrete exhibited substantial increases in both compressive and flexural strength, along with improvements in freeze-thaw resistance and sulfate attack resistance. Rajesh et al. (2023) to help understand the impact of environmental exposure on self-healing performance. The data

indicates that wet-dry cycling conditions result in improved crack healing efficiency (up to 92%) compared to saturated soil conditions, highlighting the effect of environmental context on healing function. They also indicate that carriers made of natural fibers can be effective at maintaining bacterial function and helping to close cracks across environments. Further, investigations into encapsulation methods, specifically bacterial inclusion in expanded clay (Study 4), show that protecting bacteria from the challenging environment of cement is a key factor in their survival and reactivation upon cracking. Encapsulation results in remarkable recovery of compressive strength (up to 60%) and visible formation of calcite crystals that physically seal the cracks. Lastly, the comparison of bio-concrete performance to conventional concrete performance (Study 5) demonstrates that bacterial self-healing contributes to increased strength (10–20%) in addition to improved durability with reduced permeability and improved chemical resistance.

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