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Review Article

Self-healing Concrete and Environmental Health

Mehrdad Amiri[1], Javad Majrouhi Sardroud[2*], Ali Golsoorat Pahlaviani[2]

[1]Graduate Student, Faculty of Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[2]Assistant Professor, Faculty of Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran

*Corresponding Author: Javad Majrouhi Sardrood, Email: J.Majrouhi@iauctb.ac.ir

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Abstract

Nanotechnology will serve as a suitable solution to achieve high performance in future construction. Using this new technology results in creativity and innovation in the construction industry. One of these new technologies is the smart concrete which has received much emphasis in recent years. Many research and experiments have been conducted in scientific research centers around the world in this regard. It is an undeniable fact that concrete structures are prone to cracking. Natural processes have caused cracks in the concrete through which harmful substances entered the concrete leading to steel corrosion. To tackle this issue through the conventional method of concrete restorative, materials, especially polymers which are also harmful to the environment, are used. An alternative that the scientists have achieved is to employ bacteria in concrete through which to produce self-healing concrete and also to reduce the problems regarding the maintenance of concrete for the environment. Bacteria contribute to the durability and performance of the concrete and increase the service life of the concrete.

Keywords: Cracks, Concrete restoration, Self-healing, Bacteria, Corrosion, Nanotechnology, Smart-concrete

Introduction

Concrete is one of the most important elements in civil engineering projects which is mainly used in infrastructures. However, concrete structures are susceptible to cracking. Natural processes such as earth subsidence, earthquake, humidity changes, and temperature cause cracks in the concrete. These cracks will cause harmful substances to enter the concrete leading to the corrosion of stickers and deterioration of concrete. In order to cope with this issue, the quality of concrete should be improved, but yet you can only partially stop cracking which it also costs a lot. Scientists have explored new methods for building concrete. For this reason, they investigated and studied the tissues of living organisms that could be restored. Skin is an example of such living organisms that is restored over time after wounding. In doing so, they investigated the living bacteria in order to use them in production of self-healing concrete which increases the durability and life of the concrete significantly. Employing bacteria, they were able to create the spontaneous repair of the cracks in the concrete, which is one of the most important intrusions of concrete.[1-5]

Creating micro-cracks in concrete is an undeniable fact that in the traditional way of coping with concrete restorer materials, in particular the types of polymers used, which, in addition to its high costs for the environment, are also harmful. The alternative method that scientists have achieved. The use of bacteria in concrete and the production of self-healing concrete, while reducing the cost of maintenance of concrete for the environment is not harmful and contributes to the durability and performance of concrete and also increases the life span of the concrete. Since concrete is used less than cement and because concrete restoration materials are harmful to the environment, self-healing concrete is eco-friendly.[6-8] The purpose of this study is to prove that the use of self-restraint concrete will be very beneficial for human health and leads to a healthier environment. This type of concrete also helps the application of this technology to be extended to environmental protection.

Methods

In order to do this study, the researcher got access to more than 1000 articles on the subject using the following keywords: “concrete”, “cracks”, “concrete restoration”, “self-resurfacing”, “bacteria”, “corrosion”, “nanotechnology”, and “smart concrete” in various resources. Subsequently, out of these articles, those which were more valid for referrals (over 200 articles) were selected. Then, reviewing the abstract section of these articles, the topics that were more representative (more than 70 cases) of the subject of the present research were selected. Next, studying and summarizing these papers, the researcher managed to select 23 titles deriving from the list of the resources as the main sources of research and finally wrote the present paper. Besides, out of those papers investigated (during 2007-2016), the best ones were selected owing to the novelty of their subject matter. However, it was not possible to use the old articles due to their unavailability.

Nanotechnology is now very controversial. It will be a good solution for achieving high performance in future construction. The application of nanotechnology leads to the development of creativity and innovation in the building industry. The ultimate goal of the study of nanoscale materials is to find a new class of high-performance building materials which can be used as high-performance and multifunctional materials. Multifunctional material emerges new and different properties similar to the properties of ordinary materials so that the materials can provide various applications.[1,4] One of the newest nanotechnologies is the smart concrete which has recently been focused on in numerous reputable scientific centers around the world and includes self-healing concrete.[2,3]

Self-healing Concrete

General Issues

Concrete restoration begins with the first concrete curing, but beyond this term, it includes the correction of the surface of concrete after cracking, carving, and in general, concrete demolition. To begin the restoration process, an appropriate and yet a comprehensive assessment must be conducted regarding the cause and effect of concrete damage. Using the results of this assessment, one can find the type of material and the appropriate repair method. The repaired concrete surface should be replaced by the damaged concrete in order to achieve the required structural performance like the initial state and to protect the underlying layer. All possible stresses including those in the joint section are repaired and the underlying layer must be examined and analyzed as well. The joints in the restored part due to the change in the relative volume between the restoring part and the bottom concrete layer as well as in the types of loading the tensions in restored part must be within the capacity of the existing materials, otherwise failure may occur. When a part of the material is affected by a variety of tensions, it restores around the restored part. It is repeatedly distributed as well. In order to prevent reloading the negative effect on the restored part, restoration should be during the course of the complete recovery operation. The repair process is carried out by candling and jacking and the restoration materials are fully utilized and put into operation. Then, after reaching the specified resistance, having a load bearing, and reloading on the member, it is intended to avoid damage to the restored part.[9,10]

Restoration Materials

In order to choose the correct repair materials, a proper understanding of the behavior of the restoration materials in the operating and non-operating conditions is of necessity. Their behavior towards the underlying or the same concrete is available is one of the greatest challenges regarding the successful operation of the repair materials. Relative variations of the dimensions lead to internal stresses in the repair materials and the underlying floor. High internal tensions may cause tensile or cracks. In order to minimize these stresses, it is necessary to select materials for repairing in which the ratio of changes to dimensions are compatible with existing structures.[9-11]

The durability of restorative materials increases adding special pozzolans such as microsilica, polymers like latex, or permeation reducing additives. Concrete condensation and concrete treatment should be considered for the use of restorative materials containing Portland cement. Attention should be given to minimize the use of shrinkage materials.

The biggest problem for the application of these restorative materials is that they are harmful to the environment and cause environmental contamination.[9-11]

Protecting Refined Concrete

Concrete protection methods are typically selected in such a way that the intervals between periods of repair and maintenance are considered long. Protecting concrete against exploitative conditions as well as attacking and injurious environments is carried out using rivets, membranes, and coatings. There are several techniques to protect the concrete. Protective systems can be installed at the time of construction or at any time throughout the life of the structure. A good design for the new building will provide the required protection conditions. The protection of existing structures is usually very difficult and gives us less choice over the new buildings. The purpose of protection strategies is to prevent the corrosion of concrete reinforcing steel and as a result to create cracks, to degrade the layer, and also to engrave the concrete layer. Corrosion protection of steel is a direct way of coping with chloride corrosive effects. The epoxy-coated adhesive bonded by the fusion method is the most common method of covering the joints and also one of the effective ways to reduce the amount of chloride ion penetration in the coating of membranes and intrusion agents on the surfaces. Intrusive substances consist of silane and siloxane and coating membranes include epoxies, urethanes, chlorinated synthetic rubbers, and methacrylates. Unfortunately, the use of these coatings has a negative impact on the environment as well.[9-11]

One of the smartest concretes that has received much emphasis in recent years is self-healing concrete. Think of a type of concrete that begins to restore and repair only by water and carbon dioxide when leaving, self-healing, or when no intervention is concerned on the part of the human. The creation of micro-cracks in concrete is an irrefutable fact. The conventional way of dealing with such a condition is to use concrete restorer materials in particular, polymers which in addition to their high costs for the environment, are harmful as well. There exists an alternative for this, being investigated by the scientists. They found that bacteria can be employed in concrete to produce self-healing concrete and also to reduce further cost. In addition to reducing costs, such as maintenance and repair of concrete for the environment, it is not harmful and contributes to the durability and performance of concrete and increases the useful life of concrete. If a human's hand gets a small scratch, his/her body can easily repair it as long as the size and depth of the scratch. However, if the injury is very wide and deep, external surgical operations such as suture are required. Similarly, self-healing concrete performs in such a way that, by continuous restoration and maintenance of the resulting fine cracks, it does not allow any cracks to break and to create deep gaps even if the concrete piece is loaded several times.[7-9,12-14]

Use of Bacteria in Concrete

So far, high quality concrete has been applied for using materials such as ash, slag, oven, silica, metakaolin and other similar materials as an additive. Recently, a new technology called bacterial mineral deposit has been developed which is a sediment of metabolic activity. Specific microorganisms originate from concrete and improve the durability of the concrete and its properties in the long run. This process can occur inside or outside of the microbial cell or even at a distance, within the concrete field. The activity of this type of bacteria is based on a change in the soluble chemistry contained in the bacterial activity environment to create an over-saturation and mineral deposit. Using this mineral-mineral technology in concrete leads to a new potential for innovations in production of type A new concrete which has been used as a bacterial concrete. Bacterial concrete is designed and constructed based on the ability of calcite sedimentation by bacteria. This bacteria-induced calcite sedimentation phenomenon is called MICP (microbial instigation carbonate precipitation). Calcium carbonate sediments, as a microbial sealant, have proven their superior ability to fill cracks and tiny gaps in granites, rocks, and sand. Calcite sedimentation with bacteria is an attractive and valuable process. The main attraction is due to the lack of environmental pollution and the natural nature of this technology.[15] This technology can be used to improve the compressive strength and toughness of cracked concrete samples or concrete structures under crack stress. The continuous formulation produces a super-impenetrable calcite layer on the surface of the concrete. The deposition created by Chris's structure has a coarse texture that is easily bonded to concrete surfaces. In addition to an ability to be produced and grow continuously, these layers are extremely impervious to water. They are exposed to harmful agents (e.g., chlorides, sulfates, and dioxides carbon), resist against concrete, and therefore, the impact of these harmful agents on concrete is reduced. Because of the innate ability of bacteria to create constant calcite sedimentation, this type of bacterial concrete can be considered as an intelligent biocide for the repair of concrete. The MICP contains a series of complex biochemical reactions that can be greatly influenced by factors such as environmental porosity and the number of cells available, and the amount of added nutrients. Phosphate or urea and calcium-containing substances like calcium chloride ($CaCL_2$) can be applied as a very good nutrient. Bacteria in the presence of these nutrients create calcite sediment. Sensitization or pH is an important factor in the activity or inactivity of bacteria in the concrete environment.[13,14,16-18]

The bacteria used as self-repair agents in concrete should be of a specific nature. They should, preferably have the capability of cracking in the entire lifespan of a structure over a long period of time. The basic mechanism of bacterial cessation restoration is that bacteria act as a catalyst. Primary primers are used as a suitable filler. The newly produced materials, such as calcium-based minerals, must be used as bio-cements and effectively closed cracks. Thus, for proper self-regulating capability, bacteria and the primer must be in the concrete. The concrete needs to be changed. Therefore, these materials are added to the concrete Bacteria that can withstand the environmental conditions of the concrete are inherent in a specific category of alkaline-resistant bacteria. An interesting feature of this bacterium is the production of cells with thick and spherical walls similar to plant seeds. These spores are biotic in the form of cells enclosed in concrete and can tolerate the stresses of the concrete environment. If used in a dry environment, these bacteria can survive for 50 years. Unfortunately, when they are directly added to the concrete, their life span is limited to one or two months. The reduction in bacterial spores from decades in a dry environment for several months in concrete can be due to hidratation. It is important to note that the addition of organic and inorganic materials to the concrete does not reduce its properties. It has previously been shown that these materials including yeast extract and calcium acetate cause a sharp reduction in the compressive strength of the concrete. The only exception is the calcium lactate exception which increases the strength of the prototype up to 10%.[14,17,19, 20]

Types of Bacteria Used in Concrete

The types of bacteria that have already been studied for their usage in bacterial concrete include:

- *Bacillus pasteurii* (*Sporosarcina pasteurii)*
- *Bacillus sphaericus (Lysinibacillus sphaericus)*
- *Bacillus subtilis*, and
- *Bacillus cereus*

The above-mentioned bacteria which have been used in manufacturing of bacterial concrete have entered a process that produces calcite deposits and improves the properties of concrete, which can be called bactericidal stimulation. Calcium carbonate is performed by many bacteria and is a common process among many bacteria. Therefore, it has been investigated by many scholars owing to its scientific value.[3]

Mechanism of Action of Bacteria

Different mechanisms have been proposed in order to clarify the role of bacteria in the formation of calcareous sediments. Based on the research carried out in this field, it has been accepted that this activity of bacteria can be affected by physical-chemical as well as physical-environmental parameters and can also be related to activity of metabolic and superficial cellular structure. All of the appropriate metabolic pathways for increasing the alkaline pH of the environment can lead to calcium carbonate precipitation in the presence of calcium ion. Some studies have been carried out to investigate the increase of bacteria life in the concrete and the effect of these factors on it. The result obtained indicate that protection of bacterial spores without moving them into particles of high-porosity clay and before adding them to the concrete mix increases the life of bacteria. Based on the research conducted, it has been determined that bacterial calcium carbonate sediments, unlike calcium carbonate sediments, are very sticky with lime water and more compatible with concrete.[13,16,19,21]

Self-healing Concrete Performance

In simple terms, the self-healing concrete acts in such a way that, when cracks are created, some cementitious materials contained in the cracks in the cracks react in the presence of carbon dioxide and water and a very thin layer of white It works from calcium carbonate and prevents cracks from cracking and actually repairs cracks. The cracks penetrate the concrete causing corrosion in the reinforcement and reducing the overall strength of the reinforced concrete. Since there is no need for reinforcement and arming for keeping the cracks less secure, it is completely safe to reverse concrete decay and to significantly reduce the cost and environmental impact of constructing new buildings using this. Self-repairing concrete can be restored for a longer period of time so as to optimize the application of self-healing concrete.[14,16,22]

Self-healing Biological and Chemical Interactions

According to the research, the application of biological or bacterial sedimentation operations significantly reduces the absorption of water and thus increases the resistance of concrete samples to the influence of carbon dioxide, chlorine, freezing, and melting. This is more evident in samples with high porosity or higher water-to-cement ratio. In addition, similar results have been obtained for samples containing bacteria in surface protection methods such as silane, siloxane, silicate, and acrylate, which indicate the proper function of this method. A microscopic analysis of concrete sections revealed that a layer of crystals with a thickness of 10 to 40 μm had covered the surface and some areas of the environment. Continuous research has been conducted through applying calcium chloride as a source of calcium. Considering the destructive nature of ion chloride, choosing substitute materials such as calcium acetate is also accounted for the durability and stability of steel reinforcement in concrete. In the case of calcium acetate, spherical crystals were formed, but in general, in terms of crack repair, there was no difference in the use of different calcium sources (calcium chloride and calcium acetate). Therefore, according to the researchers, with regard to this issue and better compatibility of calcium acetate with concrete and steel reinforcement, it is better to use calcium acetate as a source of calcium in the concrete environment.[13,19,23]

The amount of calcium carbonate depends on the structure of the material cavities. For limestone specimens, the amount of weight gain is three times more than that of ordinary grains in concrete owing to the formation of sediment. Due to the lower amount of sediment, more bacteria and urea should be added to the amount of calcium carbonate precipitated in the concrete. In addition, it increases the porosity which depends on the ratio of water to cement in the concrete. Samples with a water to cement ratio of 0.7 result in more sediment than 0.5 porosity samples (water to cement ratio) of 0.5.[16,20]

The Yunker Research Group conducted a research to confirm the efficiency or inactivity of concrete containing bacteria. Concrete carbonation process through cracking is a very destructive process in which concrete pH decreases. A large volume of high-temperature concrete properties is associated with alkaline properties. Inside the cavities of calcium hydroxide solution concrete, cracking, hydrated, and calcium hydroxide are produced by cracking. This calcium hydroxide reacts with water-soluble carbon dioxide gas and also reacts to concrete and produces calcium carbonate which precipitates, with the process continuing, this calcium hydroxide is leaked out of the concrete (through cracks) and thus the production of calcium carbonate precipitates. If the cracks are fine, the concrete can repair itself. However, if the size of the cracks is more than one, then the concrete will not be self-healing and therefore, the valuable calcium hydroxide of the concrete which is characterized by the unique properties of the concrete, penetrates into the water and as a result, reducing the alkalinity of the concrete will lose its properties. In case of the presence of steel reinforcements in concrete, such reinforcements are protected by concrete. By reducing the alkalinity of the concrete and also its pH, this protection is lost and eaten. The production of corrosion products is associated with increased volume and leads to the reduction of new cracks in concrete and their severe degradation. The process of taking and removing calcium hydroxide is based on the following reaction which is stated by the following equation:

$$Co_2 + Ca(OH)_2 \rightarrow CaCo_3 + H_2o \qquad \text{Eq. (1)}$$

Creation of these sediments is presented at the crater. The presence of bacteria and the formation of calcium carbonate sediment are very valuable and of high efficiency due to the fact that these deposits are formed inside the cracks without consuming calcium in alkaline concrete. In this process, calcium lactate or other calcium sources (by oxygen) are converted into calcium carbonate by the bacteria. This material is added to the concrete as bacterial nutrition according to the equation provided below:

$$Ca(C_3H_5O_2)_2 + 7O2 \rightarrow CaCo_3 + 5Co_2 + 5H_2o \qquad \text{Eq. (2)}$$

The carbon dioxide produced by the bacterium is also restored in the cracking process. This carbon dioxide reacts with non-hydrated particles of cement and leaves the restoration of the calcium carbonate production at the internal surfaces and the deposition makes it to exacerbate the calcium carbonate precipitation by bacteria. Comparing these results with those related to self-repair of the concrete in the absence of bacteria after 2 months, a maximum of 33% of Turks restoration was due to the process of using calcium hydroxide. In the presence of bacteria and lactate, this amount is increased by 100%. This effect is due to the double effect of the consumption process of calcium and lactate on the bacteria and the production of calcium carbonate. Besides, carbon dioxide again reacts with calcium hydroxide and the production of calcium carbonate sediments more in the cavities and cracks.[13,16,17,19,20,23]

Self-resistive Concrete (Bacterial) Resistance Test

The findings of the experiments conducted to determine the resistance of bacterial concrete (bacterial mortars) using *B. subtilis* bacteria are presented below. The results of these tests in the relevant tables indicate that the resistance of the specimen, made with the bacterium, is higher than that of the samples that are ordinary (without the use of bacteria) and this, in addition to the other positive points previously mentioned for self-healing concrete, convince the researchers and scientists to use this product instead of traditional concrete repair materials.

In experiments conducted by Sunil Pratap Reddy et al at the Department of Civil Engineering at Jahar Lal Nehru Hyderabad, India, the optimum concentration of *B. subtilis* bacteria was obtained with regard to the average compressive strength obtained, the results of which are presented in Table 1.[3]

The difference between the 28-day compressive strength of the concrete using the bacteria as well as the conventional state in concrete (normal, standard, and high strength concrete) are presented in Table 2.[18]

Conclusion

The application of concrete structures' repair, instead of conventional concrete repair methods, reduces the

Table 1. Effect of the *Bacillus* Bacteria Addition on Mortar Strength

Cell Concentration/mL of Mixing Water	Average Compressive Strength off Mortar in Mpa					
	3 Days	% Increase	7 Days	% Increase	28 Days	% Increase
Nil (Control)	25.55	0	38.34	0	51.81	0
10^4	27.91	9.23	41.24	7.56	58.02	11.99
10^5 (Optimum)	29.97	11.73	44.31	13.47	61.79	16.15
10^6	27.4	7.24	42.14	9.91	57.21	10.42
10^7	26.2	2.54	40.16	4.75	54.66	5.51

Table 2. Effect of *Bacillus subtilis* Addition on Compressive Strength

Type of Concrete	Compressive Strength (Mpa) at 28 Days		
	Controlled Concrete	Bacterial Concrete	% Increase
Ordinary grade concrete (M20)	28.18	32.74	16.18
Standard grade concrete (M40)	51.19	60.17	17.54
High grade concrete (M60)	72.61	94.21	29.75
High grade concrete (M80)	93.8	119.2	27.08

cost of concrete repair. It will also be more reasonable to consume less cement or not to employ polymeric materials which were used in healing materials, especially since the use of concrete - resistant concrete to reduce this replacement will be more reasonable. In the case of the self-healing concrete, it starts immediately following the cracking of the concrete and does not damage concrete.

Ethical Approval

Not applicable.

Conflict of Interest Disclosures

None.

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