Recycling and Sustainable Development 16 (2023) 01-14

Recycling and Sustainable Development

www.rsd.tfbor.bg.ac.rs

RSD

Online ISSN 2560-3132
Print ISSN 1820-7480

A Review on Self-healing Concrete - A Biological Approach

Dilshad Kakasor Jaf

Salahaddin University-Erbil, College of Engineering, Department of Civil Engineering,
Erbil, Kurdistan Region, Iraq

ARTICLE INFO

Received 20 April 2022
Accepted 05 October 2022

Review article

Keywords:
Self-healing
Cracks
Bacteria
Bacillus
Bacterial-concrete
Durability

ABSTRACT

Concrete is one of the most popular and used construction materials. It is strong, durable, and relatively inexpensive, but it has a higher tendency to form cracks. The cracks provide a low service life for the concrete and high maintenance costs. The penetration of aggressive ions through cracks results in corrosion of steel reinforcement, carbonation, sulphate attack, alkali-aggregate reaction, etc. However, prevention of cracks formation is impossible, however, they can be controlled or repaired by various methods. Self-healing concrete is well known as a suitable remedial method to improve concrete's long-term durability. It is a new, rapid, and environmentally friendly approach. In this technology, when concrete is exposed to water, the healing agent material produces calcium carbonate ($CaCO_3$), which fills in the cracks and decreases permeability while enhancing concrete durability. The materials that are used as the healing agents are mostly bacteria, polymers, and chemical compounds. Bacteria are the most preferred material in concrete for healing. Therefore, bio concrete or bacterial concrete is another name for self-healing concrete. This article provides a comprehensive overview of self-healing concrete including, the system, process, mechanical properties, and durability of healed concrete.

1. Introduction

Concrete is the most well-known construction material globally because it is strong, durable, and it has low cost (Wiktor and Jonkers, 2011). Aggressive ions can enter concrete through cracks, which is a common property of the material. Concrete cracking is mostly caused by restrained deformation, external loads, and temperature gradients (Jonkers et al., 2010). Concrete is low in tensile strength, it cracks due to shrinkage, chemical reactions, etc (Luo et al., 2015). Khaliq and Ehsan (2016) stated that the deterioration of reinforced concrete resulted in high maintenance costs for both steel and concrete. Repairing cracks in concrete structures is required because cracks significantly affect service life and safety (Zhong and Yao, 2008). Therefore, to increase the service life of cracked concrete, it should be repaired.

Typically, two forms of crack repair are available; passive treatment and active treatment. In the passive treatment method, after detecting the cracks, repair agents are applied manually to the concrete, however, this method requires more effort and is costly. However, the active treatment method, also known as self-repair or self-healing, involves filling in the cracks without the assistance of humans.

Monitoring, detecting, and repairing are steps in the conventional repair process. Repair work can be done once the cracks have been found. A repair agent is applied from outside of the concrete and afterward it penetrates into the cracks. Repairing large cracks with

---

[#] Corresponding author: dilshad.jaf@su.edu.krd

doi: 10.5937/ror2301001J

this technology is quite suitable, but it is difficult for small and deep cracks. Therefore, an alternative repair method has been established which is called self-healing.

Self-healing concrete is a type of concrete that can repair its small cracks autonomously. It can prevent small cracks from developing into larger ones and is effective at healing deep micro-cracks (Wang et al., 2012). In the last ten years, numerous studies on the phenomenon of healing concrete have been conducted (Li and Yang, 2007). Only a few articles on self-healing concrete were published in the 1980s, but since the late 1990s, significant research has been done. Bacterial-concrete was developed by a microbiologist Dr. Henk Jonkers from the Netherlands during 2011. In this technology during concrete casting, some healing agents are added into the matrix. Later, if any cracks develop, the concrete's internal healing agents can be released by dripping into the cracks and sealing (Tziviloglou et al., 2016). Cracks can heal without any external human intervention. The healing is done only by activation of the healing agent which is released later during crack formation, thus bridging the crack openings.

The concept of self-healing in concrete was provided from the idea of the organic phenomena of organisms like plants and animals. Animals and trees can repair their own damaged skin on their own (Breugel, 2007). The healing agent is mostly calcium-based nutrients, also called calcium lactate with a small fraction of bacterial spores. The spores become active and the bacteria can access the bacterial substrate by activating to carbon dioxide (CO_2) when water flows into the cracks. Due to the calcium-rich environment and pH of 12 - 13 of the concrete, the formed CO_2 reacts with calcium ions resulting in the formation of calcium carbonates. Thus, bacterial development may cause the development of mineral precipitates in cracks, and significant reduction in the water permeability of the concrete (Vermeer et al., 2021).

The material using healing agents is mostly bacteria, polymers, and chemical compounds such as sodium silicate (Na_2SiO_3) and magnesium oxide (MgO). Since bacteria are the most commonly used healing agent, self-healing concrete is also called bacterial concrete or bio concrete. Siddique and Chahal (2011) stated that the bacteria's capacity to survive in an alkaline environment plays a crucial part in the selection of the bacteria. The majority of microorganisms will die and be unable to survive at a pH of 10 or higher. There are two distinct kinds of self-healing process: natural and artificial. In the natural process which is called autogenous, the cracks between 0.1 and 0.3 mm can be repaired by hydration of un-hydrated cement. But in an artificial process called autonomous, engineered admixtures are introduced to the concrete by chemical or biological methods. Biological methods are the youngest approaches among all self-healing designing methods. This article reviews the general concept, production mechanisms, and properties of self-healing concrete.

2. Self-healing concrete system

In concrete, self-healing systems can be divided into two categories: autogenic and autonomic (De Rooij et al., 2013).

2.1. Autogenic self-healing

It is an inherent material-healing characteristic where the process of self-healing starts with the currently available generic materials. For instance, the ability of cementitious materials to self-heal is caused by the property of hydration of the un-hydrated cement that remains on the crack surface (Neville, 2002).

In this system the volume of the healing product is limited. Concrete cracks that have been autogenously repaired come in sizes varying from 5 to 10 mm (Edvardsen, 1999; Aldea, et al., 2000), 100 μm (Jacobsen et al., 1996), 200 to 300 μm (Wiktor et al., 2011), and 0.05 to 0.87 mm (Gavimath, 2012). Because of a high content of un-hydrated cement at an early ages, autogenic self-healing has higher performance at this stage. Superplasticizer in engineered cementitious composite (ECC) can be used to lower the water/cement ratio while fibers can be used to control crack opening to improve the autogenic healing mechanism.

2.2. Autonomic self-healing

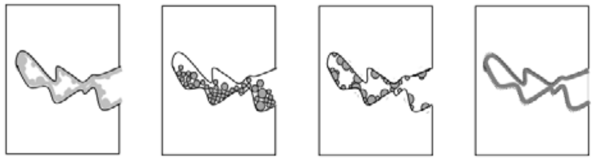
Unlike the autogenous healing system, this system requires the releasing of healing agent from a continuously formed vascular network or reserved encapsulation. The commonly used materials in autonomic self-healing mechanism can be categorized as bacteria, chemical compounds such as Na_2SiO_3, MgO, and polymers such as; superabsorbent polymers (SAP) and non-absorbent polymers. The healing capacity for this method is greater than the autogenic method.

3. Process of self-healing concrete

Concrete can undergo three different types of self-healing: natural, chemical, and biological self-healing.

3.1. Natural self-healing

As illustrated in Figure 1, there are several natural processes that can partially fix the concrete fracture. In natural processes, four different processes can block concrete cracks: (A) formation of $CaCO_3$ or calcium hydroxide ($Ca(OH)_2$) which block cracks; (B) cracks are blocked in the presence of water by some impurities; (C) cracks are further obstructed by hydration of un-hydrated cement or cementitious materials; and (D) cracks are prevented from forming by the development of hydrated cementitious pattern in the crack flanks (such as swelling of calcium-silicate-hydrate gel).



(A) Formation of calcium carbonate (B) Blocking by impurities (C) Hydration of unreacted cement (D) Expansion of the hydrated cement

Figure 1. Mechanisms of natural self-healing in cementitious materials, adapted from Talaiekhozani and Abd Majid (2014)

One or more of these mechanisms may operate in parallel in many circumstances. Actually, the majority of these techniques are unable to completely fill the cracks; only some of them can. However, it is helpful to stop cracks from forming and the entry of harmful chemicals like acids introduced into the crack. $CaCO_3$ and $Ca(OH)_2$ formation is the most successful natural healing technique among the described techniques. The concrete's exterior surface in this mechanism has a white residue that is $CaCO_3$. On the exterior of the concrete, $CaCO_3$ can be seen as a white residue in this mechanism. The fundamental mechanisms for the production of $CaCO_3$ are described in equation 1-3.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3{}^- + H^+ \leftrightarrow CO_3{}^- + 2H^+ \quad (1)$$

$$CO_3{}^{-2} + Ca^{+2} \leftrightarrow CaCO_3 \quad (2)$$

$$HCO_3{}^- + Ca^{+2} \leftrightarrow CaCO_3 + H^+ \quad (3)$$

The first step is started by dissolving CO_2 in the water, resulting in releasing CO_3^- ions. Next, these free CO_3^- ions react with Ca^{+2} released ions from cement hydration and form $CaCO_3$ crystals. Those developed crystals can grow, thus covering the cracks and filling the gaps. Actually, the second and third reactions can only occur at pH above 8 or within 7.5 and 8. Hence, it is needed to control the pH around these values. However, the natural process can only be used on concrete that is still quite young, and as concrete ages, the formation of $CaCO_3$ is likely what prompts self-healing. Natural self-healing is useful for cracks that are between 0.1 and 0.2 mm wide.

3.2. Chemical self-healing

Chemical self-healing is the term for artificial healing that involves adding chemicals to the crack to promote healing. In a small container, freshly mixed cement is combined with chemical liquid reagents (glue) to create the concrete. Two well-known chemical techniques are used to employ addition into concrete for self-healing.

3.2.1. Hollow pipettes and glue-filled vessel networks

Concrete can chemically self-heal in two different ways: (A) active mode and (B) passive mode. The glue is distributed in the active mode using a vessel network connected to an external supply. However, the glue in passive mode, which is not connected to any external glue source, is distributed using hollow pipettes, vessel networks, or capsules. Depending on the active or passive mode, either the vessel network or hollow pipettes can be utilized to create self-healing concrete. Different lengths of hollow pipettes have been used to create various self-healing materials, including polymers. It has glue mixed into it, which will rupture whenever cracks are growing and allow the glue to leak into the cracks, which will then heal them. A blood vessel in a creature served as inspiration for the design of self-healing pipettes.

Ethyl cyanoacrylate, methyl methacrylate, epoxy resin, and acrylic resin are a few types of glue that can be utilized to fill the pipettes in concrete (Homma et al., 2009).

Other than using hollow pipettes filled with glue for concrete self-healing. In order to distribute glue, Dry (1994) suggested using a network of vessels inside a concrete sample. A concrete specimen housed the delicate vessel network; one end of the network was attached to the glue supply, and the other end was sealed. Other researchers, including Mihashi et al. (2000) conducted a related study as well.

3.2.2. Encapsulated glue

Both macro and micro-scale applications are possible for glue encapsulation. The size of capsules at the micro-scale level varies from micro-capsules to nano-capsules. The concept of encapsulation is producing the capsules containing glue into the concrete for self-healing purposes. When the crack occurs, the glue is released from the capsules into the crack faces resulting in filling the cracks.

3.3 Biological self-healing

The use of microorganisms has been categorized as a biological strategy to design self-healing concrete (Siddique and Chahal, 2011; Wu et al., 2012). Nearly anywhere, including oil and water reservoirs, soil, acidic hot springs, and industrial wastewater, is a suitable environment for the growth of microorganisms. Several researchers have proposed using microorganisms to create self-healing concrete, including Bang et al. (2001), Jonkers et al. (2010), and Su et al. (2021). The three main categories of microorganisms are viruses, fungi, and bacteria. This technique involves pouring microbial broth right into the freshly mixed concrete. The additions could be distributed by vascular networks as described in the chemical method, or they could take the form of spores, capsules, immobilized forms on activated carbon or silica gel. A bacteria cannot grow in concrete because of its moisture content, temperature, or pH. As a result, in some situations a resistant type of bacteria (spores) is used instead of fresh microbial broth. Over 60 years is the maximum lifespan of some spores. It is also possible to use microorganisms that have been enclosed to withstand the harsh concrete environment, but this method is costly and difficult.

Another way to protect microorganisms from inappropriate conditions is using vascular networks for distributing the microbial broth throughout the cementitious matrix. However, this approach is difficult to implement and has poor constructability when using current technology. The best method in terms of the economical aspect was suggested to immobilizing of microorganisms on silica gel or activated carbon. However, it is still unclear how using these materials will affect the strengthening of concrete.

The most well-known and used healing agent in concrete is calcium-based nutrient also called calcium lactate $Ca(C_3H_5O_2)_2$, which is added to the concrete with a small amount of bacterial spores. The ratio of calcium lactate to the spores is commonly 2:1. When the bacteria come into contact with both water and oxygen, they begin to activate and can convert the available lactate to limestone ($CaCO_3$) resulting in filling the crack openings. Table 1 shows various types of bacteria with crack-healing capacity.

Selecting the type of microorganism is the first step of the process. If bacteria are chosen, the process will use one of two mechanisms to create self-healing concrete:

3.3.1 Precipitation of $CaCO_3$ (*Ureolytic process*)

The temperature of self-healing concrete can arise up to 70 ºC and its pH is between 10 to 13, also the water content reduces with drying the concrete. The selected bacteria need to be highly resistant to high temperature, pH, and serious limitations of water. In these conditions, mesophilic microorganisms typically cannot grow. Thermophilic bacteria were successfully tested by Ghosh et al. (2006) to create self-healing concrete to address this issue. During photosynthesis, hydrolysis, and surface reduction, microbial $CaCO_3$ may precipitate as a by-product. Gas and water permeability may be decreased by bacterial $CaCO_3$ precipitation on concrete surfaces. All over the world, carbonate precipitation occurs most frequently in the oceans. Because of their ability to increase the pH of the surrounding environment through a variety of bacterial metabolisms, bacteria are thought to have a major role in the precipitation of $CaCO_3$. One of the most popular biological ways is applying $CaCO_3$ using urolytic bacteria to design self-healing concrete. The shape of bacteria is commonly Bacilli, Cocci, or Spirilla. Different families of microorganisms, such as Mesophilic (Al-Thawadi, 2011) and Thermopilic (Ghosh et al., 2006), can be utilized in design of self-healing concrete. Among the shapes and types of bacteria, Bacillus pasteurii and sphaericus family are the most commonly used microorganisms.

It is clear that microorganisms, particularly bacteria, are capable of producing a variety of minerals, including phosphates, carbonates, and silicates (Fortin et al., 2018). $CaCO_3$ is one of the best fillers for concrete because of its high compatibility with cementitious compositions.

Calcium carbonate is produced through a series of biochemical processes (Stocks-Fischer et al 1999; Dick et al., 2006; Mitchell et al., 2010): 4) Urease-producing bacteria speed up the precipitation of calcium carbonate by hydrolyzing urea to produce ammonia (NH_3) and carbamic acid (NH_2COOH), 5) The carbamic acid spontaneously breaks down into one mole of ammonia and carbonic acid (H_2CO_3), 6) the carbonic acid decomposites, 7) As ammonia hydrolyzes, ammonium and hydroxide ions are produced, 8) As a result of the formation of hydroxide ions, the pH of the medium will rise, which promotes the production of bicarbonate (HCO_3^-) and carbonate ions (CO_3^{-2}), 9) During microbial metabolic activity, the negatively charged bacterial cell wall can draw positively charged calcium ions (Ca^{+2}) and deposit them on the cell wall surface, and 10) $CaCO_3$ is precipitated as a result of the reaction between the calcium and carbonate ions.

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \tag{4}$$

$$NH_2COOH + H_2O \rightarrow H_2CO_3 + NH_3 \tag{5}$$

$$H_2CO_3 \leftrightarrow HCO_3{}^- + H^+ \tag{6}$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4{}^+ + 2OH^- \tag{7}$$

$$HCO_3{}^- + H^+ + 2NH_4{}^+ + 2OH^- \leftrightarrow 2NH_4{}^+ + 2H_2O + CO_3{}^{-2} \tag{8}$$

$$C_a{}^+ + Cell \rightarrow Cell^-Ca^+ \tag{9}$$

$$Cell^-Ca^+ + CO_3{}^{-2} \rightarrow CaCO_3{}^-Cell \downarrow \tag{10}$$

The rate of biological calcite precipitation is influenced by several factors such as: 1) concentration of the inorganic carbon content in dissolved solutions, 2) the rate of biological calcite precipitation, 3) concentration of calcium ions (Ca^{+2}), 4) pH, and 5) presence of nucleation sites (Li and Yang, 2007).

3.3.2. Polymorphic iron-aluminum-silicate precipitation (Silica process)

A complex iron-aluminum-silicate $[(Fe_2Al_3)(SiAl)O_{10}(OH)_5]$ precipitation was found in a lake contaminated with metal sediment, and it was located on the surface of isolated bacteria cells (Jonkers et al., 2010). In areas with acidic soils, the bacteria *Leuconostoc mesenteroides* play a significant role in the silica precipitation. This bacterium uses carbohydrates to produce lactic acid, which results in an acidic environment and lower colloidal silica solubility, which causes precipitation (Gollapudi et al., 1995). Due to the acidic condition, this method is not popular, also regarding the durability of concrete, it is not a good choice.

Table 1
Types of bacteria with crack-healing capacity in concrete

Types of bacteria	Crack-healing capacity	References
Bacillus pasteurii	Crack depth = 3.175 mm	(Ramchandran et al., 2001)
	Crack width = 3.18 mm Crack depth = 25.4 mm	(Bang et al., 2001)
Sporosarcinapastuerii, Bacillus sphaericus	-	(Kashyap, 2013)
Bacillus subtilisaureolytic	-	(Naveen and Sivakamasundari, 2016)
Bacillus megaterium	Crack depth = 4000 µm Crack width = 0.3 mm	(Su et al., 2021)
Bacillus sphaericus	Crack depth = 10 and 20 mm Crack width = 0.5 mm	(Van Tittelboom et al., 2011)
Bacillus subitilis	Crack width = 1-1.8 mm	(Huynh et al., 2017)
Bacillus cohnii	Crack width = 0.1-0.4 mm	(Xu and Yao, 2014)
Bacillus sp. CT-5	Crack width = 3.0 mm Crack depth =13.4-27.2 mm	(Achal et al., 2013)

4. Evaluating self-healing concrete

According to numerous research studies, self-healing concrete shows better behavior than conventional concrete without healing agents. Testing the self-healing concrete samples is necessary to ensure the property of the material compared to the normal concrete sample. Table 2 shows the most common techniques and methods used for evaluating self-healing concrete. The simplest way is evaluating visually either by the naked eye or using simple tools such as optical microscopy. Similar to conventional concrete, checking the material to resist various stresses such as; compression, tension, bending, etc. is required. In terms of durability, the self-healing concrete must be checked for various exposure conditions during its service life, for example; permeability and corrosion, etc. Testing the material for its microstructure is very important to ensure the healing performance at that level, tests such as; X-ray diffraction analysis, Scanning electron microscopy, etc. can be carried out. The combination of those tests can give an exact indication of the healing in the concrete.

Table 2
Concrete measurement techniques for self-healing performance

Self-healing evaluation technique	Methods	References
Visual observation	Digital image correlation Optical microscopy Crack sealing observation with eye	(Van Tittelboom et al., 2011)
Mechanical strength recovery	Compressive strength test	(Park et al., 2010; Abo-El-Enein et al., 2013; Xu et al., 2018)
	Tensile strength test	(Van Tittelboom et al., 2011)
	Three-point bend test	(Qureshi and Al-Tabbaa, 2014)
	Four-point bend test	(Snoeck et al., 2014)
	Impact loading slab	-
	Resonance frequency analysis	-
	Structural element deformation measurement	-
Durability	Air permeability	(Qureshi et al., 2018)
	Water permeability	(Van Tittelboom et al., 2011; Abo-El-Enein et al., 2013; Snoeck et al., 2014; Xu et al., 2018)
	Sorptivity/capillary water uptake	
	Chloride permeability	(Siddique and Chahal, 2011; Achal et al., 2013; Sahmaran et al., 2013)
	Freeze-thaw test	-
	Corrosion test	-
	Neutron radiography	-
	Ultrasonic transmission measurement	(Van Tittelboom et al., 2011)
	Osmotic pressure	-

Table 2 continued
Concrete measurement techniques for self-healing performance

Microstructural evaluation	Environmental scanning electron microscopy (ESEM)	(Li et al., 1998; Jonkers et al., 2010)
	Scanning electron microscopy (SEM)	(Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013; Xu et al., 2018)
	X-ray diffraction analysis (XRD)	(Park et al., 2010; Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013)
	Energy dispersive X-ray spectrometer (EDS)	(Chahal et al., 2011; Abo-El-Enein et al., 2013; Sahmaran et al., 2013)
	X-ray radiography/tomography	-
	Infrared analysis	-
	Thermogravimetric analysis (TGA)	(Qureshi et al., 2018)
	Raman spectroscopy	-

4.1. Mechanical properties

Mechanical properties mainly include compressive, shear, flexural (three-point bending and four-point bending), and tensile strength of concrete. The ability of a material to resist a compression load is known as its compressive strength. Compressive strength is the most crucial factor in structural design and concrete quality control among mechanical properties. Normal concrete has a 25-50 MPa range for its compressive strength. Ordinary concrete continues to be constructed using self-healing technology.

The ability of a material to resist deformation while under load is known as its bending strength, and it corresponds to the material's maximum internal stress at the time of rupture. Two different bending tests exist, both the three- and four-point bending tests. The uniform stress area under the center loading point in a three-point bending test is relatively small and concentrated there. In the four-point bending test, the region of uniform stress is located between the inner span loading points. Numerous research studies can be found which achieved an amount of regain in compressive strength of concrete by self-healing. They tested the samples before and after healing and the regain strength efficiency of the healed concrete was present. The compression test results of some studies when the different types and concentrations of bacteria were used are collected in Table 3. For most of these studies, the temperature of the media was about 25 ºC, which is a suitable degree for bacterial activation.

Other researchers used various polymers as concrete healing agents. After testing the samples using various methods, they could achieve good results in terms of sample strength improvement, Table 4. Healing agents such as sodium silicate (Na_2SiO_3) and magnesium oxide (MgO) were used by previous researchers for the purpose of healing the concrete, Table 5.

Table 3
Compressive strength improvement caused by different bacteria

Type of bacteria	Concentration	pH of media	Test methods	Regain efficiency	References
Bacillus megaterium	30×10^5 cell/ml	6.5	Compression	24 %	(Andalib et al., 2016)
Sporoscarcina. pasteurii	5.2×10^7 cell/ml	8.6	Compression	12 %	(Ramchandran et al., 2001)
Sporoscarcina. pasteurii	-	9.25	Compression	33 %	(Abo-El-Enein et al., 2013)
Sporoscarcina pasteurii	10^3 cell/ml	-	Compression	22 %	(Chahal et al., 2012)
Bacillus subtilis	0.33 cell/ml	8	Compression	14.8 %	(Pei et al., 2013)
Bacillus subtilis	10^5 cell/ml	-	Compression	19.2 %	(Vempada et al., 2011)
Bacillus cereus	10^6 cell/ml	8.5	Compression	38 %	(Maheswaran et al., 2014)
Shewanella sps	10^5 cell/ml	7.2	Compression	25.3 %	(Ghosh et al., 2005)
Bacillus subtilis	2.8×10^8 cell/ml	-	Compression	12 %	(Khaliq and Ehsan, 2016)
Bacillus sp. CT-5	Optical density (OD_{600} of 1)	8	Compression	36.15 %	(Achal et al., 2013)
Bacillus sphaericus	-	-	Compression	14.3 %	(Gandhimathi and Suji, 2015)
Bacillus sphaericus	-	10 - 11	Compression	11.2 %	(Gavimath et al., 2012)

Table 4
Strength improvement from various types of polymers

Type of polymers	Methods	Test methods	Efficiency	References
Epoxy resin	Microcapsules	Compression	1.9 time normalized strength	(Li et al., 2013)
		Three-point bending	1.3 time normalized strength	
Polyurethane	Encapsulation	Three-point bending	54 % improvement in strength and 52 % stiffness	(Van Tittelboom et al., 2011)
Polyurethane	Encapsulation	Three-point bending	35 % stiffness	(Feiteira et al., 2016)
Superabsorbent polymers (SAP)	-	Three-point bending	8 % improvement in strength	(Gruyaert et al., 2016)
Methyl methacrylate monomer	Micro-encapsulation	Compression	30.4 % improvement in strength	(Yang et al., 2010)

Table 5
Strength improvement of concrete by using sodium silicate (Na_2SiO_3) and magnesium oxide (MgO)

Healing concrete	Methods	Test methods	Efficiency	References
By using sodium silicate (Na_2SiO_3)	Mixed with concrete	Three-point bending	5 % improvement in compressive strength	(Qureshi and Al-Tabbaa, 2016)
	Encapsulated	Three-point bending	6 % load regain	(Qureshi et al., 2016)
	Encapsulated	Three-point bending	12 % load regain	(Kanellopoulos et al., 2015)
By using magnesium oxide (MgO)	Encapsulated	Three-point bending	17 % load regain	(Kanellopoulos et al., 2015)
	Micro-encapsulated	Ultrasonic wave transmission	12.3 % specific stiffness regain	(Mostavi et al., 2015)
	Micro-encapsulated	Three-point bending	26.2 % flexural regain	(Pelletier et al., 2010)

Alkali-resistant bacteria that produce spores were used by Luo et al. (2015) in their investigation into self-healing concrete. The results demonstrated a reduction in crack width with increasing repairing time, Figure 2. Additionally, bacteria were used as a healing agent in concrete by Gavimath et al. (2012). The samples were then examined for tensile and compressive strength in both normal and healed concrete. Bacterial concrete samples outperformed the controls in terms of strength, Figure 3.

4.2. Durability

For concrete structures, durability is the main concern because it has to do with the material's service life. Durable concrete means resisting or penetrating any aggressive ions into the concrete. Sulphate resistance, alkali-aggregate reaction, steel reinforcement corrosion, and carbonation are the main factors of concrete deterioration. Deterioration of concrete mainly occurs by being permeable. A system of self-healing is a novel technique used to make the concrete more durable by bridging the cracks, thus resisting opening and making the concrete impermeable.

The durability of self-healing concrete can be assessed and verified using a variety of test methods. Table 6 shows various studies which used different healing materials and then tested the samples for water absorption, their results showed a significant reduction in porosity.

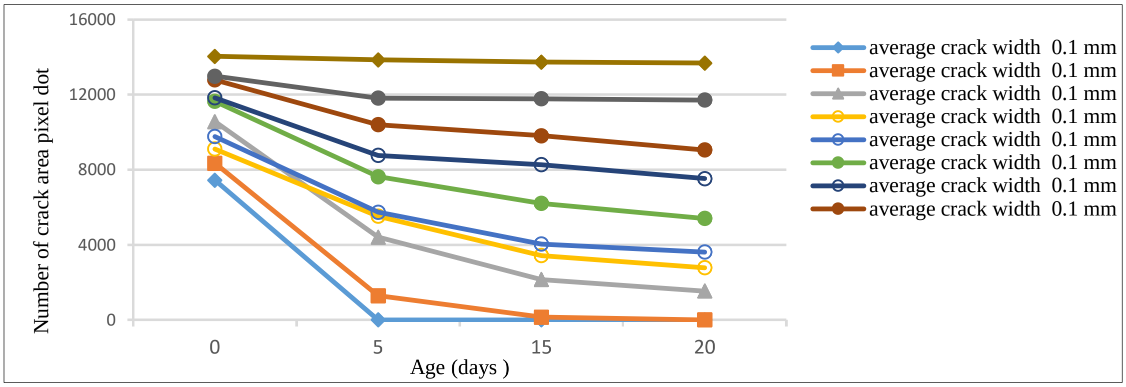


Figure 2. Number of crack area versus average crack width with time (Luo et al., 2015)

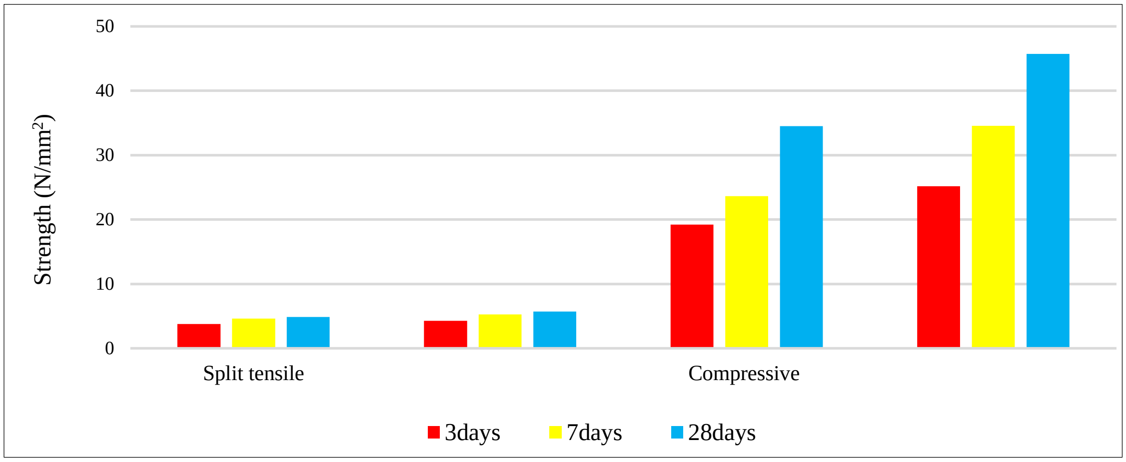


Figure 3. Strength comparison in control and bacterial concrete (Gavimath et al., 2012)

Table 6
The effect of various healing materials on water absorption after cracking

Type of healing materials	Methods	K-value untreated	k-value treated (healing agent)	Efficiency factor	References
Polyurethane in ceramic capsule	Water entering a repaired crack	1×10^{-6}	1×10^{-12}	2	(Van Tittelboom et al., 2011)
Bacillus. sphaericus with hydrogel	Water entering a repaired crack	1×10^{4} - 1×10^{5}	1×10^{5} - 1×10^{6}	1.25	(Wang et al., 2014)
Superabsorbent polymers (SAP)	Water entering a repaired crack	1×10^{-6}	1×10^{-10}	2	(Snoeck et al., 2014)
Bacillus. sphaericus immobilized in polyurethane	Water entering a repaired crack	1×10^{-5}	1×10^{-10}	2	(Wang et al., 2012)
Bacillus. sphaericus in sol gel+$CaCl_2$	Water entering a repaired crack	1×10^{-4}	1×10^{-12}	3	(Van Tittelboom et al., 2010)

Achal et al. (2013) investigated how healing mortar samples were impacted by Bacillus sp. CT-5. The samples' porosity was examined and contrasted with the control samples' porosity percentage. Figure 4 shows the reduction in porosity of self-healed mortar samples.

The durability of self-healing concrete was also investigated by Tziviloglou et al. (2016). The mortar samples were examined for water permeability. Healing agents were used in some of the samples and then compared to the controls. According to their research, samples that had been healed had much lower water leakage than samples that had not been healed, Figure 5.

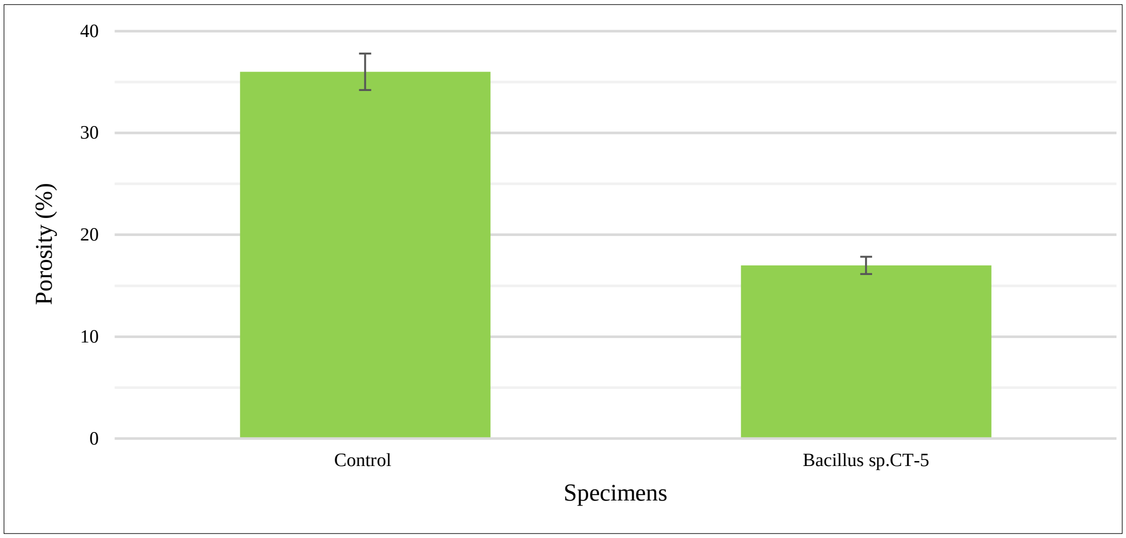


Figure 4. Comparison of total porosity in control and Bacillus sp. CT-5 bacterial mortar (Achal et al., 2013)

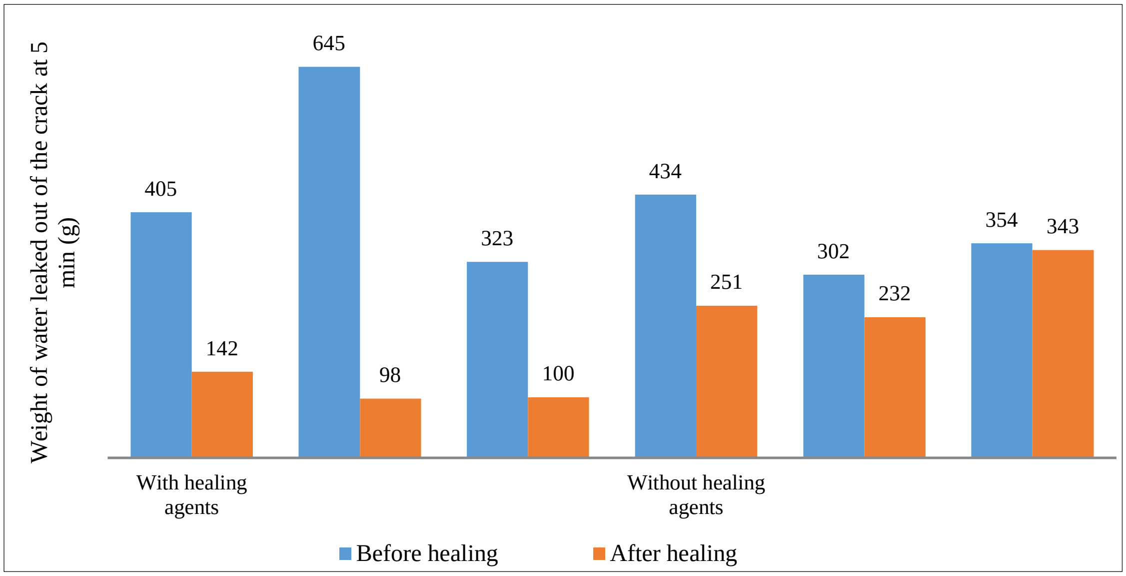
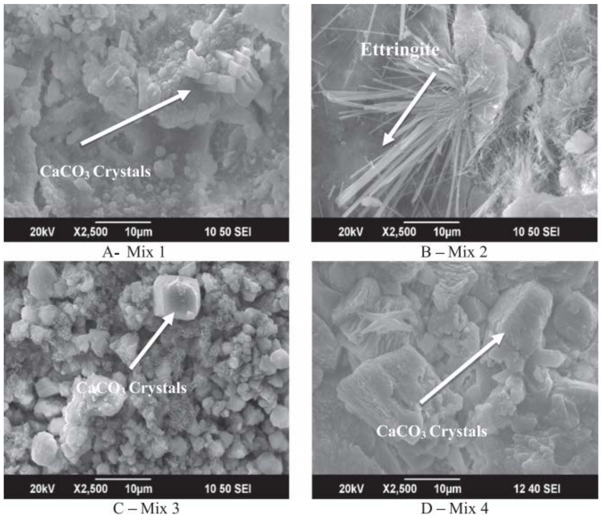


Figure 5. Effect of healing agents on mortar specimens' permeability both before and after healing (Tziviloglou et al., 2016)

4.3. Microstructural evaluation

Microstructural evaluation is needed for healed crack visualization, crystal materials determination, deposited crystal visualization, etc. There are a lot of evaluation techniques that are used for microstructural measurement of self-healing concrete, such as X-ray diffraction, scanning electron microscopy, energy dispersive spectrum, etc. Majority of the research studies on self-healing concrete have tested the samples for analyzing their microstructures besides testing for mechanical properties and durability such as strength, permeability, corrosion, etc.

Khaliq and Ehsan (2016) prepared four concrete mixtures. The mixture was the same in all but incorporation techniques of the bacteria were different in all. The first one was a control mix without adding bacteria. While for the second mix, the bacteria were added directly to the water during mixing the concrete. However, nanoplatelets were utilized for the third and fourth mix carrier compounds, such as light aggregate and graphite, respectively. The formation of $CaCO_3$ for all mixes through scanning electron microscopy analysis was observed, Figure 6.



A- Mix 1 B – Mix 2 C – Mix 3 D – Mix 4

Figure 6. Magnified Scanning Electron Microscopy; analysis of 28 days of samples before cracking (Khaliq and Ehsan, 2016)

Furthermore, Tziviloglou et al. (2016) used EDS analysis on the crystalline formation to check the formation of $CaCO_3$. High peaks of calcium (Ca), carbon (C), and oxygen (O) were detected in the test results, indicating that $CaCO_3$ was in fact present. Gruyaert et al. (2016) used scanning electron microscopy (SEM) to check the healing process on mortar specimens using SAP as a healing agent, Figure 7. Qureshi et al. (2018) used ESEM, XRD, and TGA analysis to check the healing performance. The crack width before healing was 0.17mm, and after 28 days of healing was reduced to 0.14mm, Figure 8.

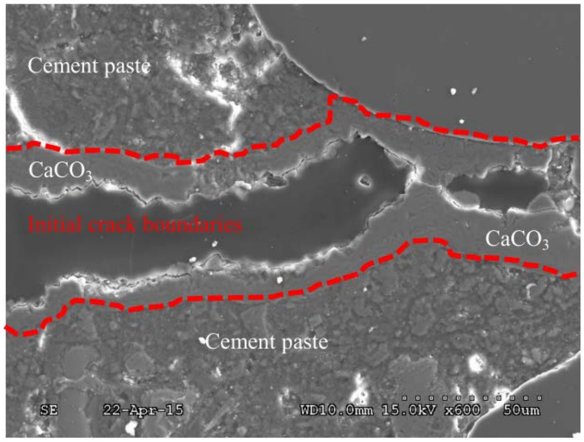


Figure 7. SEM for a mortar specimen with cracks and some healing that contains SAP (Gruyaert et al., 2016)

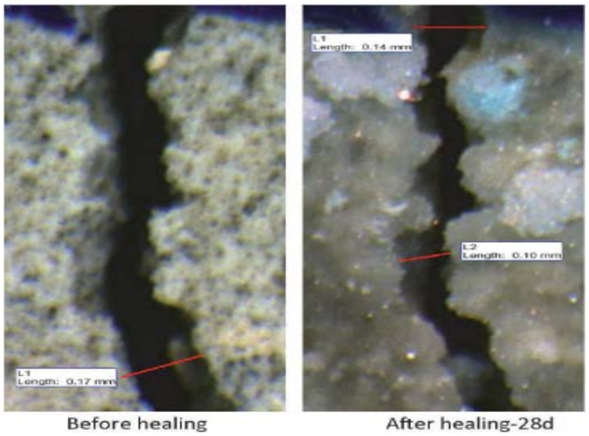


Figure 8. Crack width comparison of cement mix before and after healing by ESEM analysis (Qureshi et al., 2018)

5. Advantages

In a summary, the main advantages of self-healing in concrete can be drawn as:

1. Improvement of the compressive strength of concrete.
2. Remedying cracks quickly.
3. Reduction in corrosion of reinforcement.
4. Reduction in permeability of concrete.
5. Increasing the durability of concrete.
6. Eco-friendly, natural and it is pollution free.
7. Lower repair and maintenance costs.
8. Decreasing production of concrete.
9. Through this solution system, the aesthetic appearance is not harmed.
10. Better resistance to freezing-thawing.
11. Reducing CO_2 emission from concrete production.

6. Disadvantages

Despite the advantages explained, the self-healing approach has some disadvantages in various manners such as:

1. The price of bacterial concrete is higher; it is almost twice as expensive as regular concrete.
2. In any environment or medium, bacterial growth is insufficient. The cultivation of calcifying microorganisms involves the use of a variety of nutrients and metabolic products that influence the survival, growth, biofilm, and crystal formation of the organisms. A lot of research has been conducted on the metabolic products and retention of nutrients in building materials.
3. No IS code is provided yet because it is a new research material, therefore it is difficult to get optimum performance when the bacteria are used in concrete.
4. The cost of the investigation process will be high because bacteria have different properties thus they contribute to different behavior. Therefore, some testing methods are needed to investigate the microstructure of the concrete such as SEM, which is costly, and good skill to carry out the test are required as well.
5. The self-healing agent, which accounts for 20 % of the concrete volume, is carried by the clay pellets.

7. Applications

Using of bacterial concrete has become increasingly popular, it can be used for:

- Healing of concrete cracks and
- Repairing of monuments constructed in limestone.

Also for:

- Durable roads with low cost,
- River banks,
- High - strength buildings, and
- Durable housing with low cost.

For creating self-healing concrete, a number of processes have been proposed. It has not yet been used in all new constructions, and self-healing bacteria-based concrete is still in the early stages of development.

8. Conclusions

Based on reviewing various research study articles on self-healing concrete, some points can be drawn. Self-healing is a novel strategy that can be used to remediate the cracks in concrete internally when they start to grow. Since cracking is the main problem in concrete structures, it cannot be prevented, but controlling and repairing the cracks is necessary. Externally remediating the cracks on the concrete surface is one of the classic techniques, and it requires special materials, machines, and skilled labor. Hence, self-healing is a good alternative to classical repairing. Self-healing concrete needs some material as a healing agent, and bacterial spore is usually used and added to the concrete during mixing. By reducing permeability, this technology significantly improves the durability of concrete. It can also reduce inspection labor, maintenance cost, and cement production by providing safer and more sustainable material. Despite the positive results of self-healing, the application of self-healing concrete in all engineering constructions is still quite limited because of a few drawbacks, most notably economic ones. The optimum volume fraction of the bacteria is still unknown, and there is no design code to produce appropriate bacterial-healing concrete. Self-healing concrete is an interested subject for research studies, the concept can be improved by using other materials and using new technology in order to withstand the small detect.

References

Aldea C. M., Song, W. J., Popovics J. S., Shah S. P., Extent of healing of cracked normal strength concrete, Journal of Materials in Civil Engineering, 12 (1), 2000, 92-96,

Al-Thawadi S. M., Ureolytic bacteria and calcium carbonate formation as a mechanism of strength enhancement of sand, Journal of Advanced Science and Engineering Research, 1 (1), 2011, 98-114,

Abo-El-Enein S. A., Ali A. H., Talkhan F. N., Abdel-Gawwad H. A., Application of microbial biocementation to improve the physico-mechanical properties of cement mortar, HBRC Journal, 9 (1), 2013, 36-40,

Achal V., Mukerjee A., Reddy, M. S., Biogenic treatment improves the durability and remediates the cracks of concrete structures, Construction and Building Materials, 48, 2013, 1-5,

Andalib R., Abd Majid M. Z., Hussin M. W., Ponraj M., Keyvanfar A., Mirza J., Lee H. S., Optimum concentration of Bacillus megaterium for strengthening structural concrete, Construction and Building Materials, 118, 2016, 180-193,

Breugel K. V., Is there a market for self-healing cement-based materials?, In proceedings of the first international conference on self-healing materials, 2007, 1-9,

Bang S. S., Galinat J. K., Ramakrishnan V., Calcite precipitation induced by polyurethane-immobilized Bacillus pasteurii, Enzyme and Microbial Technology, 28 (4-5), 2001, 404-409,

Chahal N., Rajor A., Siddique R., Calcium carbonate precipitation by different bacterial strains, African Journal of Biotechnology, 10 (42), 2011, 8359-8372,

Chahal N., Siddique R., Rajor A., Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete, Construction and Building Materials, 28 (1), 2012, 351-356,

Dry C., Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices, Smart Materials and Structures, 3 (2), 1994, 118,

Dick J., De Windt W., De Graef B., Saveyn H., Van der Meeren P., De Belie N., Verstraete, W., Bio-deposition of a calcium carbonate layer on degraded limestone by Bacillus species, Biodegradation, 17 (4), 2006, 357-367,

De Rooij M., Van Tittelboom K., De Belie N., Schlangen E. (Eds.)., Self-healing phenomena in cement-based materials: state-of-the-art report of RILEM technical committee 221-SHC: self-Healing phenomena in cement-based materials, Springer Science & Business Media, 11, 2013, 226,

Edvardsen C., Water permeability and autogenous healing of cracks in concrete, Innovation in Concrete Structures: Design and Construction, 1999, 473-487,

Feiteira J., Gruyaert E., De Belie N., Self-healing of moving cracks in concrete by means of encapsulated polymer precursors, Construction and Building Materials, 102, 2016, 671-678,

Fortin D., Ferris F. G., Beveridge T. J., Surface-mediated mineral development by bacteria, Geomicrobiology, 2018, 161-180,

Gollapudi U. K., Knutson C. L., Bang S. S., Islam M. R., A new method for controlling leaching through permeable channels, Chemosphere, 30 (4), 1995, 695-705,

Gandhimathi A., Suji, D., Studies on the development of eco-friendly self-healing concrete- A green building concept, Nature Environment and Pollution Technology, 14 (3), 2015, 639,

Gavimath C. C., Mali B. M., Hooli V. R., Mallpur J. D., Patil A. B., Gaddi D. P., Ternikar C. R., Ravishankera B. E., Potential application of bacteria to improve the strength of cement concrete, International Journal of Advanced Biotechnology and Research, 3 (1), 2012, 541-544,

Ghosh P., Mandal S., Chattopadhyay B. D., Pal S., Use of microorganism to improve the strength of cement mortar, Cement and Concrete Research, 35 (10), 2005, 1980-1983,

Ghosh P., Mandal S., Pal S., Bandyopadhyaya G., Chattopadhyay B. D., Development of bioconcrete material using an enrichment culture of novel thermophilic anaerobic bacteria, Indian Journal of Experimental Biology, 44, 2006, 336-339,

Gruyaert E., Debbaut B., Snoeck D., Díaz P., Arizo A., Tziviloglou E., Schlangen E., De Belie N., Self-healing mortar with pH-sensitive superabsorbent polymers: testing of the sealing efficiency by water flow tests, Smart Materials and Structures, 25 (8), 2016, 1-11,

Homma D., Mihashi H., Nishiwaki T., Self-healing capability of fibre reinforced cementitious composites, Journal of Advanced Concrete Technology, 7 (2), 2009, 217-228,

Huynh N. N. T., Phuong N. M., Toan N. P. A., Son N. K., Bacillus subtilis HU58 Immobilized in micropores of diatomite for using in self-healing concrete, Procedia Engineering, 171, 2017, 598-605,

Jacobsen S., Sellevold E. J., Self healing of high strength concrete after deterioration by freeze/thaw, Cement and Concrete Research, 26 (1), 1996, 55-62,

Jonkers H. M., Thijssen A., Muyzer G., Copuroglu O., Schlangen E., Application of bacteria as self-healing agent for the development of sustainable concrete, Ecological Engineering, 36 (2), 2010, 230-235, Kashyap V. N., A study on effect of bacteria on cement composites, International Journal of Research in Engineering and Technology, 2013, 356-360,

Kanellopoulos A., Qureshi T. S., Al-Tabbaa A., Glass encapsulated minerals for self-healing in cement based composites, Construction and Building Materials, 98, 2015, 780-791,

Khaliq W., Ehsan M. B., Crack healing in concrete using various bio influenced self-healing techniques, Construction and Building Materials, 102, 2016, 349-357,

Li V. C., Lim Y. M., Chan Y. W., Feasibility study of a passive smart self-healing cementitious composite, Composites Part B: Engineering, 29 (6), 1998, 819-827,

Li V. C., Yang E. H., Self healing in concrete materials, Self Healing Materials, 2007, 161-193,

Li W., Jiang Z., Yang Z., Zhao N., Yuan W., Self-healing efficiency of cementitious materials containing microcapsules filled with healing adhesive: Mechanical restoration and healing process monitored by water absorption, Plos One, 8 (11), 2013, 1-18,

Luo M., Qian C. X., Li R. Y., Factors affecting crack repairing capacity of bacteria-based self-healing concrete, Construction and Building Materials, 87, 2015, 1-7,

Mitchell A. C., Dideriksen K., Spangler L. H., Cunningham A. B., Gerlach R., Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping, Environmental Science & Technology, 44 (13), 2010, 270-5276,

Maheswaran S., Dasuru S. S., Murthy A. R. C., Bhuvaneshwari B., Kumar V. R., Palani G. S., Iyer N. R., Krishnamoorthy S., Sandhya S., Strength improvement studies using new type wild strain Bacillus cereus on cement mortar, Current Science, 106 (1), 2014, 50-57,

Mihashi H., Kaneko Y., Nishiwaki T., Otsuka K., Fundamental study on development of intelligent concrete characterized by self-healing capability for strength, Transactions of the Japan Concrete Institute, 22, 2000, 441-450,

Mostavi E., Asadi S., Hassan M. M., Alansari M., Evaluation of self-healing mechanisms in concrete with double-walled sodium silicate microcapsules, Journal of Materials in Civil Engineering, 27 (12), 2015, 4015035,

Neville A., Autogenous healing-a concrete miracle?, Concrete International, 24 (11), 2002, 76-82,

Naveen B., Sivakamasundari S., Study of strength parameters of bacterial concrete with controlled concrete and structural elements made with concrete enriched with bacteria, In International conference on Engineering Innovations and Solutions, 2016, 53-59,

Park S. J., Park Y. M., Chun W. Y., Kim W. J., Ghim S. Y., Calcite-forming bacteria for compressive strength improvement in mortar, Journal of Microbiology and Biotechnology, 20 (4), 2010, 782-788,

Pelletier M. M., Brown R., Shukla A., Bose A., Self-healing concrete with a microencapsulated healing agent, Technical Report, University of Rhode Island, Kingston, USA, 2010,

Pei R., Liu J., Wang S., Yang M., Use of bacterial cell walls to improve the mechanical performance of concrete, Cement and Concrete Composites, 39, 2013, 122-130,

Qureshi T., Al-Tabbaa A., The effect of magnesia on the self-healing performance of Portland cement with increased curing time, In 1st International Conference on Ageing of Materials & Structures, 2014, 635-642,

Qureshi T. S., Al-Tabbaa A., Self-healing of drying shrinkage cracks in cement-based materials incorporating reactive MgO, Smart Materials and Structures, 25 (8), 2016, 084004,

Qureshi T. S., Kanellopoulos A., Al-Tabbaa A., Encapsulation of expansive powder minerals within a concentric glass capsule system for self-healing concrete, Construction and Building Materials, 121, 2016, 629-643,

Qureshi T., Kanellopoulos A., Al-Tabbaa A, Autogenous self-healing of cement with expansive minerals-I: Impact in early age crack healing, Construction and Building Materials, 192, 2018, 768-784,

Ramchandran S. K. Ramakrishnan V., Bang S. S., Remediation of concrete using micro-organisms, ACI Materials Journal-American Concrete Institute, 98 (1), 2001, 3-9,

Stocks-Fischer S., Galinat J. K., Bang S. S., Microbiological precipitation of CaCO3. Soil Biology and Biochemistry, 31 (11), 1999, 1563-1571,

Siddique R., Chahal N. K., Effect of ureolytic bacteria on concrete properties, Construction and building Materials, 25 (10), 2011, 3791-3801,

Sahmaran M., Yildirim G., Erdem, T. K., Self-healing capability of cementitious composites incorporating different supplementary cementitious materials, Cement and Concrete Composites, 35 (1), 2013, 89-101,

Snoeck D., Van Tittelboom K., Steuperaert S., Dubruel P., De Belie N., Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers, Journal of Intelligent Material Systems and Structures, 25 (1), 2014, 13-24,

Su Y., Zheng T., Qian C., Application potential of Bacillus megaterium encapsulated by low alkaline sulphoaluminate cement in self-healing concrete, Construction and Building Materials, 273, 2021, 121740,

Talaiekhozani A., Abd Majid M. Z., A review of self-healing concrete research development, Journal of Environmental Treatment Techniques, 2 (1), 2014, 1-11,

Tziviloglou E., Wiktor V., Jonkers H. M., Schlangen E., Performance requirements to ensure the efficiency of bacteria-based self-healing concrete, In 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures, Berkeley, 2016,

Van Tittelboom K., De Belie N., De Muynck W., Verstraete W., Use of bacteria to repair cracks in concrete, Cement and Concrete Research, 40 (1), 2010, 157-166,

Van Tittelboom K., De Belie N., Van Loo D., Jacobs P., Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent, Cement and Concrete Composites, 33 (4), 2011, 497-505,

Vempada S. R., Reddy S. S. P., Rao M. S., Sasikala C. I., Strength enhancement of cement mortar using microorganisms-an experimental study, International Journal of Earth Sciences and Engineering, 4, 2011, 933-936,

Vermeer C. M., Rossi E., Tamis J., Jonkers H. M., Kleerebezem R., From waste to self-healing concrete: A proof-of-concept of a new application for polyhydroxyalkanoate, Resources, Conservation and Recycling, 164, 2021, 105206,

Wang J., Van Tittelboom K., De Belie N., Verstraete W., Use of silica gel or polyurethane immobilized bacteria for self-healing concrete, Construction and Building Materials, 26 (1), 2012, 532-540,

Wang J. Y., Snoeck D., Van Vlierberghe S., Verstraete W., De Belie N., Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete, Construction and Building Materials, 68, 2014, 110-119,

Wiktor V., Jonkers H. M., Quantification of crack-healing in novel bacteria-based self-healing concrete, Cement and Concrete Composites, 33 (7), 2011, 763-770,

Wu M., Johannesson B., Geiker M., A review: self-healing in cementitious materials and engineered cementitious composite as a self-healing material, Construction and Building Materials, 28 (1), 2012, 571-583,

Xu J., Wang X., Zuo J., Liu X., Self-healing of concrete cracks by ceramsite-loaded microorganisms, Advances in Materials Science and Engineering, 2018.,

Xu J., Yao, W., Multiscale mechanical quantification of self-healing concrete incorporating non-ureolytic bacteria-based healing agent, Cement and Concrete Research, 64, 2014, 1-10,

Yang Z., Hollar J., He X., Shi X., Laboratory assessment of a self-healing cementitious composite, Transportation Research Record, 2142 (1), 2010, 9-17,

Zhong W., Yao W., Influence of damage degree on self-healing of concrete, Construction and building Materials, 22 (6), 2008, 1137-1142.

Osvrt na samozaceljujući beton - biološki pristup

Dilshad Kakasor Jaf

Salahadin univerzitet u Erbilu, Fakultet inženjerskih nauka, Odsek za građevinarstvo, okrug Kurdistan-Irak

INFORMACIJE O RADU

Primljen 20 april 2022
Prihvaćen 05 oktobar 2022

Pregledni rad

Ključne reči:
Samoisceljivanje
Pukotine
Bakterije
Bacillus
Bakterijski beton
Trajnost

IZVOD

Beton je jedan od najpopularnijih i najviše korišćenih građevinskih materijala zbog svoje čvrstoće, izdržljivosti i relativno niske cene, ali on ima i veću tendenciju za stvaranje pukotina. Pojava pukotina smanjuje vek trajanja betona i povećava troškove održavanja. Prodiranje agresivnih jona kroz pukotine dovodi do korozije čelične armature, karbonizacije, stvaranja sulfata, alkalno-agregatne reakvije, itd. Međutim, sprečavanje nastanka pukotina je nemoguće, ali one se mogu kontrolisati ili popraviti brojnim metodama. Samozaceljujući beton je poznat kako prikladna metoda za ispunjavanje pukotina, kao i za poboljšanje dugoročne trajnosti betona. To je nov, brz i ekološki prihvatljiv pristup. U ovoj tehnologiji, kada je beton izložen vodi, materijal za popunjavanje stvara kalcijum karbonat ($CaCO_3$) koji ispunjava pukotine i smanjuje propustljivost, a produžava trajanje betona. Materijali koji se koriste za popunjavanje pukotina su uglavnom bakterije, polimeri i hemijska jedinjenja. Bakterije predstavljaju najpoželjniji materijal za ovaj postupak. Zbog toga, drugo ime koje se koristi za samoisceljujući beton glasi biobeton ili bakterijski beton. U ovom radu je predstavljen pregled tehnologije samozaceljujućeg betona koji obuhvata sistem, proces, mehanička svojstva i trajnost ovog betona.