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# Principles in the Production of Self-Healing Concrete: A Short Review

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**Abstract**

*Self-healing concrete is an example of concretes with unique properties. In general, concrete is one of the building materials that is always used in the construction industry. This material is a simple combination of cement, water and aggregate and is used to build various structures. This material is one of the most widely used and durable building materials that can be shaped into any shape due to its high flexibility, so it is a very suitable option not only for strengthening the structure but also for shaping it. After drying, concrete becomes a hard and durable body, but one of its disadvantages is cracking against various factors, which require time and money to repair, and this is not economically viable. The main reason for concrete cracking is its low resistance to tensile forces. When force is applied to it, the concrete deforms and cracks. Although these gaps may be very small and cannot be seen with the naked eye, they deepen over time and can lead to structural damage. Many efforts have been made to strengthen the concrete, but this material will be damaged after a few years, which will cause water and moisture to penetrate into the rebars used in it.*

## 1. Introduction

### 1.1. Carbon Nanotubes

One type of nanoparticle that has remarkable properties is carbon nanotube (CNT) and research is currently underway on the positive effects of adding CNT to concrete to create self-healing concrete in the world. Adding small amounts of CNT to cement can improve the mechanical properties of samples consisting of the two main phases of Portland cement and water, one of the most important of which is self-healing. Carbon nanotubes (CNTs) are a type of carbon that was first discovered in Russia in 1952, but have been forgotten. It again found a special place in the nanotechnology circle in 1990. Nanotubes are produced in cylindrical form in single-walled carbon nanotube (SWNT) and multi-walled carbon nanotubes (MWNTs) up to several millimeters in length. The grouping of the tubes together and the lack of molecular attraction between them and the main body are among the problems of adding carbon nanotubes to each substance. In other words, the connection of nanotubes to each other is in the form of filaments, and this lack of sufficient adhesion between them and concrete, which is one of the

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problems of this method (Arani and Kolahchi, 2016; Feizbahr *et al.*, 2020; Kakooei *et al.*, 2012b; Kakooei *et al.*, 2012a; Ruan *et al.*, 2018; Golrokh *et al.*, 2020; Kumar and Kumar, 2021).

### 1.2. Hollow Fibers

Dry and Sottos (1993) investigated the chemical release method stored in intermediate fibers, which was originally used in cementitious materials to modify and improve properties such as permeability, crack repair, and corrosion prevention and flexibility. In this method, by using fluorescent dyes in the current repair agent in these fibers, the phenomenon of bruising in living organisms is simulated, which itself plays an important role in identifying the damaged area. In this way, the repair agent is released from the thin hollow fiber to fill the created cracks and the crack is repaired.

Concrete section, beginning of section cracking and fibers containing repair agent in wall (I)

Filling of cracks by repair agent (II)

Complete repair of cracks (III)

### 1.3. Engineered Cementitious Composite ECC

Engineered cement concrete (ECC) is made, inspired by the healing of injuries to living organisms. Thus, by continuously repairing the resulting small cracks, it does not allow cracks to spread and create deep cracks, even if the damaged concrete piece is loaded many times. In fact, the most important characteristic of engineered cement that is made using nanomaterials is that it will only be possible to create hair cracks with a maximum width of 60 micrometers close to each other, instead of deep cracks in the resulting concrete. In other words, new concrete (ECC) has a very significant flexibility compared to conventional concrete (Wu *et al.*, 2020).

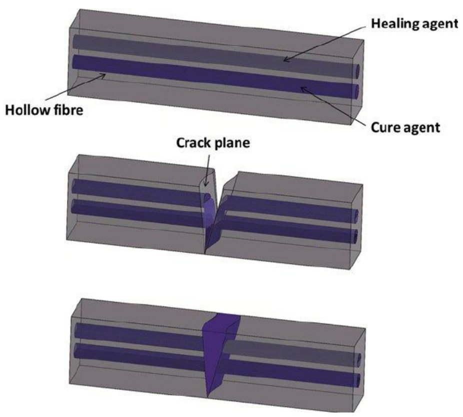


**Figure 1.** Mechanism of crack repair by hollow fiber method (Banea *et al.*, 2014).

**Figure 2.** Self-healing images of the ECC specimen (Wu *et al.*, 2020).

The performance of concretes that, using sensor-like composites, detects a slight strain at the crack site and, by sending a message to the repair unit, such as the function of neurons in the animal body, releases the repair agent and repairs the crack. The mechanism of sending a message is to cut off part of the current in the affected area, increase the electrical resistance and consequently increase the temperature and melt the shell containing the repair agent. Of course, the design of this system, which uses thermal energy for repair to release the repair agent trapped in the cover, is associated with many sensitivities. So that the increase in temperature in concrete should not lead to evaporation of internal water and the collapse of its structure. Research shows that using fly ash pozzolans along with ECC greatly improves its performance (Tian *et al.*, 2019).

Air ash reacts with calcium hydroxide Ca(OH)2, a principle of the cement hydration process, to produce a white gel that is capable of suturing hair follicles and self-healing. This type of self-compacting concrete is very important for the protection of reinforced concrete in corrosive environments, such as chlorinated environments where the possibility of dissolved chlorine ions in water can penetrate through microcracks and corrosion of reinforcements and reduce the overall strength of reinforced concrete (Gong *et al.*, 2020).

The concrete operates in such a way that when cracks form in it, some of the hydrated cement material present in the crack joints reacts in the presence of carbon dioxide and water and a very thin white layer of calcium carbonate along the crack. It forms and prevents the spread of cracks, and in fact repairs cracks, resulting in improved durability , permeability and potential mechanical properties.

The ultimate tensile strain capacity of ECCs is more than 3% (several hundred times that of ordinary concrete) while keeping crack widths below 60m μ. The very small crack width is due to the ability of the ECC material to distribute the crack surface so that it increases its crack length by keeping the crack width constant. Unlike ordinary concrete or fibrous concrete , this ECC feature allows you to control the crack width regardless of the ratio of reinforcement and dimensions of the structure. Due to this feature, the low crack width in laboratory samples is equal to the crack width in full-scale structures. With this feature, ECC materials are expected to have good potential for self-healing in a variety of environmental conditions, even when stretched by a few percent strain (Zhou *et al.*, 2010).

## 1.4. Design principles in the production of self-healing concrete

### 1.4.1. Microencapsulated Healing Agent

Inspired by the role of red blood cells in blood clotting and repair, this method injects capsules containing repair nanoparticles into concrete. These thin spherical microcapsules filled with Agent Healing repair fluid are mainly Dicyclopentadiene (Morrison *et al.*, 2015).

These microcapsules are released during contact with the broken crack, the repair agent is released inside the crack and collides with the catalyst. In this way, the polymerization process is performed and the crack is repaired by forming a hard material. The chemical reaction between the repair agent and the catalyst repairs the material and prevents the growth of cracks.

Catalyst, onset of cross-section cracking and tubes containing repair agent (I)

Fracture of the thin shell of the microcapsule due to the ripening of the crack, release of the repair agent and its penetration into the crack (II)

Polymerization in the vicinity of the catalyst, hardening and finally crack repair (III)

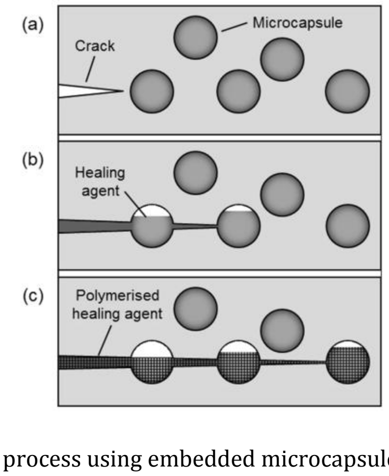


**Figure 3.** Schematic of the self-healing process using embedded microcapsules. (a) A crack forms in the matrix due to damage; (b) the growing crack ruptures microcapsules in its path, thereby releasing the healing agent into the crack plane; (c) polymerization occurs and the crack faces are bonded closed (White *et al.*, 2001).

Since the failure in a concrete structure is caused by the formation of small cracks, their spread and widening, it is necessary to use small capsules with a size of about 100 micrometers to repair the initial small cracks and prevent their expansion. In addition, the wall of the microcapsules must be very thin so that as soon as the crack reaches the wall, the microcapsules can be easily broken and the repair action can be released. This system has advantages such as long service life, completion of polymerization in a few minutes and filling of transverse cracks in the material (Li *et al.*, 2013).

From various experiments, it is inferred that as the system progresses to the state where the repair agent, along with the catalyst or, more properly, the polymerized repair fluid, is automatically injected from an external source into the concrete cracks by an intelligent system, We will see an increase in the percentage of sample repair. This will give rise to the capillary network method.

**1.4.2. Selective Heating**

One of the most intelligent self-healing systems that has been considered in concrete samples is the heating zone Selective system. This method is known as the most efficient system, which most of the time is 100% for repair. This system consists of two main parts:

1. Composite Diagnosis-Self composite composites, which are made of fibers and conductors of electricity that have both the capabilities of a strain gauge and as a functional material, the ability to record the time history of failure in the structure have. In fact, the first part, as a sensor or sample eye, detects wherever a turkey occurs and activates this part by sending a message other than the repairman (like the function of neurons in the body of animals), and the repair system tries to fix the failure.
2. Repair part of pipe Film Organic Plasticity-Heat, which contains nanomaterials of repair and in the form of pipes made of materials with the property of plasticity against heat. In such a way that it prevents the repair agent from leaving before the spread of any crack.

When a crack occurs in a part, the first part detects a slight strain at the crack site as a sensor, and by sending a message to the repairing part, a repair agent is released and repairs the crack. The mechanism of sending a message is to cut off part of the current in the affected area, increase the electrical resistance and thus increase the temperature and melt the shell containing the repair agent (Nishiwaki *et al.*, 2006).

This system, as a complete system, can monitor the pathological information, display and control the demolition process outside the structure to provide external human factors, which will lead to a huge change in the concrete improvement and repair industry in sensitive structures.

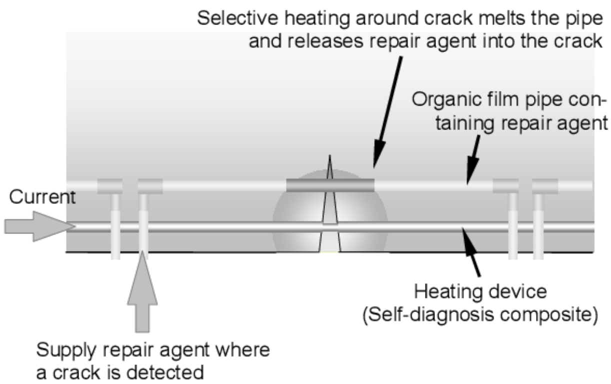


**Figure 4.** Self-healing system (Nishiwaki *et al.*, 2006).

#### 1.4.3. Capillary network construction

In microcapsule repair, the microcapsules are broken during contact with the crack, polymerization is performed in the vicinity of the catalyst, and the crack is repaired by forming a hard material.

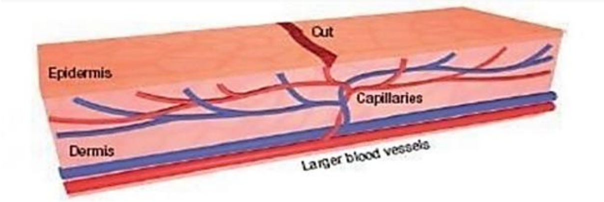


**Figure 5.** Schematic diagram of a capillary network in the dermis layer of skin with a cut in the epidermis layer (Wool, 2008).

In this method, by increasing the amount of microcapsules, the homogeneity and uniformity of concrete may be affected and reduce the strength and toughness of the concrete piece. Therefore, to improve performance, there is a need to inject repair fluid through an intelligent system. Recent research suggests the possibility of implanting a Micro Vascular Network in the form of transfer of repair nanoparticles based on the capillary property from the source to the site of failure and polymerization in the vicinity of the catalyst and consequently the formation of hard material and crack repair. Future research is aimed at developing a capillary network in concrete containing restorative agents, quite intelligently like a biological system.

#### 1.4.4. Self-healing concrete with Bacteria

Another method has been developed as a combination of natural materials and nanomaterials for intelligent concrete restoration. This method is used to make self-healing concrete with the help of a special type of bacteria in nature that are able to live in the alkaline environment above concrete.

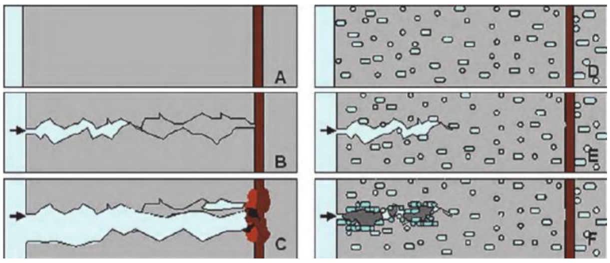


**Figure 6.** Schematic drawing of conventional concrete (A–C) versus bacteria-based self-healing concrete (D–F). Crack ingress chemicals degrade the material matrix and accelerate corrosion of the reinforcement (A–C). Incorporated bacteria-based healing agent activated by ingress water seals and prevents further cracking (D–F) (Dhami *et al.*, 2012).

An example of this bacterium is called Bacillus, which has been able to live in alkaline lakes in Russia and Egypt for a long time. These bacteria, along with their power supply, are embedded in small ceramic pellets and suspended in concrete water to prevent untimely activation in the wet concrete mixture. This concrete can repair itself with the help of bacteria in the microcapsule and in case of water injection. The microcapsule provides nutrients and calcium lactate for its growth by intercepting and protecting bacteria.

Bacteria remain proactive or so-called dormant in concrete until cracks form, and then are activated by the expansion of cracks and the infiltration of water into the cross section, and by reacting with concrete compounds, hard precipitate of calcium carbonate is produced and produced. It will close the cracks.

When they begin to feed, they greedily swallow water and produce large amounts of crystalline limestone, which quickly fills pores and holes. This new concrete increases the life of the structure by up to 50% and reduces the need for periodic repairs, and can also prevent rusting of the steel inside the concrete.

- Activation of hydrolysis due to water reaching the bacteria due to cracking and infiltration of water into the sample
- Formation of calcium carbonate precipitate in the presence of sufficient Ca+2 ions
- Closure of cracks by deposition of calcium carbonate and prevention of permeability
- The choice of the type of bacteria that enters as a suspension in a part of concrete is the most important design parameter in this system. In this regard, the selected bacteria is essential:
- Ability to survive for a long time in alkaline concrete environment with a pH of about 11 to 13.
- Have sufficient mechanical strength for mixing time.
- Do not reduce the initial and final strength of concrete.
- Water absorption rate for bacterial and control samples

An interesting feature of this type of bacteria is that they are able to form spores, which are spherical cells with a thick wall similar to plant seeds. These spores are viable but inactive and able to withstand mechanical and chemical stresses and can survive in the dry state for more than 50 years.

When bacterial spores are added directly to the concrete mixing plan, their shelf life is limited to one or two months. In order to significantly increase the lifespan and performance of concrete containing bacteria, the effect of bacterial spores and at the same time the immobility of leading organic mineral compounds (calcium lactate) in high porosity clay particles were tested and it was concluded that protection and Preservation of bacterial spores by immobilizing or immobilizing organic compounds within high-porosity clay particles before adding to the concrete mix actually increases the length significantly.

It should be noted that before the discovery of the bacterium, mineral bacterial products were used to repair cracks in concrete. Due to the need for manual ventilation of these bacteria in the area damaged by manpower and the production of ammonia toxin due to the reaction of these bacteria with concrete compounds, did not last long and developed in subsequent studies concluded that other leading bio-mineral compounds such as juice Yeast, peptone and calcium acetate significantly reduce compressive strength. The only exception is calcium electate, which increases compressive strength by 10% compared to other control samples. To ensure the rapid onset of crack repair, the use of calcium lactate and bacteria, which can cause metabolic conversion of this compound, seems to be the preferred option or the best method. Experiments show that the viability of bacterial spores increases from 2 to more than 6 months when added in a protected form to porous expanded clay particles (Leica) compared to direct (unprotected) addition.

Further research is ongoing to select the right bacteria that can survive and become active in the concrete environment and be productive over time, as well as have the least negative impact on the behavioral and strength properties of concrete. The overall conclusion is that the two proposed biochemistry agents, composed of bacterial spores and the leading organic cement-bio compounds that use Leica as a source of water storage, are promising biologically and resilient options; Especially in cases where parts of the concrete structure can not be inspected and repaired manually. However, before doing anything, the proposed system needs to be further optimized. The required amount of repair agent should be minimized by the present techniques; Both for economic efficiency and to reduce consequences such as lower compressive strength.

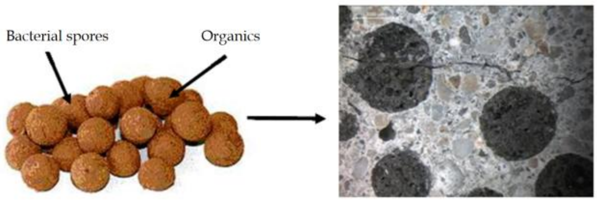


**Figure 7.** Self healing admixture composed of expanded clay particles (left) loaded with bacterial spores and organic bio-mineral precursor compound (calcium lactate) (Jonkers, 2021).

## 2. Results

Using nanotechnology and the production of materials at the nanoscale, intelligent concrete can be achieved that, as soon as a crack is created, identifies the location of the crack and tries to repair it. In this article, a comprehensive discussion was made about each of the methods that scientists have used to make and produce this smart concrete, which is now known as self-healing concrete. The results indicate that the types of methods available are divided into two categories: implementation principles and design principles.

Implementing principles are methods that are out of the initial testing and manufacturing phase and can enter the project phase, and design principles include methods that are being researched and tested in the laboratory. Making engineering cement composite is one of the methods that has attracted a lot of attention in the present era. This concrete is similar in appearance to ordinary concrete, but it is 500 times more resistant to cracking, 40% lighter in weight and its useful life is much longer than ordinary concrete.

Although long-term studies are still needed to fully determine the effectiveness of this material, comparative studies show that significant savings can be achieved by using this composite. Carbon nanotubes have problems in the process of making self-healing concrete due to the lack of adhesion between them and concrete. But in general it can improve the mechanical properties of concrete. According to the research, it was found that hollow fiber has a very good ability to repair cracks, prevent corrosion and also detect the damaged area. According to the experiments mentioned in the article; We conclude that the bacteria in the concrete mix with the production of calcium carbonate precipitate lead to the closure of cracks and prevent permeability. Bacterial concrete increases the life of the structure by up to 50%, reduces the need for periodic repairs and prevents rusting of the steel inside the concrete. One way to prevent the loss of water resources in agriculture is to use suitable materials to cover the canals to prevent losses and increase the efficiency of water transfer and distribution.

Due to the high volume of water consumption in agriculture, it is necessary to cover the existing canals in different areas in terms of reducing losses and proper use of water resources. Many factors cause the destruction of concrete and cracks in it, resulting in wastage and loss of water in it. For this reason, the concrete cover of irrigation canals in many cases faces problems of cracking and destruction.

If the destruction factors and repair ways mentioned in the target structure are identified, these materials will be used optimally, the efficiency of the structure will be created and the self-healing process will take place, as a result, water losses will be greatly prevented. Also, there is no need for frequent costs to repair the structure in the traditional way, and the strength and useful life of the structure will increase. Finally, we find that although the initial cost of producing and manufacturing self-repairing concrete types is higher than conventional concrete, using alternative methods to the traditional method described in this article are ways that in addition to reducing concrete maintenance costs It is not harmful to the environment, helps the durability and performance of concrete and increases the useful life of concrete.

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