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Incorporating Bacteria for Self-Healing Properties in Innovative Concrete Technology

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Abstract

Nanotechnology is poised to offer a viable solution for achieving high performance in future construction projects. Among the innovative technologies being explored, smart concrete has garnered significant attention and undergone extensive research in reputable scientific centers worldwide in recent years. A notable advancement within this field is the development of self-healing concrete. Concrete structures are undeniably susceptible to cracking, primarily due to natural processes. These cracks serve as pathways for harmful substances to infiltrate and corrode the reinforcement bars, ultimately leading to the degradation of the concrete. Traditional approaches to address this issue involve the use of repair materials, particularly various polymers. However, these materials not only complicate the repair process but also have adverse environmental consequences. In light of these challenges, scientists have discovered an alternative method that involves incorporating bacteria into concrete production to create self-healing properties. This method not only reduces maintenance and repair costs but also minimizes environmental impact, thereby enhancing the durability and performance of the concrete while extending its service life. By harnessing the power of bacteria, self-healing concrete represents a significant breakthrough in sustainable construction practices. (DOI:**https//doi.org/10.52547/JCER.5.4.31**)

Keywords: Concrete; Self-healing; Bacteria; Smart concrete; Civil engineering

1. Introduction

Currently, one of the most prominent and widely discussed topics in scientific communities worldwide is nanotechnology. Among the various innovative technologies within this field, smart concrete has garnered significant attention and has been extensively studied in reputable scientific institutions globally [1]. One specific area of focus is self-healing concrete. Concrete plays a vital role in civil engineering projects and is extensively utilized in infrastructure development. However, it is an undeniable reality that concrete structures are susceptible to cracking. Natural processes such as ground settlement, earthquakes, moisture fluctuations, and temperature variations contribute to the formation of cracks in concrete, allowing harmful substances to penetrate and corrode

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the reinforcement bars, ultimately leading to the deterioration of the concrete structure [2, 3]. To address this issue, it becomes imperative to enhance the quality of concrete. Nevertheless, completely preventing cracking is only achievable to a certain extent and often involves substantial costs. Therefore, scientists have turned to researching the use of bacteria in concrete production for self-healing concrete technology, which significantly increases the durability and service life of concrete [4]. The creation of microcracks in concrete is an undeniable reality, and traditional methods combat this issue by using repair materials, particularly various polymers, which not only incur high costs but also have negative environmental impacts. The alternative method that scientists have discovered involves using bacteria in concrete production to create self-healing concrete. This method not only reduces maintenance and repair costs but also has minimal environmental impact, contributing to the durability and performance of concrete and extending its service life [5, 6].

2. Concrete repair using traditional methods

Concrete repair using traditional methods begins from the time of the first concrete casting, but this term is mostly used for surface repair after cracking, spalling, and overall concrete deterioration. To initiate the repair process, a proper and comprehensive assessment of the cause and impact of concrete deterioration must be conducted. Based on the results of this assessment, the appropriate materials and repair method can be determined. The repaired surface of the concrete should replace the damaged concrete and restore the required structural performance, similar to its initial state, while also protecting the underlying layer [7, 8]. All potential stresses in the consumable materials of the repaired section, as well as stresses at the interface between the repaired section and the underlying concrete layer, need to be examined and analyzed. Stresses in the repaired section occur due to relative volume changes between the repair area and the underlying concrete layer, as well as various types of loading. Stresses in the repaired section should be within the capacity of existing materials and new materials; otherwise, failure may occur [9]. In areas where some materials are affected by different stresses, they are redistributed around the repaired section multiple times. To prevent additional negative effects on the repaired section during reloading, complete load transfer should be achieved from adjacent members through shoring and jacking during repair operations. Repair materials should be fully utilized and applied until reaching a predetermined strength capable of bearing loads before reloading is performed on the targeted member to avoid any damage to the repaired section [10].

3. Repair materials

To select the appropriate repair materials, a proper understanding of the behavior of these materials in different operating and non-operating conditions, as well as in various environmental conditions, is necessary. One of the major challenges for successful performance of repair materials is their behavior relative to the underlying layer or existing concrete. Relative dimensional changes can create internal stresses in the repair materials and the underlying layer, which can lead to tensile cracking or failure. To minimize these stresses, repair materials should be chosen that have relative dimensional changes compatible with the existing structure.

Another challenge in selecting repair materials is their suitability for structural applications. The ultimate goal of selecting repair materials is to restore the stress tolerance level in the repaired section to its pre-damaged state [11, 12]. To fully achieve this goal, the following factors should be considered: firstly, during the repair process, loading should be removed from the targeted area; secondly, there should be a compatible interaction between the repaired section and the underlying or adjacent section, which is often quite challenging; thirdly, suitable materials should be found that can completely fill cracks or voids without undergoing excessive shrinkage during the repair process; and finally, they should exhibit behavior similar to the original concrete in terms of initial deformations [13-15].

In most cases, cementitious materials such as mortar and well-graded aggregate materials are used for deep repairs. The durability of these repair materials can be enhanced by adding special pozzolans such as microsilica, polymers like latex, or permeability-reducing additives. When using repair materials containing Portland cements, attention should be paid to shrinkage and concrete processing phenomena. It is important to use materials with minimal shrinkage whenever possible [16, 17].

4. Methods and Practical Tips for Repairing Concrete

In each of the methods for implementing repair materials, the selected repair materials should be able to be applied onto the prepared underlying layer according to the technical specifications. The repair materials should have proper and sufficient adhesion and bonding with the existing layer, fill the voids, and completely cover the reinforcement. The adhesion of repair materials to the underlying layer largely depends on the mechanical interlock with the prepared concrete surface. Sufficient force should be applied to the repair materials to establish complete contact with the prepared surface in order for this to occur [18, 19]. Additionally, the repair materials should have sufficient flowability to penetrate into the voids of the underlying layer and interact with the prepared surface. The method of applying load to the repair materials depends on the desired level of adhesion and varies depending on the implementation technique. In methods that involve troweling, for example, pressure applied during troweling can cause the repair materials to enter into voids and irregularities on the prepared surface [20-22].

5. Protection of repaired concrete

Concrete structures are exposed to various conditions that may have undesirable effects on their performance. These unfavorable conditions can sometimes occur even after repair, resulting in the failure of the repair operation and damage to the repaired structure. Protective measures are implemented to control and prevent the causes of failure and improper utilization of the structure. These measures include: 1. Improving operating and environmental conditions, 2. Enhancing the physical properties of concrete, 3. Installing a barrier between environmental conditions and concrete, 4. Modifying electrochemical behavior when steel corrosion occurs within reinforced concrete.

Protective methods for concrete are usually selected in a way that allows for longer intervals between repair and maintenance cycles. Protecting concrete against aggressive operating and environmental conditions and damaging agents is achieved through the use of coatings, membranes, coverings, and sealants [23, 24]. However, protecting concrete in terms of improper utilization of the structure involves modifying and changing conditions that disrupt the operation of the structure. There are various techniques and methods for protecting concrete. Protective systems can be installed during construction or at any time during the lifespan of the structure. Good design for new buildings ensures the fulfillment of expected protective requirements. Protecting existing structures is usually more challenging and provides us with fewer choices compared to new buildings. The goal of protective strategies is to prevent corrosion of reinforcing steel in concrete, which can lead to cracking, delamination, and spalling of the concrete layer. One important cause of steel corrosion is the ingress of chloride ions. Protecting steel against corrosion involves directly combating the corrosive effects of chlorides [25-27]. The application of an epoxy coating by fusion bonding onto the reinforcement is the most common method for coating rebars. Additionally, additives in concrete mixtures, such as calcium nitrite, can prevent chloride-induced damage. Another method for protection against chlorides is low permeability concrete. One effective approach to reduce chloride ion penetration in concrete is the use of surface coatings and penetrating sealers. Penetrating sealers include silanes and siloxanes, while surface coatings include epoxies, urethanes, chlorinated rubber, and methacrylates [28, 29]. Carbonation is another condition in concrete that allows for the occurrence of corrosion in the presence of moisture and oxygen. Carbonation of concrete occurs when it comes into contact with acidic gases, and the best way to combat it is by using low permeability concrete. The attack of aggressive chemicals on the surface of concrete can be controlled by adding chemical-resistant materials to the concrete mixture or by using surface coatings, membranes, or other surface protection systems [20, 30, 31].

6. Self-healing concrete

One of the smart concretes that has gained attention in recent years is self-healing concrete. Imagine concrete materials that, when cracked, can self-initiate repair and reconstruction without human intervention, solely through water and carbon dioxide. The creation of microcracks in concrete is an undeniable reality, and traditional methods for dealing with it involve the use of concrete repair materials, especially various polymers, which not only incur high costs but also have adverse environmental effects. The alternative approach that scientists have discovered is the use of bacteria in concrete and the production of self-healing concrete, which not only reduces the costs of concrete repair and maintenance but also contributes to the durability and performance of concrete, increasing its service life [32-34]. Under flexural conditions, self-healing concrete only experiences small flexural cracks, whereas non-reinforced conventional (ordinary) concretes would exhibit significant failure and collapse with the same amount of flexural deformation [35].

We can demonstrate this concept using a straightforward illustration. When a human hand sustains a minor scratch, as long as the size and depth of the scratch are small, the body has the ability to naturally heal it without difficulty. However, if the injury is significantly extensive and deep, external surgical procedures such as sutures are required. The performance of self-healing concretes follows a similar pattern in that continuous healing and maintenance of small cracks prevent their propagation and the formation of deep fissures, even under repeated loading of the concrete specimen. The initial report on this matter was made public in April 2009 by a team of researchers from the University of Michigan. Professor Victor Li, the original creator, conducted a series of experiments on self-healing concrete, and we will now delve into the findings of his study.If the applied force increases the length by up to 3%, this sample repairs the resulting cracks or, in other words, withstands this level of strain. Steel in this state undergoes minimal deformation, while ordinary concrete collapses dramatically. Furthermore, in Europe, specifically in the Netherlands, a group of researchers also delved into this subject [35-37]. Henk Jonkers from Delft University of Technology in the Netherlands invented a bio-concrete that can self-heal using bacteria. This concrete is composed like other regular concretes but has an additional primary material that facilitates its self-repair. This material remains untouched during the mixing process and only becomes active if cracks occur in the concrete and water penetrates. He initiated this project in 2006 when a concrete specialist asked him if it was possible to use bacteria in concrete to create self-healing properties. It took Henk Jonkers several years to solve this issue, but there were still some challenges that needed to be overcome. He needed a type of bacteria that could survive in the harsh environment of concrete [38, 39]. Concrete is a hard and very dry material. It is highly alkaline, and the repairing bacteria had to remain inactive for years until activated by water. He used Bacillus bacteria for this purpose because these bacteria can survive in alkaline conditions and produce spores that can remain alive for decades without food or oxygen [40].

The next challenge was activating the bacteria in the concrete. Additionally, these bacteria had to produce repairing materials for the concrete, which turned out to be limestone. The bacteria needed to be fed to produce limestone. They could have used sugar, but sugar weakened the concrete. Ultimately, they used calcium lactate, and they encapsulated the bacteria with calcium lactate inside plastic capsules. These capsules were added to moist concrete. When the concrete cracked, water penetrated it and caused the capsules to open. The bacteria then grew, multiplied, and fed on the calcium lactate. In this process, calcium combined with carbonate ions to form calcium carbonate or limestone, which filled the crack [41].

7. Scientific investigation of the use of bacteria in concrete

In order to achieve high-quality concrete, various materials such as fly ash, blast furnace slag, silica fume, metakaolin, and similar substances have traditionally been used as additives. However, a recent advancement in technology known as bacterial mineral precipitation has emerged. This innovative approach involves the use of specific microorganisms within the concrete that engage in metabolic activities to initiate precipitation. The result is an enhancement in the long-term durability and stability of concrete properties. This process can occur either inside or outside microbial cells, or even at a distance from them within the concrete matrix. The effectiveness of these bacteria often relies on their ability to alter the chemistry of the solution present in their environment, thereby creating supersaturation and facilitating mineral deposition [42].

The use of this biomineralization technology in concrete has created a new potential for innovations in producing a new type of concrete known as bacterial concrete. Bacterial concrete is designed and constructed based on the ability of bacteria to precipitate calcite. The carbonate precipitation, known as Microbially Induced Calcium Carbonate Precipitation (MICP), has proven its high capability in filling cracks and fine fissures in granites, stones, and sands as a microbial sealant. The calcite precipitation technology using bacteria is an attractive and valuable process. The major appeal of this technology stems from its environmentally friendly nature and natural occurrence. This technology can be used to improve the compressive strength and hardness of cracked concrete specimens or concrete structures under tensile stress [43, 44].

Bacteria can continuously produce an impermeable layer of extraordinary calcite on the surface of concrete. The formed precipitation has a coarse crystalline structure that easily adheres to the surface of the concrete in the form of shells. In addition to their continuous production and growth capability, these exceptional layers are highly impermeable to water. They resist the penetration of harmful agents such as chlorides, sulfates, and carbon dioxide into the concrete, thereby reducing the detrimental effects of these factors on the concrete [45, 46].

Due to the inherent ability of bacteria to continuously precipitate calcite, this type of concrete can be considered as a smart biomaterial for concrete repair. The acidity or pH is an important factor in the activity or inactivity of bacteria in the concrete environment. The fundamental mechanism of bacterial crack healing is based on bacteria acting as catalysts, converting the initial materials into a suitable filler. The newly produced materials, such as calcium carbonate-based minerals that precipitate, should act as a type of bio-cement and effectively seal the created cracks. Therefore, both bacteria and initiator materials should be present for effective self-healing capability in concrete. The presence of these added materials should not alter the desired properties of the concrete [47, 48]. Bacteria that can tolerate the concrete environment are naturally occurring and belong to a specific group of alkali-resistant spore-forming bacteria. An interesting characteristic of these bacteria is their production of thick-walled spherical cells similar to plant seeds. These spores can exist as dormant cells within the concrete and withstand environmental stresses. In dry environments, these bacteria can remain alive for over 50 years. Unfortunately, when these bacteria are directly added to concrete, their lifespan is limited to one or two months [49]. The reduction in spore lifespan from several decades in a dry environment to several months in concrete may be due to continuous hydration of cement. It is important to note that adding organic-mineral initiator materials to concrete should not result in a reduction in concrete properties. Previous studies have shown that these materials, such as yeast extract and calcium acetate, significantly reduce compressive strength in concrete. The only exception is calcium lactate, which increases strength by up to 10% compared to the initial sample [8, 50, 51].

8. Types of bacteria used in concrete

The types of bacteria that have been investigated for their application in bacterial concrete include: Bacillus pasteurii, Bacillus sphaericus, Escherichia coli, and Bacillus subtilis. These bacteria have been used in the production of bacterial concrete and have contributed to improving its properties, mainly through the process of calcium carbonate precipitation induced by bacterial activity. As mentioned earlier, this process is referred to as bacterial-induced mineral precipitation. Calcium carbonate precipitation is carried out by many bacteria and is a common process among them, which has led to its scientific investigation by many researchers [52-54]. The mechanisms of action of bacteria in the formation of calcareous precipitates have been proposed to be diverse. Based on research conducted in this field, it has been accepted that the activity of bacteria can be influenced by various chemical and physical parameters of the environment. It can also be dependent on metabolic activity and surface structure of the bacterial cells. In general, suitable metabolic pathways for increasing the alkaline pH of the environment can lead to the precipitation of calcium carbonate in the presence of calcium ions. In some studies conducted to investigate the increase in bacterial lifespan in concrete environments and the influence of factors, it has been found that protecting bacterial spores by immobilizing them within porous clay particles before adding them to the concrete mixture increases their lifespan. Based on research conducted, it has been shown that bacterial-induced calcium carbonate precipitates are much more adhesive compared to lime-induced calcium carbonate precipitates and have better compatibility with concrete [55, 56]

Overall, four key factors have been identified to influence the chemical process of calcium carbonate precipitation: 1. Calcium concentration, 2. Dissolved mineral carbon concentration, 3. pH, and 4. Availability of sites for initial precipitation. It is assumed as a fundamental principle that microorganisms have the necessary ability to function in an alkaline environment while performing various physiological activities. In addition to aging the environment, bacteria can induce calcium carbonate precipitation by creating sites for initial deposition or increasing local calcium concentration [57, 58].

9. Performance of self-healing concrete

In simpler terms, self-healing concrete works by reacting a small amount of dry cementitious material present in the cracks with carbon dioxide and water, forming a thin white layer of calcium carbonate. This layer acts as a barrier and prevents the cracks from expanding, essentially repairing them. Calcium carbonate is a very durable compound that is abundantly found in strong structures like shells, turtle shells, and snails in nature. It may take 4 to 5 cycles of wetting and drying for the concrete to fully heal the cracks. Nowadays, builders reinforce concrete with steel bars to minimize crack formation, but these cracks are still not small enough to be self-repaired [53, 59]. As a result, salts that penetrate the concrete through cracks for de-icing purposes can cause corrosion in the reinforcement bars and weaken the overall strength of reinforced concrete. Self-healing concrete does not require reinforcement and strengthening to keep cracks small, making it resistant to corrosion. By reversing the deterioration process of concrete and reducing costs and environmental impacts, using this self-healing concrete in new construction projects can extend the lifespan of buildings and optimize its use [60, 61].

10.Use of bacteria for self-healing concrete

When William McDonough and other pioneers of sustainable architecture first expressed their ideas about the concept of living buildings, it is safe to say that they did not have structures made of real-life organisms and bacteria in mind. However, it was Henk Jonkers from Delft University in the Netherlands who first introduced this idea [62]. What Henk and his colleagues possibly expanded upon was a hybrid of self-healing bacterial concrete, which could potentially set the course towards sustainable architecture that McDonough had envisioned. While this may seem unprecedented, scientists have been using bacteria for building repair for several years now. Bacterial mineral products have been used in various practical applications such as sand hardening and repairing cement cracks. However, there are two main forms of this method: the reaction of these bacteria to certain substances and the production of ammonia, which is a toxic material. Since the bacteria need to be manually applied, a worker or a team of workers must inspect and repair every small crack in each concrete slab for several weeks [63, 64]. But Jonkers' solution was to search for bacteria with different characteristics that could survive in concrete for a long time and easily thrive. Since the bacteria need to be mixed into the concrete from the beginning, they can quickly repair any small cracks before they are exposed to water and resulting deterioration. Researchers found suitable options: a group of highly resilient spores belonging to the Bacillus group that have been able to survive for a long time in alkaline lakes in Russia and Egypt. Jonkers and his colleagues prevented their premature activation by placing these spores and their food source in small ceramic capsules within the wet concrete mixture. The spores remain dormant until the formation of a crack that allows hidden movement into the concrete, and it is at this point that they become active and start working. When they start feeding, they avidly absorb water and nutrients and produce a significant amount of crystalline limestone, quickly filling up pores and holes [59, 65].

10. Self-healing concrete and the environment

More than seven percent of global CO2 emissions are attributed to cement, which is a major component of concrete, and new materials need to be developed to reduce greenhouse gas emissions. Self-healing concrete can increase the lifespan of buildings by 50% and reduce the need for annual repairs. It can also prevent corrosion of steel reinforcements, making self-healing concrete an environmentally-friendly solution [66, 67].

11. Conclusion

By employing self-healing concrete instead of traditional methods of concrete repair, the exorbitant costs of maintenance and repair of concrete structures can be reduced. Additionally, using less cement and avoiding the use of polymer materials in repair materials can significantly contribute to environmental preservation. In the case of self-healing concrete, the healing process begins immediately after the occurrence of a crack, preventing harmful substances from penetrating into the concrete and causing damage. However, in the case of ordinary concrete, cracks first appear, allowing harmful substances to enter and damage the concrete. This requires time and expense to search for cracks and damages, find suitable repair materials, and then dedicate further efforts to maintaining the repaired section.

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