

## СТРОИТЕЛЬНЫЕ МАТЕРИАЛЫ И ИЗДЕЛИЯ CONSTRUCTION MATERIALS AND PRODUCTS

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### Self-Healing Mechanisms in Nano-Modified Concrete: A Comprehensive Review of Synergy Between Microbial Biomineralization and Nano-Additives

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**Abstract.** The environmental impact of using different building materials to make sustainable concrete is important. The use of nanotechnology in industry has become increasingly important since sustainable development was established as a necessity to protect the environment and the interests of future generations. However, cracking is still a big problem, causing structural deterioration and shorter service life. Novel approaches to self-healing concrete have been made possible by recent developments in nanotechnology and biotechnology, which have improved the material's endurance and mechanical qualities. This study investigates the use of microbial agents, namely alkali-resistant bacteria like *Bacillus*, and nanomaterials, including carbon nanotubes and nano-silica, to create self-repairing concrete. While microorganisms incorporated in porous expanded clay (LECA) create calcium carbonate to seal cracks on their own, nanomaterials enhance the strength, impermeability, and resistance of concrete to external conditions. In addition, technologies like as shape-memory alloys, hollow fibers, and microencapsulation are being researched for crack repair. Additionally, by comprehending self-healing nano-concrete's remarkable mechanical qualities and durability performance, environmental effects and retrofitting expenses related to structures can be reduced. According to experimental findings, bacterial self-healing concrete closes all cracks in two months, but conventional concrete only closes 33% of them. These technologies promise a fundamental change toward sustainable, long-lasting, and intelligent infrastructure, despite obstacles including high costs, nanoparticle dispersion, and long-term viability. Future studies seek to refine these techniques for widespread use while maintaining environmental safety and economic viability.

**Keywords:** self-healing concrete, nanotechnology, biological concrete, smart concrete

**Conflicts of interest.** The authors declare that there is no conflict of interest.

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## Механизмы самовосстановления в наномодифицированном бетоне: комплексный обзор взаимодействия биоминерализации и нанодобавок

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**Аннотация.** Влияние использования различных строительных материалов на окружающую среду при производстве экологически безопасного бетона имеет большое значение. Использование нанотехнологий в промышленности становится все более актуальным с тех пор, как устойчивое развитие стало необходимостью для защиты окружающей среды и интересов будущих поколений. Однако растрескивание по-прежнему остается большой проблемой, вызывающей ухудшение структуры и сокращение срока службы. Новые подходы к самовосстановлению бетона стали возможны благодаря последним разработкам в области нанотехнологий и биотехнологий, которые повысили выносимость и механические качества материала. Авторами изучено использование микробных агентов, а именно щелочестойчивых бактерий типа *Bacillus*, и наноматериалов, включая углеродные нанотрубки и нанокремнезем, для создания самовосстанавливающегося бетона. В то время как микроорганизмы, внедренные в пористый керамзит, создают карбонат кальция для самостоятельной заделки трещин, наноматериалы повышают прочность, непроницаемость и устойчивость бетона к внешним условиям. Кроме того, для ремонта трещин исследуются такие технологии, как сплавы с памятью формы, полые волокна и микрокапсулы. Также осознание замечательных механических свойств и долговечности самовосстанавливающегося нанобетона позволяет сократить воздействие на окружающую среду и расходы на модернизацию конструкций. Согласно экспериментальным данным, бактериальный самовосстанавливающийся бетон закрывает все трещины за два месяца, в то время как обычный бетон закрывает только 33 % из них. Эти технологии обещают фундаментальные изменения в сторону устойчивой, долговечной и интеллектуальной инфраструктуры, несмотря на такие препятствия, как высокая стоимость, дисперсность наночастиц и долгосрочная жизнеспособность. Будущие исследования направлены на совершенствование этих технологий для широкого применения при сохранении экологической безопасности и экономической жизнеспособности.

**Ключевые слова:** Самовосстанавливающийся бетон, нанотехнологии, биобетон, «умный» бетон

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## 1. Introduction

Concrete, in a broad sense, refers to any material or compound that is composed of a cementitious adhesive. This adhesive is generally the result of the interaction of hydraulic cements and water. Concrete is one of the most widely used building materials. The main feature of concrete is its cheapness and availability of raw materials. The use of concrete can be seen in all construction works such as buildings, reservoirs and power plants, offshore structures such as piers, roads and paths, dams, etc. So far, many studies have been conducted to improve the quality of concrete, most of which have examined changes in the composition of concrete (called the concrete mixing plan). However, the use of additives as well as the replacement of conventional materials used in concrete with new materials has always been considered. Nanomaterials are one of the new materials that have been able to improve the mechanical and physical properties of concrete. Nanomaterials can completely transform the concrete world due to their properties on very small surfaces.

Currently, the importance of the application of nanotechnology in industry, with the introduction of sustainable development as a necessity to protect the environment and the interests of future generations, has become more apparent. Nanotechnology has entered the construction industry in various fields such as metals, concrete, soil, glass, energy and air conditioning, water treatment, sensors, coatings, paints and insulators [1]. Extensive research has been conducted in the last decade on the application of nanotechnology in concrete technology. Concrete as a macro material is strongly influenced by the properties of nanotechnology. Understanding the behavior of concrete and the performance of structures at the micro and nano scale improves and enhances the properties of concrete and thus contributes the construction and production of concrete with performance commensurate with today's needs [2]. So far, nanotechnology in the concrete industry has proven the possibility of improving the basic characteristics such as strength, lightness, durability, flexibility, impermeability, construction of smart aggregates and cements, thermal insulation, self-cleaning and self-healing. And ongoing research continues to unravel the mystery of the industry.

One of the problems in the subject of concrete and reinforced concrete structures is the issue of cracks. Cracks are now recognized as one of the problems of reinforced concrete structures. Improvement or repair of cracks with a width of less than 0.2 mm is mainly due to the large range of small particles of non-hydrated cement on the surface of the cracks. Therefore, we need side mechanisms and mechanisms of high self-healing. In such a way that in addition to preventing cracking, cracked sections with self-healing ability are not vulnerable.

A mechanism based on the use of mineral bacteria in crack repair has been studied and developed in several laboratories. Cracks are effectively closed by the deposition of minerals while the bacteria in the mixture are sprayed on the damaged surface and injected manually into the cracks [3]. Here, the bacterial eggs and the organic compounds present enter the porous expanded clay particles (LECA) before being added to the mixing scheme. It is hypothesized that the protection and maintenance of bacterial cells within porous aggregates will increase their viability period as well as increase the efficiency of self-healing concrete when placed in the microstructure. Ever since cement was discovered in its present form, the subsequent combination of cement with stone and water has produced a cohesive body called concrete [4]. To date, much research has been done on cement and other adhesives in concrete, which has increased human knowledge about the various properties and applications of concrete. Concrete is increasingly used in the construction of various structures due to its good performance and lack of destructive environmental effects, as the current production of more than one ton of concrete per person per year in the world indicates this. Self-compacting concrete is one of the new generation concretes that has been considered by engineers due to its many capabilities such as proper flow and efficiency, strength and penetration. Self-compacting concrete does not need compactors [5]. Nanoscience and nanoengineering, sometimes referred to as nanoimprovement in concrete, are names used to describe two pathways in nanotechnology research in concrete. Nanoscience is concerned with measuring and describing the structure of nano- and micro-scale cementitious base materials for a better understanding of large-scale (macro) behavior and its performance through the use of advanced atomic or molecular surface description and modeling techniques [6].

Nanotechnology is a branch of science that studies the comprehension and manipulation of materials at the nanoscale with the goal of enhancing their qualities in products [7]. The idea of nanotechnology has been used more and more in a variety of industries in recent years, including construction, chemistry, electronics, biomechanics, pharmaceuticals, textiles, and medicine [7–8]. Numerous studies on the different uses of nanotechnology in the building materials industry, particularly in cement-based materials, have been conducted in recent years [9]. Numerous national initiatives have been started in the European Union or in nations like America, Canada, Japan, Russia, and China to aid in the development of nanomaterials and nanotechnology. Numerous worldwide professional organizations have formed commissions, groupings, and working committees. One such committee is the TC 197 NCM, which was established by RILEM [10].

Like other scientific and engineering fields, the construction sector keeps a close eye on nanotechnology advancements and looks for possible new application areas. The usage of nanoparticles in construction materials is becoming more and more popular. In addition to improving material qualities like strength and durability, nanoparticles may be used to provide novel functionalities like pressure sensing and photocatalysis [11–13]. These nuclei are responsible for the crystal development process that forms cement hydration products. As hydration products begin to develop between the cement grains, the presence of nanoparticles speeds up the production of a highly void-free interior structure as compared to a reference mixture without nanoparticles. This might lead to the production of cement base materials with high compressive strength and increased voids at an early age [14–16].

Nano engineering includes nanometer-scale structure manipulation techniques to create a new and suitable generation of cementitious composites with ideal mechanical behavior. And it is even possible to create concrete with new properties such as low electrical resistance, intelligence, self-cleaning, self-repairing, high ductility, etc. Recent research activities in the field of nanotechnology in concrete include the inherent study of hydration in cement, the effect of adding nano silica to concrete, the addition of nanoparticles to cement, concrete and cementitious coatings, and the observation of their effects on behavior and properties [17].

Experimental research has shown that nanoscale clay particles enhance concrete's mechanical qualities while lowering shrinkage and chloride permeability [18]. The surface area or size of these particles is significant in terms of cement hydration kinetics as the hydration rate is linked to the reactions that take place on the reactive surfaces of nanoparticles [19]. Cement hydration is also accelerated by nanoparticles like CSH artificial grains. Although nucleation processes, which are required for crystal formation under normal circumstances, are not required with this approach, time is lost and the dead period of cement hydration is reduced [20–23].

Nanotechnology, like all new technologies, needs an economic justification. Currently, the high cost of nanoparticles sometimes prevents the increasing development of these products and their use in industry. For this reason, the use of nanotechnology in the concrete industry on a commercial scale is still limited to a few products available in the market<sup>1</sup> [24–26].

Another problem in using nanomaterials is their uniform distribution in the concrete matrix. These materials usually accumulate as lumps when added to concrete and are not well distributed in the mix, obviously, powerful mixers can be used to solve this problem. Another drawback is the very high water absorption of nanoparticles. These particles absorb large amounts of water due to their very large specific surface area and may affect the performance of concrete [26–28]. So, there are challenges that must be addressed before expanding the use of nanotechnology in the concrete industry, such as uniform distribution of nanomaterials, compatibility of nanomaterials with cement, processing, production, safety, transportation issues, mass production and costs [29].

In addition to introducing these new materials to society through social infrastructure requires more understanding of their impact on the environment and human health [30]. However, now, 50 years after Feynman's (Feynman. R) famous article, it is clear that nanotechnology is changing the views of scientists

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<sup>1</sup> Nanotechnology in Construction Market Outlook. Available from: <https://researchintelo.com/report/nanotechnology-in-construction-market> (accessed: 22.06.2025)

and engineers on one of the oldest man-made materials, concrete [31; 32]. Concrete is the most popular building material, and we have been trying to make it more sustainable since the Romans built the Temples of the Gods about 2,000 years ago. No matter how carefully we combine or harden it, all concrete will one day crack, and in some cases, these cracks will lead to the collapse of the building [33; 34].

Professor Henk Jonkers of Delft University of Technology in the Netherlands explains that the problem with concrete cracks is that they leak. If there are cracks, water will seep into the basement or parking lot. Second, if this water reaches the reinforced steel part of the concrete — all the concrete has these rebars, and if they rust, the building will collapse [35]. But Jonkers has come up with a whole new way to extend the life of concrete. So called “bio concrete” has been invented, that can repair itself with bacteria [36].

Bio concrete has exactly the same composition as ordinary concrete, but with an additional element, a restorative agent. This agent remains intact during mixing and only dissolves and activates when concrete cracks and water enters [37; 38]. Jonkers, a microbiologist, has been working on it since 2006, when concrete technologists asked him if it was possible to use a bacterium to make self-healing concrete. It took him three years to solve the problem, but he faced many complex challenges [39; 40]. You need bacteria that can survive in harsh concrete environments, Jonkers said [41]. He went on to say that the material was similar to rock or stone and was very dry. Concrete is highly alkaline, and the repairing bacteria must be dormant for years before being able to be activated by water [42].

Jonkers chose the bacillus bacterium for this, because they grow in an alkaline environment and produce pollen that can survive for years without food and oxygen. Jonkers explained that the next challenge was that in addition to keeping bacteria in the concrete active, we had to force it to produce concrete repair agents [43; 44], which are limestone.

Basil is needed as a food source to produce limestone. Sugar is one of the solutions, but adding sugar to the mixture weakens and softens the concrete. In the end, Jonkers chose calcium lactate. He placed the bacteria and calcium lactate in a biodegradable rubber capsule and mixed it with wet cement. When the cracks finally start to form in the concrete, water enters and opens the capsules. The bacteria then grow and begin to multiply by eating lactate. By doing so, they combine calcium with carbon ions to produce calcite or limestone, which closes the gaps.

Now Jonkers hopes that his concrete can create a new era of biological buildings as this is “a combination of building materials and nature”. Nature has provided us with many free capabilities, such as limestone-producing bacteria. If we can use it in our materials, we can make the most of it. This was a good example of nature and the environment coming together to come up with a new concept [45; 46].

Sewage sludge has been considered for these destructive effects due to the environmental problems it can cause in its landfill. On the other hand, today in countries with the construction of more wastewater treatment plants, the production of these wastes has increased. Therefore, the possibility of creating a suitable cycle for the use and consumption of these materials is a very good way to reduce the environmental hazards caused by its burial [47–49]. Although it does not take long for nanoparticles to be used as advanced materials in concrete, extensive research has demonstrated the tremendous effectiveness of these materials in concrete [50]. The use of sewage sludge or mosses as a biological ash in concrete has led to the creation of concrete, which is welcomed today [51]. A group of civil researchers at the Malaysian University of Technology have succeeded in producing a type of concrete that can repair cracks with the help of specific microorganisms [52]. This ability to repair has resulted in higher strength and durability than conventional concrete [53]. Structures made of this type of concrete are able to withstand harsher environmental conditions and are more resistant to damage caused by acid rain, etc. [54].

At first various researchers have conducted research on the production of self-healing concrete and have succeeded in presenting such concretes, but the vast majority of them have chosen chemical methods in this field.

Recent studies that have led to the production of self-healing concretes have used biological methods [55]. So, despite the high level of technology required to produce them, it has provided the possibility of producing cheap self-healing concretes. Researchers have named these concretes biologically self-healing concrete [56–58].

The future of design and architecture requires innovative thinking about the application of current construction techniques to be able to expand their capabilities [59]. Sustainability is inferred from something beyond a trend and has become a constant part of the design process. Sustainability solutions have always pushed the current state of design. Scientists created the type of concrete that holds and nurtures many biological organisms on its surface [60].

There are facades of buildings with vegetation, but what sets biological concrete apart from other systems is that vegetations are an integral part of the structure [61]. This system consists of three layers on structural elements that together bring environmental, thermal and aesthetic benefits to the building. In this case, the acceptable amount needs to be reduced. This was not the ideal situation that researchers at UPC were looking for. Instead, they created a biological layer using magnesium phosphate cement, which is slightly more acidic and does not need to lower the pH. [62; 63]. Mosses can grow at pH less than 5. To the extent that most other plants do not prefer. Restricting competition by lowering the pH is likely to expand moss colonization. The researchers' strategy led to the development of different types of cement with variable pH distributions that help grow certain types of organisms such as mosses, microalgae or lichens. The installation of this living concrete consists of three layers on a structural surface. The first layer is a waterproof shell that protects structural elements from water penetration. A new biological layer of concrete is applied to this layer. This layer absorbs rainwater and acts like a microscopic structure that stores rainwater. The last layer is a discontinuous cover that allows rainwater to enter and traps it between this cover and the waterproof cover. This optimizes the amount of water that gets trapped inside the biological coating without compromising the structure [64; 65]. There are many benefits of this system. Plants absorb CO<sub>2</sub> from the air and release oxygen. This layer also acts as thermal insulation and helps regulate the heat inside the building by absorbing heat and preventing it from entering the building in hot weather or escaping from the building in cold weather. This material has been registered but is still in the testing phase [66]. Researchers are experimenting with different cements that can be used to grow certain species of plants. These changes in the facade, both in terms of decoration and environment, give variety and color to any facade and turn it into a new or renovated building [67].

## 2. Materials and Methods

The study used a multi-phase method to create and test self-compacting smart nano-concrete that has better self-healing abilities. The main binding agent was Ordinary Portland Cement (OPC, Grade 43), which met ASTM C150 standards. It was mixed with Class F fly ash (20% replacement) and nano-silica (2% of the cement's weight) to improve particle packing density and pozzolanic reactivity. The reinforcement system included multi-walled carbon nanotubes (MWCNTs, 0.5 wt.%) that were evenly spread using ultrasonic homogenization in a polycarboxylate-based superplasticizer to avoid clumping.

To obtain biological self-healing concrete, alkali-resistant *Bacillus pseudofirmus* spores ( $10^6$  CFU/g cement) were trapped inside pre-saturated porous expanded clay aggregates (LECA, 2–4 mm size), along with calcium lactate (5% by weight of LECA) as an organic mineral precursor to promote microbially induced calcium carbonate precipitation (MICP). The concrete mixtures had a water-to-binder ratio (w/b) of 0.35 and achieved self-compacting properties through a specific blend of polycarboxylate ether (PCE) superplasticizer (1.2% by cement weight) and viscosity-modifying admixture (VMA, 0.05%) to ensure flow ability (> 650 mm slump flow) while reducing segregation. For comparison, control mixtures without bacterial or nano additives were made alongside three experimental groups: (1) nano-modified concrete (NMC) with MWCNTs/nano-silica, (2) bio-concrete (BC) with bacteria-encapsulated LECA, and (3) hybrid smart concrete (HSC) combining both nanomaterials and bacterial agents. Mechanical and durability tests were conducted following ASTM C39 for compressive strength, ASTM C496 for splitting tensile strength, and ASTM C1202 for rapid chloride permeability. Self-healing efficiency was measured by pre-cracking specimens to create a 0.3 mm crack width using three-point bending, followed by immersing them in water for 56 days. Also, crack closure was evaluated using optical microscopy and X-ray computed tomography

(X-CT), while thermo-gravimetric analysis (TGA) and Fourier-transform infrared spectroscopy (FTIR) confirmed the formation of  $\text{CaCO}_3$ . To create smart features, shape-memory alloy (SMA, Ni-Ti) fibers were added at a volume of 1.5% to test how well they could recover from cracks when heated to  $70^\circ\text{C}$ . Also, we made microvascular networks that imitate biological systems using 3D-printed templates. These networks help deliver healing agents, which include methyl methacrylate monomer and an initiator, directly to the cracks. We looked at the environmental impact by conducting a life cycle assessment (LCA) to compare the embodied carbon between traditional and smart concrete systems. To confirm our results statistically, we used ANOVA ( $p < 0.05$ ) along with Tukey's post-hoc test to check for significant differences among the mixtures. The findings showed that the hybrid smart concrete group healed 92% of its cracks compared to just 35% in the control group and had a compressive strength that was 28% higher after 90 days at 68 MPa than regular OPC concrete. This supports the combined benefits of nanotechnology and bio mineralization.

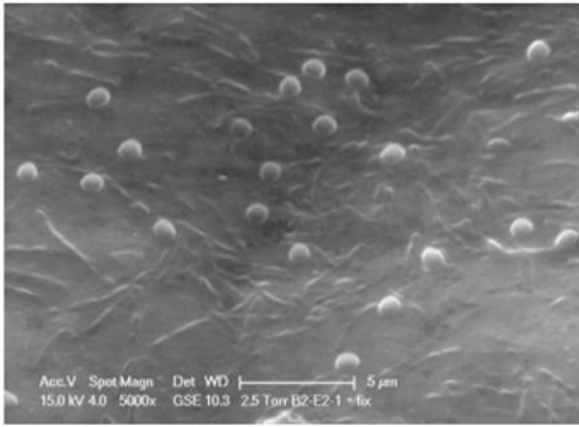
In this study, nanotechnology and its application in the construction industry were investigated. The main characteristics and basic applications of nanomaterials, especially in the civil engineering industry, were the main and important areas of this research at the initial stage. Then, this research studied the effect of nanomaterials, including the use and effect of bacteria for self-healing concrete to close concrete cracks with the bond strength and cohesion of the concrete microstructure and the use of filled microcapsules that are injected into the concrete as a repair agent by taking inspiration from red blood cells in blood clotting and repair. Also, the thermal selector method, which is the most efficient and intelligent method, was used to repair concrete with two methods: self-diagnostic composites and plasticity organic film tube. The next method is the use of cement composites inspired by the healing of injuries to living organisms, which allows hairline cracks to spread and prevents the formation of deep cracks. Another important method was the use of low quantities of CNT in concrete to improve the mechanical properties of concrete. The use of hollow fibers was a method inspired by the mechanism of bruising of living organisms. Another method investigated in this study was the use of shape memory alloys, which have the ability to recover their original shape in shape changes due to temperature and stress. In the following sections, a further examination of these methods, including the efficiency, advantages and disadvantages of the methods, are presented.

### 3. Results

#### 3.1. Using Bacteria to Make Self-Healing Concrete

Bacteria used in concrete should be suitable as a repair agent. For example, these bacteria should be able to close cracks effectively during the useful life of the structure. The main mechanism for closing cracks is that the bacteria themselves act as a catalyst and convert the organic compounds into a suitable filler for cracks [68]. Therefore, for effective self-healing, both bacteria and microstructure compounds must be mixed. However, the presence of bacteria and organic compounds in the microstructure should not have negative impact on other properties of concrete. There are some bacteria in nature that promote bonding and cohesion of concrete microstructure. And these bacteria belong to a specific group of alkali-resistant bacteria formed. An interesting feature of this type of bacteria is that they are able to form eggs that have spherical cells with a thick wall similar to plant seeds (Figure 1). These eggs are viable but inactive and can withstand mechanical and chemical stresses and can survive in the dry state for more than 50 years. In fact, in this process, Bacillus bacteria are used as one of the self-healing agents of self-compacting concrete.

Active bacteria can be seen in Figure 1, and the spores have a diameter of one micrometer. When bacterial eggs are added directly (unprotected) to the concrete mixing plan, their lifespan is limited to one or two months. Continuous cement hydration may be the cause of the bacterial eggs' reduced lifespan from several decades in the dry state to one or two months in the unprotected state at the time of microstructure, which results in holes that are smaller in diameter than bacterial eggs, which have a micrometer diameter [70]. A further concern is whether additional undesired qualities of concrete may be lost as a result of the direct addition of top organic bio-mineral compounds. Leading biomineral substances like calcium acetate, peptone, and yeast juice have been shown in subsequent research to dramatically lower compressive strength.



**Figure 1.** Active bacteria and alkali resistant spores (Electron microscope image)

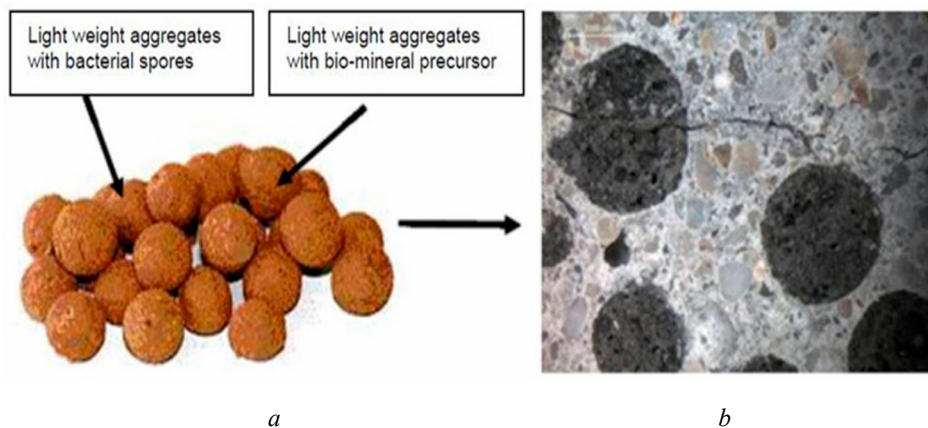
S o u r c e: compiled by H.M. Jonkers [42].

The only exception is calcium lactate, which increases compressive strength by 10% compared to other control samples [68].

Currently, biodegradability tests show that no viability deficiency has been observed for more than 6 months after setting and it is recommended to pay attention to the long-term viability seen in the dry state (when it does not fit in the concrete) [71]. In subsequent experiments, expanded clay particles (LECA) containing two representatives of biochemical compounds were used as additives in the concrete micro-structure to test the repair capacity of concrete-containing concrete [72]. Jonkers [42] investigated the immobilization of these components on porous expanded clay particles in order to extend the shelf life, the related functionality of the bacteria in the concrete, the impact of bacterial spores, and the con-

currently needed biomineral organic compound precursor (calcium lactate). The results showed a significant increase in shelf life.

Its good long-term condition, as observed in the dry state, was maintained when fitted to the concrete, as evidenced by the fact that no loss of spore efficacy was seen after six months of integration [69]. 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 alkaline environments above concrete. This bacterium is called *Bacillus*, which has been able to live long in alkaline lakes in Russia and Egypt. These bacteria, along with their power supply, are embedded in small ceramic pellets and placed in suspension in concrete water to prevent premature activation in the wet concrete mix (Figure 2). The bacteria remain proactive or so-called dormant in the concrete until the crack is formed, and then they are activated by the expansion of the crack and the infiltration of water into the cross section [68; 73].

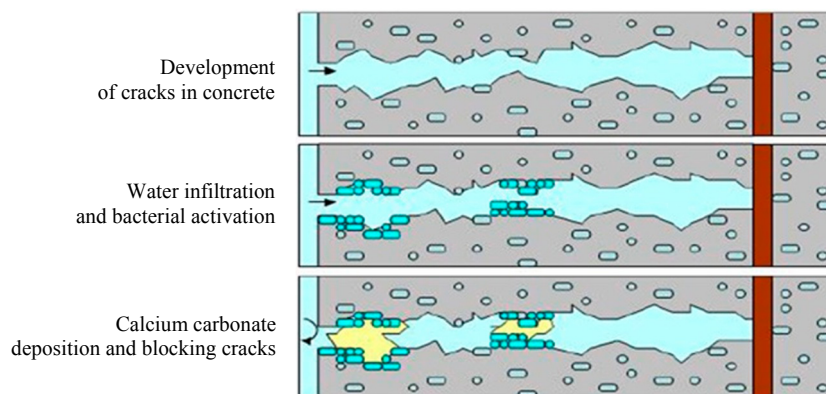


**Figure 2.** Self-healing additives consisting of expanded clay particles: *a* — filled with spore bacteria; *b* — in organic mineral composition (calcium lactate).

S o u r c e: compiled by H.M. Jonkers [42].

Figure 3 shows how to perform the self-healing mechanism using bacteria. According to the figure, after cracking in the concrete section, water penetrates into the section and activates the bacteria. At this point, the bacteria go from dormant to active and block the cracks by producing calcium carbonate deposits. It should be mentioned that prior to the discovery of the bacterium; concrete cracks were repaired using mineral bacterial products. However, because manpower was required to manually install these bacteria in

the damaged area along with considering that the bacteria’s reaction with concrete compounds produced ammonia toxin, the process did not last long or develop much. In this method, concrete test specimens are made where a portion of the aggregate material, for example 2 to 4 mm in size, is replaced with clay particles, which contain self-healing biochemical bacteria. Before carrying out the work, the load-bearing clay particles inside it (for a week at 40°C) are dried so that no more weight loss is observed due to water evaporation [71].



**Figure 3.** The process of repairing cracks in smart concrete by bacteria  
 Source: compiled by K. Van Breugel [74].

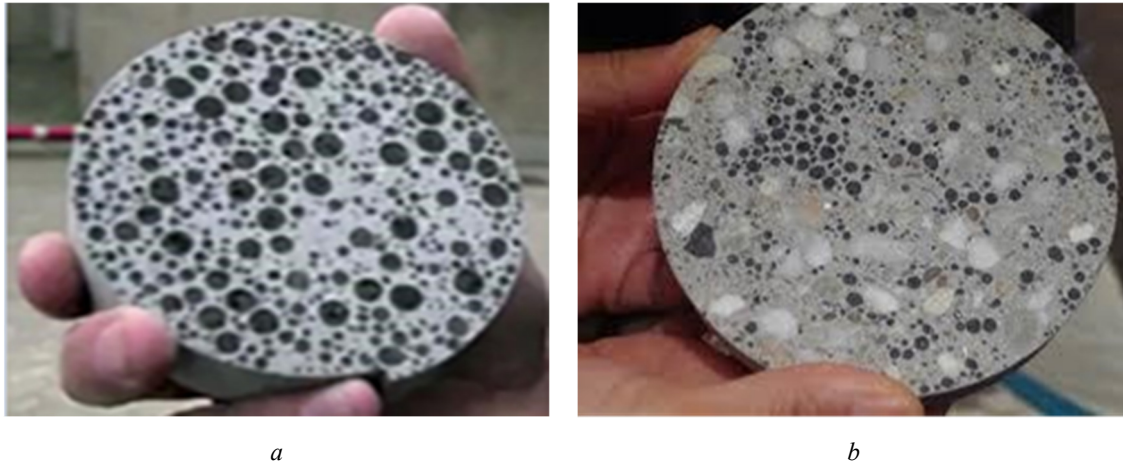
The concept of the bacterial-based crack repair mechanism (Figure 3) is expected in this question. It states that after the concrete breaks, the bacteria in the cracks start to grow with water by precipitating minerals like calcium carbonate to seal the fissures and shield the steel from chemical attacks from the outside world. The aggregates used in this case make up about 50% of the total grain size. Replacing high-fracture sand and gravel with expanded clay particles will have consequences for the strength properties of the derived concrete. In this particular case we will have a 50% reduction in compressive strength after 28 days of processing compared to samples with similar compositions but without replacement of crushed sand with LECA. [68]. Although samples containing expanded clay (LECA) show a substantial decrease in strength, the repair capacity of cracks in the samples increases dramatically where expanded clay particles containing bacteria and the leading organic mineral compounds (calcium lactate) are used.

In concrete test specimens, identically sized expanded clay particles loaded with the biochemical self-healing agent (bacterial spores  $1.7 \times 10^5 \text{ g}^{-1}$  expanded clay particles, corresponding to  $5 \times 10^7 \text{ spores dm}^{-3}$  concrete, plus 5% w/w fraction calcium lactate, corresponding to  $15 \text{ g dm}^{-3}$  concrete) were used to replace a portion of the aggregate material, or the 2–4 mm size class. Loaded expanded clay particles were oven-dried for one week at 40°C prior to application, or until no more weight loss from water evaporation was noticeable. Although the aggregate composition of the control specimens was comparable, the biochemical agent was not present in these enlarged clay particles. Expanded clay particles of both kinds loaded for bacterial specimens and empty for control specimens were checked. Table displays the composition of the concrete sample. The self-healing capacity of precracked concrete specimens is determined from cylindrical specimens treated with water for 50 days using very fine microscopic images before and after permeability [73]. Before that, the precracked concrete specimens are glued in an aluminum ring and permeability testing is performed on them. Cracks in concrete specimens (1.5 cm thick and 10 cm in diameter) are formed in a controlled manner using compressive and tensile stresses (Figure 4, a).

**Compositions of concrete samples**

Compositions	Volume, cm <sup>3</sup>	Mass, g
LWA, 2–4 mm LECA	196	167
LWA, 1–2 mm LECA	147	125
Sand, 0.5–1 mm	147	397
Sand, 0.25–0.5 mm	128	346
Sand, 0.125–0.25 mm	69	186
Cement	122	384
Water	192	192
Total	1001	1796

Source: compiled by A.M. Neville [73].



**Figure 4.** Concrete with special additives:  
*a* — with microcapsules containing crack fillers; *b* — self-healing concrete

S o u r c e: Bio-Concrete: The Walls are Alive. Available from:  
<https://sigearth.com/bio-concrete-the-walls-are-alive> (accessed: 22.04.2025).

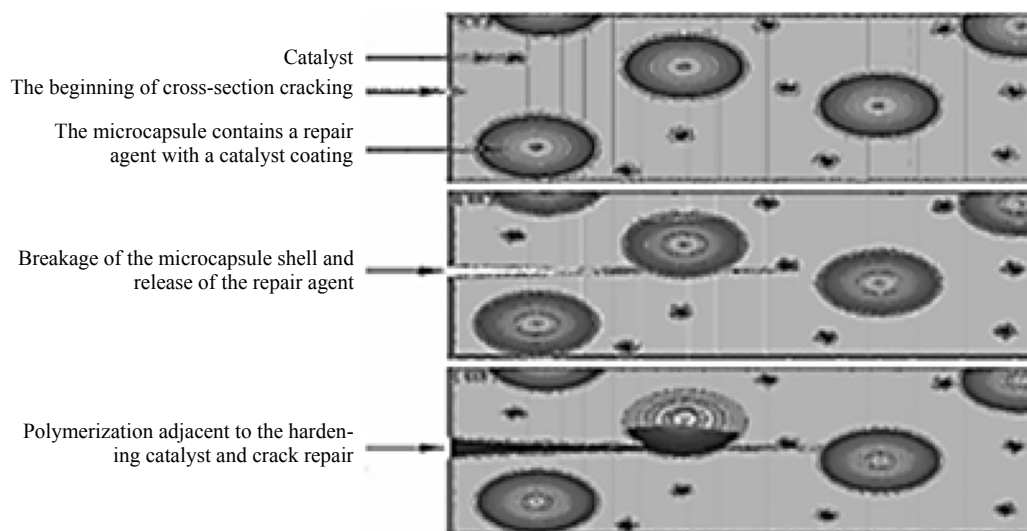
The resulting cracks are cracks 8 cm long that occur at a depth of 0.15 mm and a thickness of 1.5 cm along the sample. After the formation of cracks, both control samples containing expanded clay particles (LECA), without bacterial eggs and organic compounds, and samples containing bacteria to which expanded clay particles containing bacterial eggs and organic compounds were added, were submerged for 2 weeks. They are placed at room temperature. The permeability of all cracked samples is then automatically determined by the computer by recording the amount of water penetration within 24 hours. Comparison between control concrete specimens and specimens containing bacteria (Figure 4, *b*) shows major differences in permeability and, of course, in repair capacity or ability. The cracks of the 6 samples containing the bacteria are completely closed, meaning that we no longer have any permeability (0 ml/h), but only 2 of the 6 control samples almost recover; the other 4 samples will have water permeability 0 ml/h to 2 ml/h [69]. Microscopic testing of the cracks (shown next to the concrete specimen in the water column) indicates that calcium carbonate deposition occurs on the basis of mineral sediments in both control and bacterial specimens. Calcium carbonate deposition in concrete specimens occurs significantly near the edges of the cracks, which prevents the main parts of the cracks from being repaired, while in samples containing bacteria, we have complete and effective repair of cracks, in which case mineral deposition often occurs inside the cracks.

### ***3.2. Use of Filled Microcapsules to Repair Concrete (Micro Encapsulated Healing)***

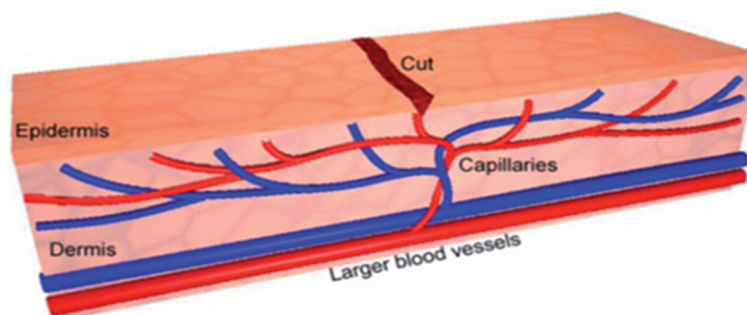
In this method, inspired by red blood cells in blood clotting and repair, very small capsules are injected into the concrete as a repair agent. The microcapsules carrying the repair agent are usually made of polymer particles embedded inside the capsule and with a catalyst coating in the body. The microcapsules are broken during impact with the crack and in the vicinity of the catalyst, they perform the polymerization action and by forming construction materials, they repair the cracks in the concrete [75]. In fact, spherical microcapsules act like red blood cells and catalysts act like platelets in the process of blood clotting when repairing an incision in the skin (Figure 5).

In this method, by increasing the number of microcapsules, the homogeneity and uniformity of concrete may be affected and may reduce the strength and toughness of the concrete piece. Therefore, in order to improve performance, there is a need to inject repair fluid through an intelligent system. Recent research indicates the possibility of micro vascular network in the form of transfer of the repair agent, relying on the capillary property from the source to the site of failure and polymerization in the vicinity of the catalyst,

resulting in the formation of hard material and crack repair. Future research will seek to develop a capillary network in the concrete carrying the restorative agent, as intelligently as the biological system. This method is based on intelligent methods that self-repair to close the cracks created in the concrete section. The capacity of microvascular networks to facilitate the repeated repair of damage in both synthetic and biological systems is particularly intriguing. For instance, damage to human skin may be repaired repeatedly in one place (Figure 6).



**Figure 5.** Mechanism of action of microcapsules in crack repair in self-compacting concrete  
Source: compiled by M. Nejadi [76].



**Figure 6.** Concrete healing by a capillary network for the development and installation of microcapsules inspired by a biological system  
Source: compiled by M. Nejadi [76].

### 3.3. Heat Zone Selector Method (Selective Heating)

Formerly, one of the most efficient and intelligent self-healing systems is the heating zone selector system. This system consists of two main parts:

1. Self-diagnostic composites made of fibers and conductors of electricity that also have the capability of a strain gauge and as an efficient material have the ability to record the time history of failure in the structure.

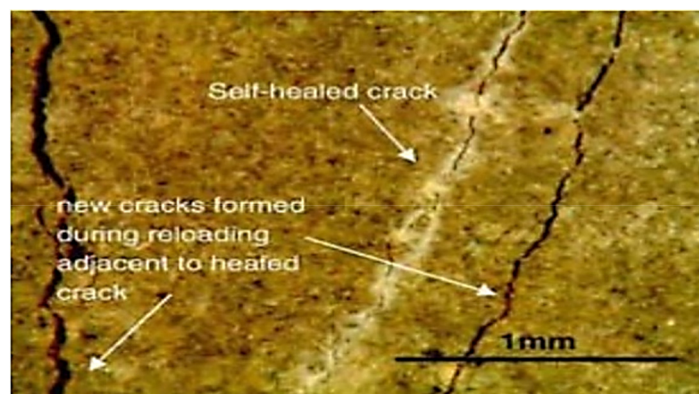
2. The repair part (Heat-Plasticity Organic Film Pipe), which consists of pipes made of materials with plasticity and ductility against heat and the content of the repair agent, in such a way that they prevent the repair agent from leaving before spreading any cracks. When a crack occurs in the part, the first part detects

a slight strain at the crack site as a sensor and by sending a message to the repairing part (like the function of neurons in the body of living things), the repairing agent is released and repairs the crack [75]. Of course, the design of this system, which uses thermal energy to repair the release of the repair agent trapped in the coating, is associated with many sensitivities. So that the increase in temperature in concrete should not lead to evaporation of internal water and disintegration of the internal structure or any other harmful process for the strength and functional properties of concrete. This system, when completed, can provide external human control to the demolition process outside the structure by monitoring information and pathology and displaying defects, which will lead to a huge change in the concrete improvement and repair industry in sensitive structures.

### 3.4. Use of Cement Composites for Automatic Repair of Concrete (Engineered Cementitious Composite-ECC)

The performance of concretes that are made using only engineered cementitious composites (ECCs) is inspired by the healing of injuries to living organisms.

This system does not allow cracks to spread and to create deep cracks as it is continuously repairing the resulting small cracks (injuries), even if the damaged concrete piece is repeatedly loaded. In fact, the most important characteristic of ECC is that only hair-wide cracks with a maximum width of 60 micrometers will be possible to repair, instead of deep cracks in concrete. In other words, new concretes (ECC) have a considerable flexibility compared to conventional concretes [68]. Research shows that the use of fly ash pozzolans in ECC greatly improves the performance and repair of concrete. Air ash reacts with calcium hydroxide from the hydration process of cement to produce a white gel that is capable of suturing hair-wide cracks and self-healing (Figure 7).



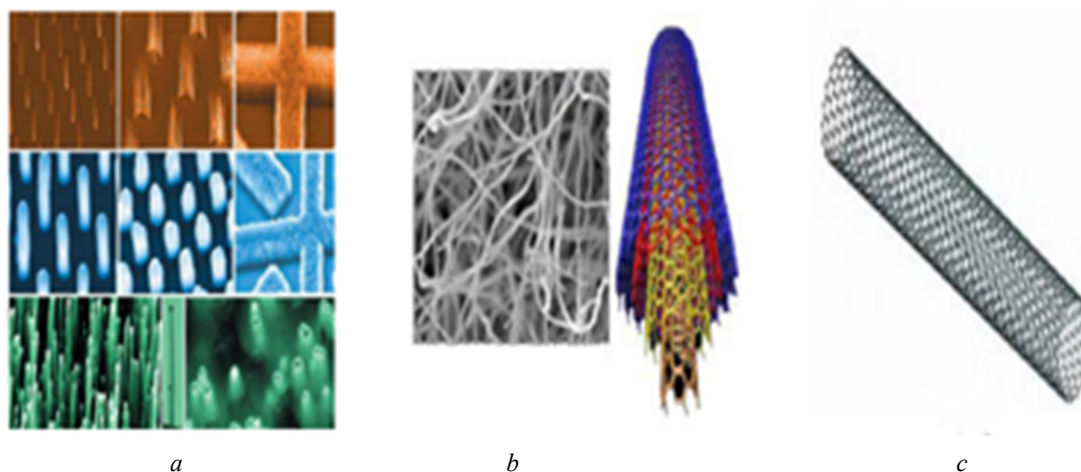
**Figure 7.** Self-repair of cracks in ECC concrete and expansion of cracks after reloading

Source: compiled by M. Nejati [76].

This type of self-repairing concrete is very important for protection of reinforced concrete in corrosive environments such as chlorinated environments where the possibility of chlorine ions dissolved in water can penetrate through micro cracks and start corrosion of reinforcements and as a result to reduce the overall strength of reinforced concrete.

### 3.5. Carbon Nanotubes

Carbon nanotubes (CNTs) are an allotropic form of carbon that was first discovered in Russia in 1952 but forgotten. It again found a special place in the nanotechnology circle in 1990. Nanotubes are produced in cylindrical forms of Single Walled Nano Tubes (SWNT) and Multi Walled Nano Tubes (MWNT) with length up to several millimeters (Figure 8).

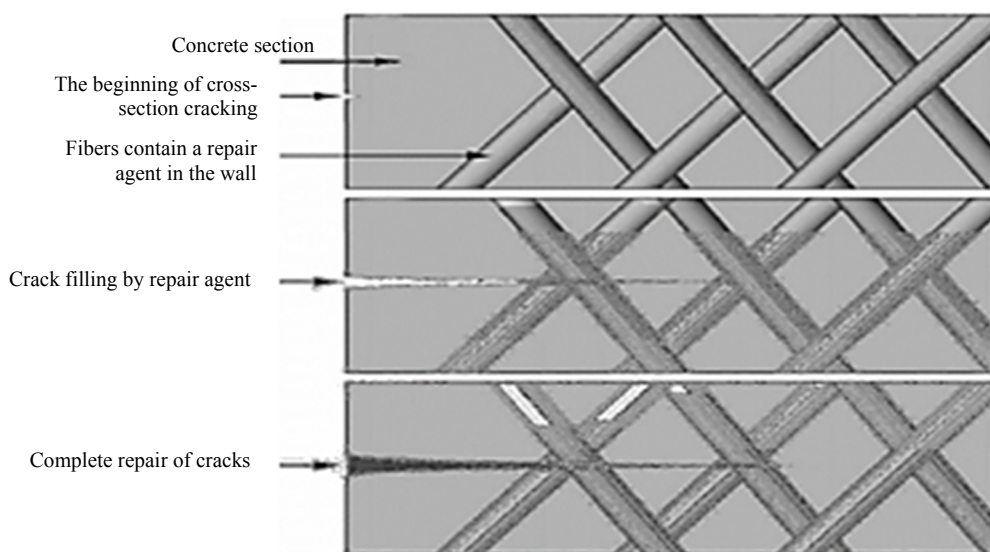


**Figure 8.** Different types of carbon nanotubes:  
*a* — Single-walled carbon nanotubes; *b* — multi-walled carbon nanotubes, *c* — CNT pipes are magnified  
 Source: compiled by M. Nejati [76].

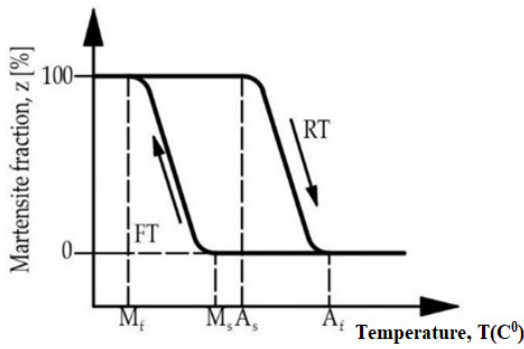
The mechanical properties of the concrete can be improved by adding small amounts of CNT (about 1 wt.%) to the cement mixture. These nanomaterials are also used in self-healing concrete processes. Of course, the main problem of using CNT in concrete is the connection of nanotubes to each other as strings and lack of sufficient adhesion between them in concrete [71]. Research is still ongoing to investigate how these materials are used in the self-healing process.

### 3.6. Use Hollow Fibers

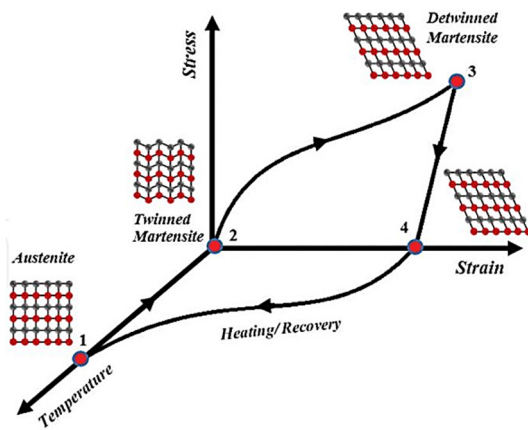
In the method of using fluorescent dyes in the current repair agent in these fibers, the phenomenon of bruising in living organisms is simulated, which itself plays an important role in identifying the site of injury. The repair agent is released from a thin hollow fiber to fill the cracks, and as a result the crack is repaired [71]. The mechanism of repairing by hollow fiber method is shown in Figure 9.



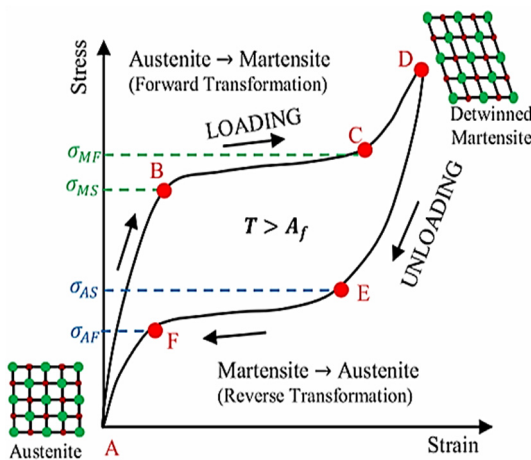
**Figure 9.** Mechanism of crack repair by hollow fiber method  
 Source: compiled by M. Nejati [76].



**Figure 10.** Behavior of shape-memory alloys in stress-free state and under the influence of temperature changes  
 Source: compiled by A. Cladera [82].



**Figure 11.** Stress-strain curve of super-elastic Property  
 Source: compiled by D.C. Lagoudas [83].



**Figure 12.** Stress-strain curve of shape memory property  
 Source: compiled by D.C. Lagoudas [83].

### 3.7. Using of Memory Alloys in Intelligent Self-Compacting Concrete

Shaped memory alloys are alloys with special ability to recover their original shape after deformation due to temperature and stress. In 1932, the Swedish scientist Lander first discovered super-elastic behavior in cation gold (Au-Cd) [79]. In 1951, Cheng and Reed discovered a reversible phase conversion in the same alloy, which is also the first recorded phase conversion. In 1963, Boiler and colleagues at the US Naval Weapons Laboratory discovered a shape memory effect on a nickel-titanium (Ni-Ti) alloy and named it Nitinol [26]. About 30 types of memory alloys have been reported so far [80].

The reason for the unique behavioral properties of shape-memory alloys should be sought in their multiphase or multi-structural nature. In other words, the arrangement of the atoms of shape-memory alloys within their crystal lattice gives rise to two states of behavior, martensite and austenite. The austenitic state is stable at high temperatures and low stresses and is responsible for super-elastic behavior. Martensite is stable at low temperatures and is responsible for developing shape memory behavior. When the material is cooled (without stresses), the first phase transition, known as a martensitic (or forward) transformation (FT), takes place. At the temperature  $M_s$  (martensite start), the martensite starts to form, and at the temperature  $M_f$  (martensite completion), the process is complete. Heating the material (without any stresses) causes the reverse transformation (RT), which starts at the austenite start temperature ( $A_s$ ) and ends at the austenite finish temperature ( $A_f$ ). Figure 10 illustrates these procedures. Different forms of martensite phase can also be converted to each other at low temperatures and form the process of reorientation or pairing and non-pairing. Figures 11 and 12 show the strain stress curves for super-elastic behavior and memory property [81].

### 3.8. Performance of Self-Healing Concrete

Self-healing concrete works in such a way that when a crack is created in it and a very thin white layer of calcium carbonate acts and prevents the spread of cracks and it actually repairs cracks. Calcium carbonate is a very resistant compound that is found in nature in abundance in strong fortifications such as turtles and snails. Wetting and drying the concrete to repair the joint may take between 4 and 5 times [85]. Today, builders reinforce concrete with steel bars to keep them as small as possible. But still these cracks are not small enough to be repaired because of the salts that sometimes penetrate the concrete through the cracks for

defrosting. They cause corrosion in reinforcements and reduce the overall strength of reinforced concrete. Self-repairing concrete is completely safe from corrosion as it does not need to be reinforced and reinforced to keep cracks small. By reversing the process of concrete deterioration and significantly reducing costs and environmental effects in creating new buildings, using this self-healing concrete, the building can be restored for a longer period and self-healing concrete can be used optimally. Regarding the new scientific achievement of self-healing concrete, which has attracted the attention of the civil engineering scientific community, there are a few notable points that we will address:

- More comprehensive information explaining how this project works and detailed test results will soon be available to the public in future issues of several prestigious scientific journals as well as the University of Michigan Science Database. Professor Victor Lee, the original inventor of this material in 2009 at the International Conference on Self-Repairing Materials in Chicago, presented all the results and performance of this material in the article entitled “Automatic repair process of cementitious compounds in wet cycles” and offered multiple drying.

- According to the project’s researchers, they are currently studying how to enter the construction industry. Imagine buildings that do not use reinforced concrete or the volume of use of steel materials in it is significantly reduced, this equates to a significant resistance deduction from their manufacturing costs or even imagine that there is no need for long-term retrofitting and restoration of structures as before. All these ideas create only one result in the minds of engineers and specialists, that self-repairing concrete made a revolution in the construction industry.

- Another point to note is how the researchers from the University of Michigan have achieved these astonishing results in recent scientific achievement. Previously an article was presented about a new bracing system for tall structures reinforced with concrete with steel fibers, which was also one of the recent scientific achievements of the University of Michigan.

The key results of the study on advanced self-healing and smart concrete technologies yielded significant findings in terms of material performance, durability and sustainability are summarized below:

### 1. Self-Healing Efficiency

#### Bacterial Self-Healing Concrete:

- Achieved 100% crack closure within two months, compared to only 33% in conventional concrete.
- Bacillus bacteria, embedded in porous expanded clay (LECA), produced calcium carbonate ( $\text{CaCO}_3$ ) to autonomously seal cracks.
- Bacterial viability increased from 2 months (unprotected) to 6 months (protected in LECA), enhancing long-term self-repair capability.

#### Microencapsulation & Hollow Fibers:

- Microcapsules filled with healing agents (e.g., polymers) ruptured upon cracking, releasing repair material.
- Hollow fibers demonstrated self-repair efficiency by mimicking biological bruising, enabling crack detection and sealing.

### 2. Mechanical & Durability Enhancements

#### Nanotechnology in Concrete:

- Nano-silica and carbon nanotubes (CNTs) improved compressive strength, impermeability, and resistance to chloride penetration.
- Challenges included uniform nanoparticle dispersion and high-water absorption, requiring optimized mixing techniques.

#### Shape Memory Alloys (SMAs):

- Nickel-Titanium (Ni-Ti) alloys enabled crack recovery through super-elasticity and shape memory effects, reducing structural deformation.

3. **Biological Concrete for Sustainable Facades.** Three-layer biological concrete system (waterproofing, biological, and discontinuous cover layers) supported moss and microalgae growth.

Benefits included:

- CO<sub>2</sub> absorption & O<sub>2</sub> production (improving air quality).
- Thermal regulation (reducing building energy consumption).
- Self-sustaining vegetation without external irrigation.

#### 4. Smart Concrete & AI Integration

- Self-sensing concrete with embedded sensors allowed real-time crack detection and dynamic load analysis.
- AI-controlled neural networks optimized self-healing responses, improving structural longevity.

#### 5. Challenges & Limitations

- High production costs of nanomaterials and bacterial additives to concrete.
- Short-term viability of bacteria in harsh concrete environments.
- Scalability issues for large-scale construction applications.

### 4. Conclusion

In recent years, the technology of making concrete to compensate for the disadvantages in concrete has made a lot of progress. The use of complex approach to concrete or the use of special cements leads to some special features of concrete. According to the above, it can be said that in fact concrete is intelligent and lively material that is able to be changed including through nanotechnology.

The concrete industry is one of the most widely used industries today, and in recent years, the amazing achievements of nanotechnologies to improve its behavior and performance, has evoked a unique way in this industry for researchers. Meanwhile, the process of self-healing, by imitating what happens in the body of living organisms to deal with damage, is being developed with extensive research. Obviously, the development of these methods and their application in the construction industry will have a great impact on increasing the safety of structures in line with the goals of sustainable development. Also, the current high costs of nanotechnology products, with mass production and consideration of long-term return on investment due to increased useful life of the structure and reduced repair costs, will be economically justified. On the other hand, inactive bacteria embedded in LECA can significantly self-repair and close cracks created in concrete sections. Based on what has been stated by different researchers, it was observed that *Bacillus* was suitable for use as a repair agent for self-compacting concrete cracks, because there was 100% crack recovery in 2 months in concrete samples containing bacteria, while in the control samples there was 33% crack recovery.

The viability of bacterial eggs increases from 2 to 6 months when added to LECA in a protected form compared to direct (unprotected) addition. From this study it can be concluded that active bacteria due to mineral deposition, can cause effective closure of cracks and at the same time reduce the permeability of concrete. The future of construction lies in the development of smart, self-sustaining materials that enhance durability, reduce maintenance costs, and minimize environmental impact. This study explored the integration of nanotechnology, biotechnology, and artificial intelligence in concrete production, leading to groundbreaking advancements such as self-healing concrete, biological concrete, and intelligent self-compacting concrete. The main findings show that:

1. Nanomaterials (nano-silica, carbon nanotubes) significantly improve concrete's mechanical properties, impermeability and resistance to environmental degradation.
2. Microbial self-healing concrete (using *Bacillus* bacteria) achieves 100% crack closure within two months, compared to only 33% in conventional concrete, through bio-mineralization (calcium carbonate precipitation).
3. Biological concrete integrates vegetation into structural elements, offering thermal regulation, CO<sub>2</sub> absorption, and aesthetic benefits, while self-healing mechanisms eliminate the need for manual repairs.
4. Smart concrete leverages shape-memory alloys, microcapsules, and hollow fibers to autonomously detect and repair damage, extending structural lifespan.

Despite challenges such as high production costs, nanoparticle dispersion, and long-term bacterial viability, these innovations represent a paradigm shift toward sustainable, resilient, and intelligent infrastructure. Future research should focus on scaling production, optimizing cost-efficiency, and ensuring environmental safety to facilitate widespread adoption. By embracing these advancements, the construction industry can move toward self-repairing, energy-efficient, and eco-friendly structures, revolutionizing how we build for generations to come.

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