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Original Research Article

Encapsulation-based self-healing concrete

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ABSTRACT

Self-healing concrete has emerged as a promising technology for enhancing the sustainability of infrastructure and minimising environmental footprint. Of the different approaches investigated, encapsulation based self-healing is an effective and efficient method for repairing cracks in cementitious materials. The healing mechanism is triggered by cracks, which cause capsules to break and release agents that subsequently react to repair the damage. These agents, which can consist of microorganisms, polymers or chemicals, are encapsulated in glass, polymer or ceramic shells for targeted activation. While this approach offers significant benefits, there is no clear guidance on criteria for measuring self-healing performance and on improving capsule survival during concrete mixing. Mechanical strength and durability are commonly used to assess healing efficiency, while non-destructive techniques and numerical modeling provide advanced evaluation methods. However, challenges such as compatibility with cementitious matrices, large-scale implementation, crack propagation control, and cost-effectiveness must be addressed to enable practical application of encapsulation-based self-healing systems.

1. Introduction

Infrastructure engineers employed a lot of cement-based materials since they were easy to get, cheap, and long-lasting. To fix these cracks, traditional procedures, including patch repairs, grouting, and external reinforcement were used, but they were time-consuming and expensive. Carbonization of $Ca(OH)_2$ a process that usually requires years showed promise for intrinsic healing in cement-based materials [1]. Materials based on cement have been enhanced with low-activity minerals, microbes, permeation crystallization materials, superabsorbent polymers, and microcapsules to create a variety of self-healing systems that enhance repair efficiency [2]. A life cycle cost analysis (LCCA) of various concrete repair methods in Europe found that the material costs between 60 and 75 euros per cubic meter, whereas the use of bacterial agents to fix the same amount of concrete costs between 15 and 20 euros per cubic meter [3]. Applying different chemical processes to regular concrete for crack repairs results in a cost of about 130 euros/m3 [4]. Two times the initial investment per cubic meter of concrete is what this sum represents. For self-healing to take place, low-activity minerals may produce new hydration products via pozzolanic reactions, which they can then use to patch gaps. Nevertheless, as time passed and these minerals were exposed to moisture, their reactivity decreased. The metabolic operations of microorganisms created CO_3^{2-}, which helped in the precipitation of Ca^{2+} into $CaCO_3$ for crack healing [5].

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

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^-$$

$$H_2CO_3 \rightarrow HCO_3^- + H^+$$

$$HCO_3^- + H^+ + 2OH^- \rightarrow CO_3^{2-} + 2H_2O$$

$$Ca^{2+} + Co_3^{2-} \rightarrow CaCO_3$$

However, these microbes did not last long in the very alkaline conditions found in cement-based materials. One cubic meter of self-healing concrete has an environmental effect that is 85% greater than that of conventional concrete. This is mainly because it uses self-healing ingredients. Also, as compared to regular concrete, self-healing concrete has a 36% larger carbon footprint and a 51% larger water impact [6]. In certain areas, self-repairing properties might lower the quantity of non-structural shrinkage steel needed to stop cracks from forming. This could improve sustainability by 12% to 50%. Self-healing concrete might help buildings cut down on carbon dioxide emissions by as much as 51 kg/m^3 [7]. The encapsulation technique was mostly utilized to keep liquid organic healing ingredients like epoxy resin and isocyanate safe. Some techniques were made to encapsulate water-based solutions such as Na_2SiO3 and $Ca(NO_3)_2$, but it was hard to make microcapsules with thick shells [8]. The encapsulation method may make chemical or biological healing agents last longer and regulate how they are released into the matrix. Evidence indicates that the capsule-based methodology is adaptable and that the quality of repair is adequate, often assessed by the restoration of mechanical and durability characteristics [9]. The primary problem of the capsule-based technique is its long-term reproducibility. Concrete buildings endure several damage cycles over their service life; hence, a capsule-based system is anticipated to provide multiple opportunities for effective repair [10]. Microcapsules may contain only a finite quantity of repair agent, resulting in the depletion of the healing agent after a single loading cycle, hence raising concerns about the efficacy of recurrent healing over an extended period. Recent research endeavors have focused on the intelligent release of restorative substances. When fractures start and spread, the tension buildup at the crack tip causes neighboring microcapsules to break apart. The healing ingredient in these capsules is then released into the fracture by capillary action, which makes it possible for the repair to happen on its own [11]. The released healing chemicals are quite likely to successfully seal fractures that are still in their early stages. This will stop them from spreading and lower the danger of structural collapse. There are a few important things that affect how well microcapsule-based self-healing systems work.

Adding a healing ingredient to concrete is an important step in making concrete that can cure itself. This paper offers a comprehensive review of the encapsulation of bacteria and their significance in self-healing concrete. It discusses the use of different physical and chemical techniques to encapsulate bacteria and healing agents in different sizes. The encapsulated components are then mixed into the concrete. The various encapsulation techniques do two things: isolate the bacteria from the damaging alkaline conditions and control the slow release of the repair agents into the matrix. Explores the purpose of encapsulation and the key parameters affecting capsule performance, such as size, composition, and method of manufacture. This work is unique in its coverage of encapsulation as a means of delivering repair to concrete, from the construction of the shell to the active repair agent itself, in both the laboratory and in commercial products.

2. Characterization of the capsule

There are a number of techniques for describing and measuring capsules, all of which are critical to the long-term success of self-healing capsules. These methods help to understand the mechanical, chemical, and structural characteristics of the capsules as well as their performance.

Fourier transform infrared spectroscopy (FTIR) examines the chemical composition of capsules by measuring how a sample absorbs or transmits light across different wavelengths. This analysis is essential for verifying the integrity, durability, and effectiveness of encapsulation in self-healing systems. In microcapsule spectra, notable absorption at 3384 cm^{-1} reflects the stretching frequencies of O-H and N-H bonds present in UF resin. The spectra also reveal epoxy-related bands, including terminal epoxide group peaks at 913 cm^{-1} and 831 cm^{-1} alongside benzene ring stretching vibrations at 1248 cm^{-1} and 1510 cm^{-1} [12]. In a separate study, FTIR was applied to analyze the molecular structure and chemical composition of four thermoplastic shells, where four distinct absorption peaks at 1732 cm^{-1}, 1451 cm^{-1}, 1151 cm^{-1}, and 990 cm^{-1} were matched to the stretching vibrations of C=O, C-H, C-O, and C-O-C bonds, respectively [13]. Scanning Electron Microscopy (SEM) is another essential tool in microcapsule characterization, providing detailed information about capsule size, shape, and structural condition. Its high-resolution imaging allows researchers to measure shell wall thickness, identify surface irregularities, and confirm that the shell is uniformly formed. SEM is also particularly useful for detecting cracks or defects in the shell that could lead to premature leakage an important check for confirming that the healing agent has been properly enclosed. Cheng Zhang [14] used SEM to examine the surface structure of microcapsules, finding that the capsules adopted a spherical shape when dispersed in deionized water. SEM was then used to conduct a more detailed examination of the capsules' internal structure. Beglarigale et al. [15] have noted that the ratio of irregular particles to spherical shapes. Energy dispersive X-ray spectroscopy (EDX) finds these X-rays and evaluates their energies, which are linked to certain elements in the sample. The spectrum that comes out shows peaks at different energy levels, and each peak stands for a particular element. The height of each peak shows how much of that element is in the sample compared to the others [13]. EDX is very helpful for figuring out what elements are in a substance, like metals, ceramics, and polymers. Facilitated enough excitation of elemental X-ray signals inside the microcapsule matrix and verified the existence of C, O, Na, and Si, signifying a polyurethane shell and sodium silicate core [16]. Measurements were conducted on polished cross-sections to reduce surface topographical artifacts and assure signal stability. Thermogravimetric analysis (TGA) helps figure out how the capsule shell and the healing agent within it break down as they are heated. It does this by measuring how much weight they lose as the temperature rises. This investigation is essential to verify that the microcapsules can endure the manufacturing and operating temperatures of their intended applications [17]. TGA also gives us information about how well the microcapsules are encapsulating things by figuring out the weight fraction of the core material within them. In addition to testing how well microcapsules encapsulate [18], TGA is also used to study how quickly they break down, which is important for figuring out how stable they will be in the long run. Researchers can use TGA to find out if microcapsules can be used with different host materials by looking at their thermal changes and breakdown temperatures.

3. Capsule-based healing mechanism

Encapsulated self-healing technology is a sophisticated method that allows materials to autonomously mend using small capsules included in them. These little capsules include unique therapeutic substances safeguarded by an external membrane. The capsules are disseminated throughout the concrete during the mixing procedure. Should a fissure form, it generates pressure that ruptures adjacent capsules. This rupture activates the release of the healing agent, which subsequently permeates the fissure to mend the injury. As shown in Figure 1, this substance then flows into the fissures and combines with a curing agent in the concrete to produce a self-healing compound that fills the cracks. In Figure 1(a), a fracture starts to form in the concrete. Figure 1(b) shows that capillary forces pull the healing agent toward the fracture, which makes the microcapsules within it break apart and release their contents. Finally, Figure 1(c) shows the complete healing crack. The released agent helps CaCO3 to fall out of the air, which fills and seals the crack [19]. Chemical triggers typically cause reactions that tear down the shell material, letting the healing chemicals out at a regulated pace. As the pH levels went down, the amount of healing agents released into a simulated concrete pore solution went up. Mechanical tension is the main cause of physical triggers. Microcapsules with a phenol-formaldehyde (PF) shell and dicyclopentadiene as the healing ingredient [20]. Because PF is so flexible, these microcapsules may spread out nicely and burst open quickly when they split. People have also looked at other ways, such as ultrasound, microwave radiation, and electromagnetic induction. Created nano-Fe_3O_4/paraffin-coated isocyanate microcapsules that are sensitive to electromagnetic fields. The heat produced by nano-Fe_3O_4 when it is exposed to electromagnetic induction melted the paraffin-composite shell, making it easier to regulate the release [21]. These investigations have greatly improved our knowledge of how to activate microencapsulated self-healing systems. They have also helped solve the problem of how to reliably break microcapsules in concrete and other comparable materials.

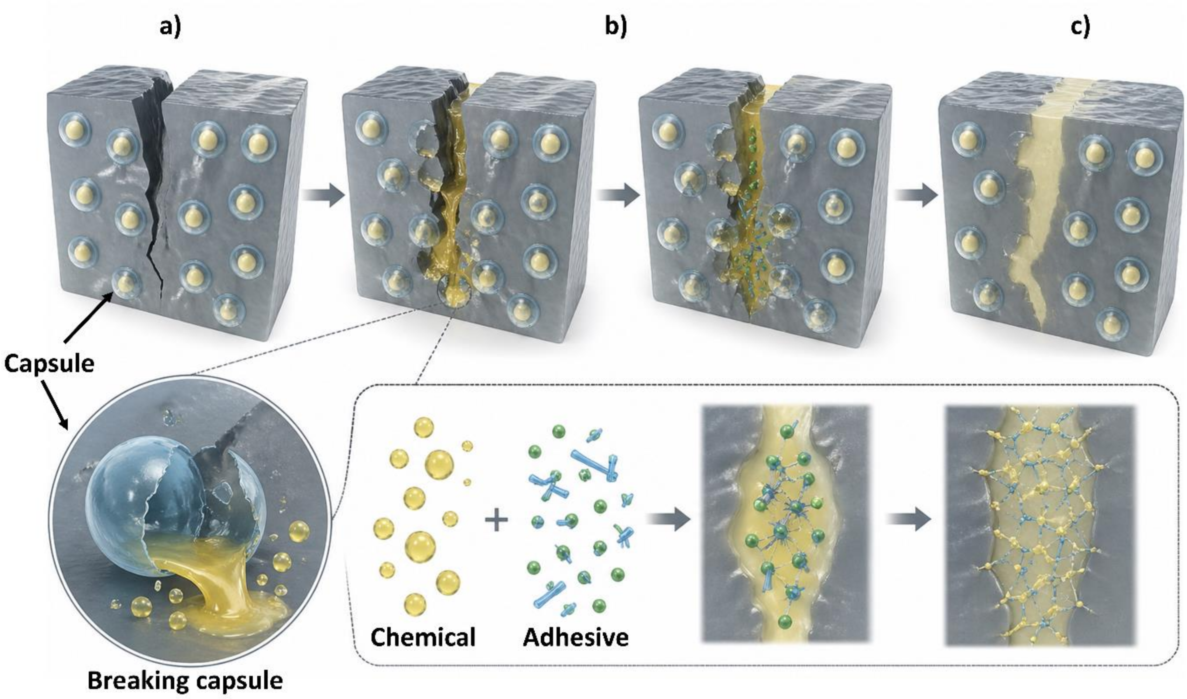

Figure 1: Self-healing mechanism by rupturing the capsule.

4. Comparative evaluation of encapsulating materials

To get the best balance of concrete qualities for a certain concrete mixture, it is important to choose the right healing agents and employ them correctly. The encapsulating substance in the self-healing concrete made from bacteria has a big influence on the concrete's qualities while it is still wet and when it is firm. Some of the qualities of fresh concrete include workability and basic setting time, rheological properties, segregation, slumping loss, bleeding, and practical problems with formwork [22]. On the other hand, the qualities of hardened concrete include compressive strength, tensile strength, elasticity, shrinkage, thermal, transport, creep, resistance to cracking, electrical, and other properties [23]. So, the impacts of encapsulating materials on concrete may have a big impact on how well it heals itself. Polymeric encapsulation materials, such as hydrogels, alginates, and melamine microcapsules, exhibit inadequate recovery of mechanical strength [23]. On the other hand, additional polymeric constituents, including rubber particles, silica gel, and polyurethane, work better when it comes to compression and flexural strength compared to the original combination. In terms of compression and flexural strength, cermasite and IONPs were the best LWA encapsulating materials since they made the best mechanical strength [24]. Almost all of the encapsulating materials that are now being explored or have been examined in bacteria-based self-healing concrete have demonstrated good results. The characteristics of new concrete are seldom examined in bacteria-based self-healing concrete [25]. Tests like workability don't directly measure how well self-healing works, but these factors might be essential for how well the concrete holds together when healing chemicals are added to the mixing process. Research investigations have shown that the use of hydrogels adversely affects the workability of concrete [26]. There is a widespread paucity of information on the quality standards for choosing encapsulating material for bacterial self-healing. The quality criteria may rely on multiple factors, including the material's excellent biocompatibility, its ability to trap bacterial cells, its capacity for moisture retention or water storage to support immobilized bacterial metabolism, its eco-friendliness during use, its cost-effectiveness for large-scale operations, its tolerance of extreme pH levels, the uniform distribution of bacterial spores, the monodispersity of the encapsulation material, the simplicity of the encapsulation process, and methods to combat climate change through enhanced waste management and reduced toxic emissions [27]. So, it would be helpful to compare the advantages and downsides of different encapsulating materials for use in self-healing concrete to help choose the best ones. Sustainability assessment approaches, including life-cycle assessment, may be used to examine and enhance the life-cycle environmental implications of using an encapsulating material for concrete healing applications.

5. Machine learning (ML) and artificial intelligence (AI) in self-healing concrete

Producing reliable concrete designs typically demands an extensive range of tests and investigations. The integration of ML and AI has emerged as a powerful means of addressing these challenges and has recently found its way into self-healing concrete research. These technologies can simplify testing procedures, accelerate data processing, and make it far more practical to explore a wide variety of concrete mix designs [28]. For researchers, ML and AI open the door to meaningful advances in developing cost-effective methods for enhancing self-healing concrete systems (Figure 2). Building a robust ML model requires as much data as possible during the training phase, while a smaller portion of the dataset is reserved for testing and validating the constructed model. A broad range of algorithms has been employed in training these ML and AI models, including Multivariate Linear Regression (MVLR), Deep Neural Networks (DNN), Extreme Gradient Boosting (XGBoost), Convolutional Neural Networks (CNN), Support Vector Machines (SVM), Gradient Boosting Regression (GBR), and Random Forests (RF), among others [29-31]. Number of different statistical methods to check the models. The statistical analysis showed that the method that best matched the expected and experimental data was the one that worked best. You may use these algorithms to accurately forecast critical output characteristics, including repaired fracture width and healing efficiency, without having to do costly experiments. In short, studies on self-healing concrete that use encapsulation have not yet looked at how ML and AI may be used [30]. There is a lot of study on the different features of capsules and how they affect concrete self-healing, even if there is a gap in the literature. You might utilize this information to create a database, which would be a good place to start for training ML algorithms.

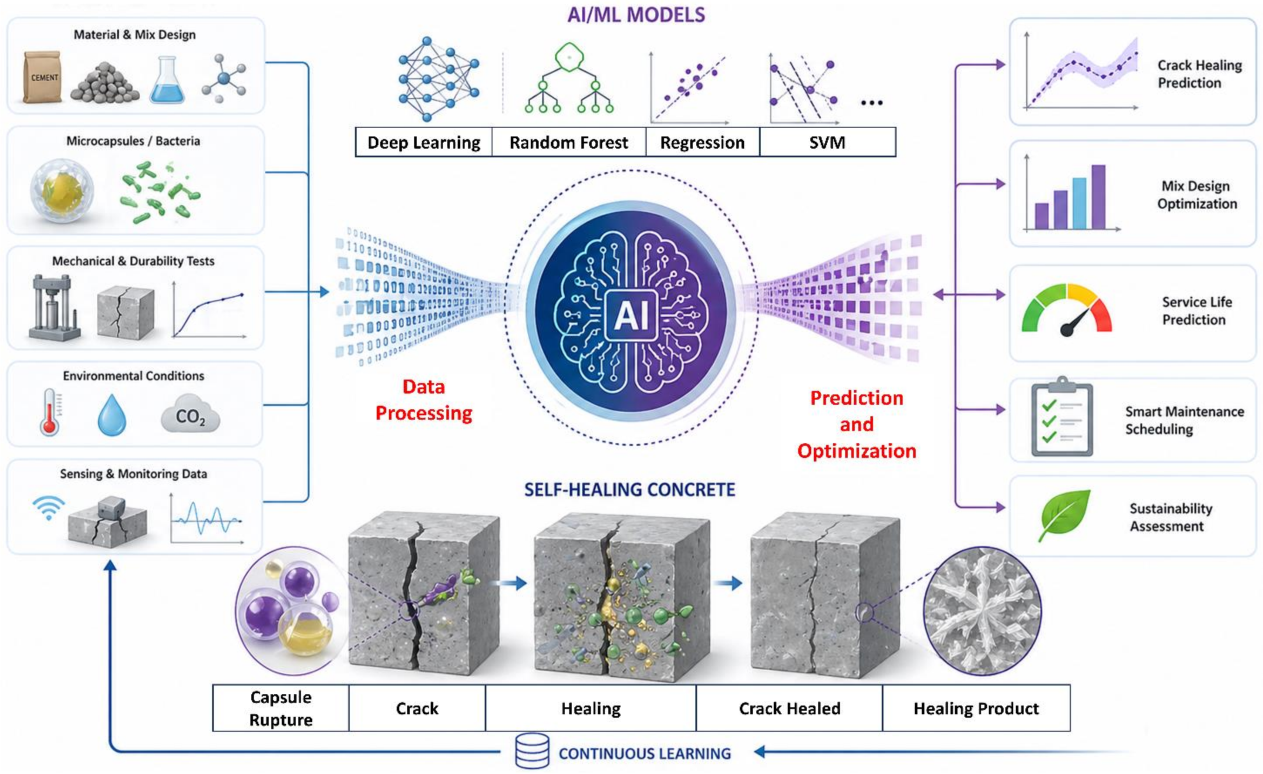

Figure 2: AI and ML detect the crack healing performance.

6. Conclusions

The significance of this study is in identifying the prevalent testing procedures used to evaluate the self-healing efficacy of bacterium-based healing treatments and the various encapsulating materials now available for bacteria. The most popular ways to encapsulate bacteria, according to earlier research, are polymers and light aggregates. The research has shown that the largest fracture width that may be repaired is around 1.8mm by encapsulation in diatomaceous earth. Lightweight aggregates and nanoparticles improve the mechanical qualities of concrete, unlike other materials used for encapsulation. The unifying trait of bacteria-based healing agents was that they made materials more durable by making them less permeable to water and more resistant to chloride. The most frequent macrostructural test used by most studies was the recovery of mechanical characteristics. The next most prevalent tests were durability and the amount of crystals that had formed. To find out how well a new bacteria-based healing agent heals itself, durability tests on permeability and water absorption can be done on a lab scale to see how water flows through cracked surfaces that have been fixed. This can be followed by TGA and EDX to measure and see how the cracks have healed. To make sure the results are correct, microstructural tests like SEM, XRD, or FTIR can be used to find and describe the products that have formed in the crack samples. Recent research have focused on the use of machine learning and artificial intelligence in forecasting various features of self-healing concrete. However, there is a dearth of research aimed at use capsule factors to forecast the characteristics of self-healing concrete. The integration of these effective strategies necessitates meticulous evaluation for future research initiatives in self-healing concrete.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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