STUDY ON SELF-HEALING CONCRETE TYPES – A REVIEW

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Abstract -*The most popular treatment for concrete structure is self-healing method to enhance the durability of concrete. This current paper a review on its types, processes i.e. natural and chemical mechanism of self-healing concrete was deeply evaluated from past journal was published about them and the main purposed of this paper as focuses on types and mechanisms of self-healing concrete. The data introduced in current study as huge substantial for bioprocess and biotechnologists engineer to provide useful details on present condition of self-healing concrete.*

KEY WORDS: **Self-healing concrete, Autonomous process, Autogenous process.**

1. INTRODUCTION

Concrete is one of the most important structural materials. Over the years, various modifications of concrete compositions have been proposed in order to improve its properties. Lately, the decrease of the environmental impact of concrete has been extensively studied.

Self-healing concrete is widely focused by research communities. Basically, the repairing capability of concrete which results to treatments its cracks automatically is called Self-healing Concrete. Self-healing concrete is mostly defined as the ability of concrete to repair its cracks autogenously or autonomously. It is also called self-repairing concrete. Cracks in concrete are a common phenomenon due to its relatively low tensile strength. Durability of concrete is impaired by these cracks since they provide an easy path for the transportation of liquids and gases that potentially contain harmful substances. If microcracks grow and reach the reinforcement, not only the concrete itself may be attacked, but also the reinforcement steel bars will be corroded. Therefore, it is important to control the crack width and to heal the cracks as soon as possible. Self-healing of cracks in concrete would contribute to a longer service life of concrete structures and would make the material not only more durable but also more sustainable.

Self-healing concrete when comes in contact with air and water, it produces lime on outer layer of concrete. In most of the traditional concrete mixtures 20-30% of the cement is left un-hydrated. If cracking of the concrete occurs, unreacted cement grains may become exposed to moisture penetrating the crack. In that case the hydration process may start again and hydration products may fill up and heal the crack.

This research focused on the autogenous and autonomous self-healing of cementitious materials. Due to a lack of confirmed, indisputable, fully understood governing mechanism, the efficiency of the autogenous self-healing process still brings concerns and does not ensure successful full-scale applications.

1.1 Objectives

- to understand the types of autogenous and autonomous self-healing of concrete.
- to use that knowledge to fully control it.
- to understand the applications of and mechanisms behind the autogenous and autonomous self-healing of concrete.

2. TYPES OF SELF-HEALING CONCRETE

Self-Healing concrete is classified into types based on the mechanisms involved:

- Autonomous Healing Concrete
- Autogenous Healing Concrete

2.1 Autonomous Healing Concrete

This type of crack healing in concrete is the type that includes closed capsules (either spherical or cylindrical) shown in (Fig.1) that contain a healing agent. When crack happens, the capsule breaks and the inside agent (sometimes special Bacteria) fills the crack due to gravitation forces. Generally, this type is called autonomous self-healing.

"To facilitate the production of self-healing concrete, encapsulated healing agents are preferably added to the concrete mix during preparation". The efficiency of such encapsulated agents can be observed in the aggressive conditions related to temperatures that can produce very difficult cracks to handle. According to Van Tittle boom and De Belie and May's literature bodies, "When temperature differences and cyclic loads cause the crack to grow wider or become more narrow, elastic behavior of the hardened agent is wanted. In order not to lose the bond between the repair agent and the cementitious matrix, and thus preserve the crack sealing ability." On the other hand, water as medium can have other significance as the autonomous healing action can start with different types of trigger mechanisms. For example, the ingress of liquids into the crack, however that has some throwbacks.

"A disadvantage is that as long as the required agent does not intrude into the crack, healing is not activated. In the period between formation of damage and activation of healing, degradation of the concrete matrix can still occur".

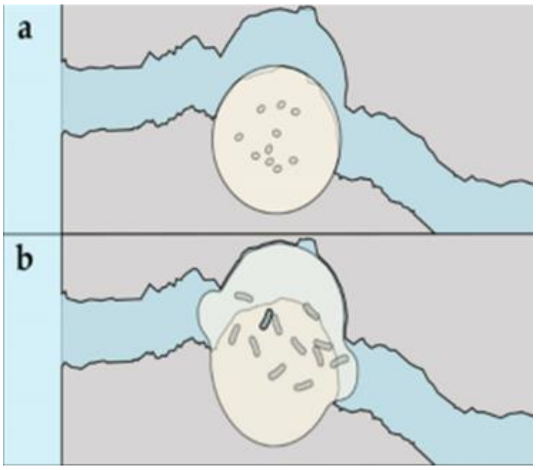

Fig -1: Autonomous self-healing concrete methods

The Autonomous self-healing concrete can be enhanced and improved in the following ways:

- Bacterial Autonomous Healing
- Capsule-Based Autonomous Healing
- Fungi spore Autonomous Healing
- Carbon Nanotube Autonomous Healing

2.1.1 Bacterial Autonomous Healing

Bacterial self-healing concrete is a type of self-healing concrete that uses bacteria to heal the cracks. The process involves adding bacteria, usually Bacillus spp., to the concrete mix. These bacteria remain dormant until the concrete cracks, at which point they become active and start to produce calcium carbonate ($CaCO_3$) through a process called microbial induced calcium carbonate precipitation (MICP). The $CaCO_3$ produced by the bacteria fills the cracks in the concrete and restores its strength. This process is sustainable and eco-friendly, as the bacteria consume carbon dioxide (CO_2) during the production of $CaCO_3$, helping to reduce the carbon footprint of concrete production.

One of the first applications of bacteria to seal cracks in concrete was mentioned by Gollapudi et al. (1995). The use of bacteria-modified mortars, which could be applied externally for concrete repair was the topic of many research projects (Oriel et al., 2002; De Muynck et al., 2008; Van Tittelboom et al., 2010; Ramakrishnan et al., 2013). Recently, the use of bacteria for self-healing concrete was also studied.

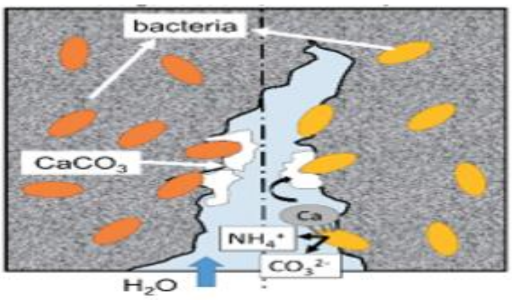

Fig -2: Bacteria-based autonomous self-healing

2.1.1.1 Different types of bacteria used in autonomous self-healing concrete are:

- Bacillus Subtilis.
- Sporosarcina Pasteurii
- Escherichia coli (E coli)
- Basillus Cohnni

Bacillus Subtilis

One type of bacteria that is commonly used in self-healing concrete is called Bacillus subtilis. This bacterium is able to produce a mineral called calcite, which can fill in cracks in the concrete and help to restore its structural integrity. Bacillus subtilis is able to survive in the harsh conditions of concrete, such as its high alkalinity and low nutrient availability.

Fig -3: Bacillus Subtilis

Sporosarcina Pasteurii

The mechanism of Sporosarcina pasteurii in self-healing concrete involves its ability to produce an enzyme called urease. Urease is able to hydrolyze urea, a compound that is commonly found in urine, to produce ammonia and carbon dioxide. This process increases the pH of the surrounding environment, making it more alkaline. When Sporosarcina pasteurii is added to concrete mix, it can remain dormant until cracks appear. Once a crack forms in the concrete, moisture enters and activates the bacteria. The bacteria then begin to produce urease, which hydrolyzes urea to produce ammonia and carbon dioxide. The ammonia reacts with carbon dioxide and calcium in the concrete to produce calcium carbonate, which is the main component of limestone. The calcium carbonate fills in the cracks, effectively healing the concrete.

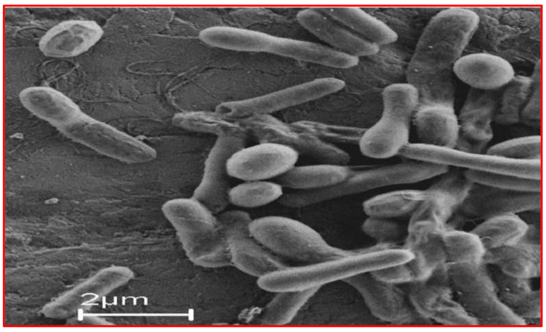

Fig -4: Sporosarcina Pasteurii

Escherichia coli (E. coli)

It is the type of bacteria that is commonly found in the lower intestine of warm-blooded organisms. Most E. coli strains are harmless, but some can cause serious food poisoning. Shiga toxin-producing E. coli (STEC) is a bacterium that can cause severe foodborne disease.

Fig -5: Escherichia coli (E. coli)

Bacillus Cohnii

Bacillus cohnii is a type of bacteria that has been explored for its potential use in self healing concrete. Like other self-healing bacteria, Bacillus cohnii has the ability to produce calcium carbonate, which is the main component of limestone and can be used to fill in cracks in concrete.

The mechanism of Bacillus cohnii in self-healing concrete is similar to that of other selfhealing bacteria. When added to concrete mix, the bacteria remain dormant until cracks appear. Once cracks appear, moisture enters and activates the bacteria, which then begin to produce calcium carbonate. The calcium carbonate fills in the cracks, effectively healing the concrete.

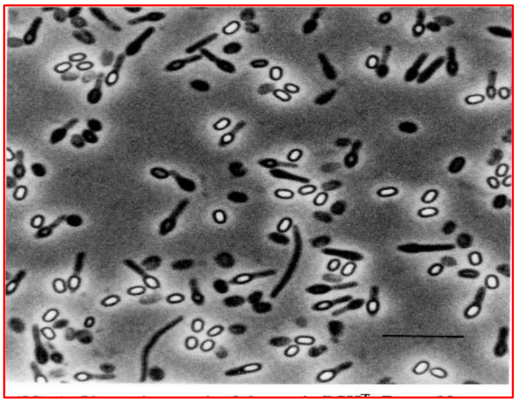

Fig -6: Bacillus Cohnii

2.1.1.2 Mechanism of The Bacterial Self-Healing

There are two main mechanisms governing bacterial self-healing of concrete, i.e. bacterial metabolic conversion of organic acid and enzymatic ureolysis. The self-healing product that fills the crack is calcium carbonate.

In the first process, bacteria act as a catalyst and transform a precursor compound to a suitable filler material. As a result, calcium carbonate-based minerals are produced which act as a bio-cement that seals the cracks. One of the calcium precursors, often used in research due to its positive effect on concrete strength, is calcium lactate. In this case, the reaction occurring in the crack can be formulated as follows:

$$Ca(C3H5O2)2 + 7O2 \rightarrow CaCO3 + 5CO2 + 5H2O$$

In addition to this reaction, the produced CO2 reacts locally with Ca(OH)2 inside of the crack leading to the production of five more CaCO3 molecules thus making the process six times more effective than the autogenous self-healing.

The second mechanism called ureolysis is based on the bacterial production of urease which catalyzes the hydrolysis of urea (CO(NH2)2) into ammonium (NH4+) and carbonate (CO3 2−) ions .

The reactions can be presented as follows:

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3$$

$$H_2CO_3 \leftrightarrow HCO^-{}_3 + H^+$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$$

$$HCO^-{}_3 + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O$$

The bacteria surface can serve as a nucleation site due to the cell wall being negatively charged and, therefore, can attract ions from the environment, e.g. Ca2+. Those ions deposited on the surface of the bacteria cell react with CO3 2- and lead to the precipitation of CaCO3.

$$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+}$$

$$Cell - Ca^{2+} + CO^{2-}{}_3 \rightarrow Cell - CaCO_3 \downarrow$$

2.1.1.3 Factors Affecting Bacterial Self-Healing

The ability of bacteria to survive in a concrete-based environment is one of the most important factors affecting the efficiency of bacterial self-healing. Unfortunately, during the cement hydration the compressive stresses tend to crush the bacteria. Therefore, spores might be considered a better solution. However, changes in the concrete porosity during maturing may lead to the decreased viability of spores and survival time reaching only several months.

Different types of calcium salts can be used in bacterial self-healing systems, such as calcium chloride, calcium nitrate or calcium lactate. The type of calcium salt affected the efficiency of the self-healing process. The usage of calcium chloride (CaCl2) was found to be not optimal due to chloride. Calcium nitrate (Ca (NO3)2) was more compatible as it is often used as a setting accelerator or anti-freeze agent. It reacts with calcium hydroxide (Ca(OH)2) forming calcium hydroxy nitrate – a mineral with needle-shaped crystals that functions as micro reinforcement for the cement matrix. However, it is not certain if it can provide a sufficient amount of Ca2+ ions. Calcium lactate (C4H6CaO4) was shown to increase the concrete strength.

The nutrients, which aid the germination of the spores and provide a source of growth for bacterial cells, also effected the efficiency of self-healing as well as concrete properties, especially when added directly into the concrete mix. The two most popular nutrients are yeast extract and urea. The latter was said to be questionable because of the formation of ammonium ions which resulted in the environmental nitrogen loading.

It was observed that the precipitation of calcium carbonate was the highest within the crack rim next to the surface. The reason for this might be the shortage of oxygen. Zhang et al. (2016, 2017) introduced a new solution, i.e. a controlled-oxygen-releasing tablet (ORT) containing CaO2 and lactic acid with a suitable ratio of 9:1. As a result, a new binary concrete crack self-healing system was able to supply molecular oxygen for the precipitation of the microbial calcium.

2.1.2 Capsule-Based Autonomous Healing

Capsule-based concrete is a type of self-healing concrete that contains small capsules filled with healing agents such as polyurethane or epoxy. These capsules are dispersed throughout the concrete mixture and are designed to rupture and release their contents when a crack appears in the concrete. When the healing agent is released from the ruptured capsules, it reacts with the surrounding materials to fill the cracks and restore the structural integrity of the concrete. The healing process can occur multiple times as the capsules continue to release their contents when new cracks occurs.

The encapsulation of the healing agent is one of the most studied approaches. In contrast to autogenous healing, the healing component is contained in microcapsules, which are added to the concrete mix. After hardening, the repair occurs when the forming crack propagates through the capsule, breaking it and releasing the healing agent. As a result, not only the crack propagation is blocked but also the material is repaired by filling the crack with the healing agent. The permeability is usually decreased and some regain of strength can occur. This method was initially applied for structural polymers. The proposed system consisted of a microcapsule with the healing agent and a catalytic chemical trigger.

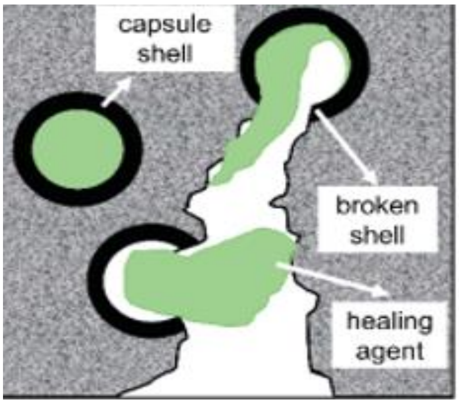

Fig -7: Capsule-Based Self-Heling Concrete

2.1.2.1 Mechanism Of The Capsule Self-Healing

The mechanism of the capsule-based self-healing systems consists of three components. The first is the trigger, which depicts the process of activating the capsule by damaging its walls. The next component is the healing agent, i.e. the substance, being the core of capsule, which is released into the crack upon activation. Finally, the capsule shell material (different protection coatings) which is used to prevent the contact of the healing agent with the healed matrix. The effectiveness of the self-healing system depends on the compatibility of those components with the repaired matrix and their successful interaction.

The most popular mechanism is based on a mechanical trigger. The stresses associated with the crack formation lead to the breakage of the brittle capsule material and to the release of the healing agent. Another solution is to use chemical triggers such as chloride ions, pH. In that case, chloride ions penetrate the concrete matrix through Nano-cracks before the actual formation of micro-cracks. These chloride ions are then used to initiate the healing mechanism. The sensitivity of the chloride trigger appeared to be higher. The encapsulated healing agent might also be released after the cement matrix is attacked by carbon dioxide. The carbonation results in a decrease of the strength of the matrix surrounding the capsules and additionally changes the microstructure thus leading to the breakage of the capsules. Expanded clay lightweight aggregate was used impregnated with a sodium monofluorophosphate (Na_2FPO_3) solution and encapsulated by a cement paste layer to produce a self-healing system in blast-furnace slag cement mortars.

Various types of healing agents for the self-healing concrete are applied (Table 2.1). They can be divided in three groups: one-, two and multi-component healing agents. The one-component self-healing agents have the ability to act alone without the need for additional chemical compounds or catalysts, e.g. sodium silica (Na_2SiO_3). On the other hand, two- and multi-component systems require another substance for instance, dicyclopentadiene (DCPD), to achieve the maximum efficiency. The polymerization (ROMP) process uses a Grubbs catalyst (transition metal catalyst), which incorporates a high metathesis method. Unfortunately, the two-component systems are more complex and have the risk of an inappropriate mixing of the two compounds resulting in the insufficient cracks sealing. The healing agent should have a low viscosity to enable its penetration into the concrete binder matrix. An optimum fluidity is yet another important factor controlling the transportation through the cracks. Finally, the healing material has to solidify in the desired place.

Table -2.1: Most common healing agents for self-healing concrete

Healing agent	Reference
Epoxy resin	(Han & Xing, 2016) (Dong et al., 2016) (Perez et al., 2015) (Wang et al., 2017)
Two component PU foam	(Tittleboom et al., 2011) (Hilloulin et al., 2015)
Methyl methacrylate MMA	(Dry & McMillan, 1996) (Yang et al., 2011)
Sodium silicate (Na_2SiO_3)	(Gillford et al., 2014) (Alghamri et al., 2016) (Tan et al., 2016) (Kanellopoulos et al., 2016) (Kanellopoulos et al., 2015)

2.1.3 Fungi Spore Autonomous Healing

In fungi spore autonomous healing process, the fungal spores alongside their nutrients, will be blended into the concrete before the curing process starts. When cracks appear and water trickles into the concrete, the dormant fungal spores will wake up, grow, consume the nutrient soup, and promote CaCO3 precipitates to fix the cracks in situ. After the cracks are finally healed, the bacteria or fungi will make spores and go dormant once more – ready to start a new cycle of self-healing when cracks form again. For existing concrete infrastructures with cracks, the fungal spores and their nutrients can be injected or sprayed into the cracks.

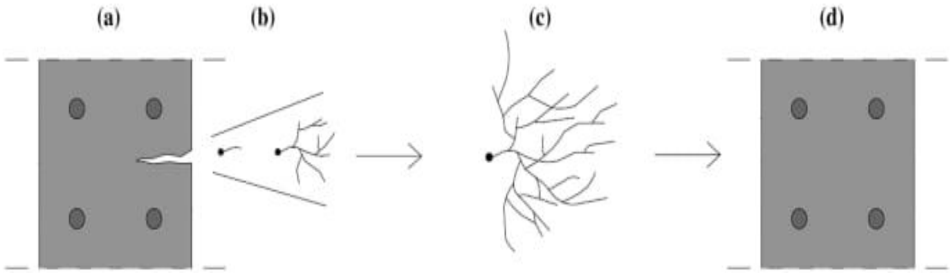

Fig -8: Fungi spore Autonomous Healing

2.1.3.1 Mechanism Of Fungi Spore Autonomous Healing

The mechanism of fungi spore autonomous healing in concrete represents a biologically inspired approach to enhancing the durability and self-repair capabilities of the material. In this process, fungi spores are deliberately introduced into the concrete mix during its formulation. These spores remain dormant within the concrete matrix until the material undergoes stress or damage, resulting in the formation of cracks. The critical trigger for activation is the exposure of these spores to moisture, commonly found when cracks allow water ingress into the concrete.

Upon activation, the fungi spores initiate a complex biological response. Germination occurs, leading to the growth of hyphae, which are thin, thread-like structures characteristic of fungi. The hyphae extend into the surrounding concrete, creating a network that actively interacts with the material. During this growth phase, the fungi absorb calcium ions present in the concrete and combine them with carbonate ions sourced from the surrounding environment. This metabolic activity leads to the biomineralization process, wherein minerals, primarily calcium carbonate, are precipitated.

The minerals generated by the fungi serve a dual purpose. Firstly, they act as a natural filler for the cracks in the concrete, effectively sealing the damaged areas. Secondly, the mineral precipitation contributes to the overall enhancement of the concrete's structural integrity, thereby reinforcing the material. This innovative autonomous healing mechanism leverages the biological functions of fungi to actively participate in the repair and strengthening of concrete structures. This approach aligns with the growing interest in sustainable and bioinspired solutions for improving the resilience of construction materials, offering a promising avenue for the development of more robust and long-lasting infrastructure.

2.1.4 Carbon Nanotube Autonomous Healing

Carbon nanotube (CNT) autonomous healing represents a cutting-edge application within the realm of self-repairing concrete. By incorporating carbon nanotubes into the concrete matrix during the mixing process, engineers capitalize on the extraordinary mechanical, electrical, and structural properties inherent to these cylindrical nanostructures. The remarkable strength of carbon nanotubes significantly enhances the concrete's tensile strength, making it more resistant to cracking and providing a solid foundation for the autonomous healing mechanism.

2.1.4.1 Mechanism of Carbon Nanotube Autonomous Healing

When the concrete experiences stress or develops microcracks due to external factors, the embedded carbon nanotubes play a dual role in mitigating the damage. Firstly, they act as reinforcements, creating a network that helps distribute and bear loads more effectively. This reinforcement contributes to the material's toughness, preventing the propagation of cracks and increasing the overall durability of the concrete structure.

Moreover, the unique characteristics of carbon nanotubes enable them to actively participate in an autonomous healing process at the nanoscale. As microcracks emerge, the carbon nanotubes work to bridge these gaps, promoting a self-repair response. Their high aspect ratio and ability to adhere to surrounding materials make them effective in sealing small fissures and preventing further deterioration. This nanoscale healing mechanism complements traditional approaches to concrete maintenance, offering a forward-looking solution to address the inherent vulnerabilities of concrete structures over time.

Beyond their structural contributions, carbon nanotubes also introduce electrical conductivity to the concrete. This property opens the door to innovative applications, such as embedding sensors to monitor the structural health of the concrete in real-time. By harnessing the multifunctionality of carbon nanotubes, autonomous healing becomes not only a reactive process but also a proactive strategy for sustainable infrastructure.

In essence, carbon nanotube autonomous healing in concrete represents a fusion of nanotechnology and construction materials engineering. It showcases the potential for advanced materials to actively respond to stress, prevent further damage, and ultimately contribute to the longevity and resilience of concrete structures. As research in this field continues, the integration of nanomaterials like carbon nanotubes into construction practices holds promise for a new era in infrastructure development, where materials play an active role in their own maintenance and repair.

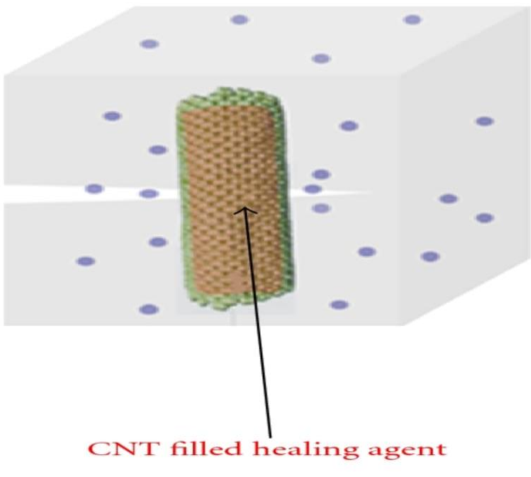

Fig -9: Carbon Nanotube Autonomous Healing

2.2 Autogenous Self-Healing Concrete

Autogenous healing concrete is a type of self-healing concrete that contains mineral admixtures such as fly ash, slag, or silica fume. These admixtures react with water and unhydrated cement particles to produce a healing agent that fills the cracks in the concrete. When the concrete cracks, the healing agent is released and fills the cracks, effectively sealing them and restoring the structural integrity of the concrete. The healing process can occur repeatedly over the lifespan of the concrete structure, improving its durability and reducing the need for maintenance.

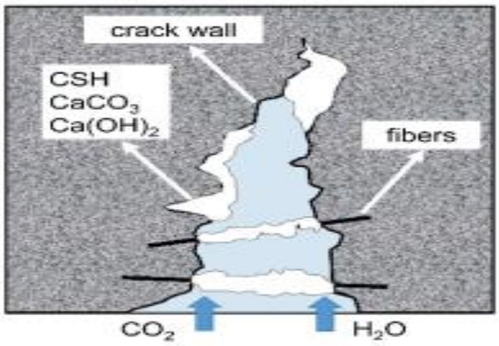

Fig -10: Autogenous Healing Concrete

Autogenous healing in concrete can be enhanced and improved in the following ways:

- The fiber in Autogenous-Healing of Concrete
- Shrinkable Polymers in Autogenous-Healing of Concrete
- Mineral Admixture in Autogenous-Healing of Concrete

2.2.1.1 Fiber In Autogenous-Healing Of Concrete

The incorporation of fibers in concrete helps to enhance the autogenous self-healing property of concrete. Fiber is an important material that is used for Fiber-Reinforced Concrete (FRCC) as well as in Engineered Cementitious Composites (ECC).

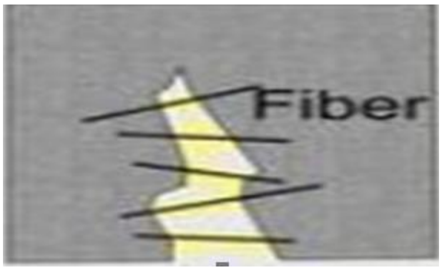

Fig -11: Fiber in Autogenous Healing of Concrete

The arrangement of fibers in a randomly distributed manner helps to bridge the cracks. This bridging helps to decrease the crack width and hence prevent the migration of aggressive agents like chloride ions and carbon-di-oxide. Hence, these activities improve the autogenous self-healing capacity of the concrete.

On the other side, the design of FRCC, ECC, and HFRCC is very costly and it is a great challenge to maintain the homogeneity of fibers in the matrix in a consistent manner to facilitate self-healing properties.

2.2.1.2 Shrinkable Polymers in Autogenous-Healing Of Concrete

Shrinkable Polymers are polymers that shrink when they are activated by heating in a specific condition. One of the examples of shrinkable polymers is polyethylene terephthalate (PET) tendons. The stress created using during this shrinking is used to bring the crack tip closure for efficient healing.

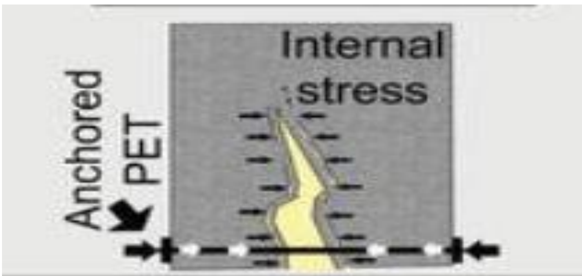

Fig -12: Shrinkable Polymers in Autogenous-Healing of Concrete

As per the study conducted by Cardiff University Self-healing research team, the restrained polymer tendons that are used in concrete are activated thermally once the initial curing of the concrete is done. Once the tendon gets activated, the used polymer tendon closes the performed macrocracks and imparts significant stress across the crack faces. This would enhance the autogenous self-healing process in concrete.

2.2.1.3 Mineral Admixture In Autogenous Healing Of Concrete

The self-healing capacity of concrete can be improved by introducing mineral admixture and supplementary cementitious materials (SCMs). The minerals introduced in concrete can help the self-healing process in the below ways:

- To remain unhydrated after the initial mixing stage of the concrete.
- To undergo reaction and produce expansive hydrated products that would heal the cracks.

Fig -13: Mineral Admixture in Autogenous Healing of Concrete

The different types of SCMs that can be used to auto-heal the concrete cracks through autogenous self-healing are silica fumes, fly ash, and blast-furnace slag, and expansive minerals like lime, bentonite clay, crystalline additive (CA), calcium sulpho aluminate, magnesium oxide.

2.2.2 Mechanism Of The Autogenous Self-Healing

The causes of self-sealing of cracks in concrete were identified as related to dissolution, continuous hydration, deposition and crystallization, etc. The autogenous healing was noticed to reduce the water permeability of concrete by more than an order of magnitude. The most significant changes in the permeability were observed in the first 100 hours of testing. The autogenous healing of concrete was found to be a flow-dependent process, i.e. the water has to flow through the cracks exposed to the atmosphere. The $CaCO_3$ formation in the cracks was found to be the main reason of the autogenous healing mechanism in concrete. The calcite formation in the area of water bearing cracks can be formulated in the following way:

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \ (\text{pH water} > 8)$$

$$Ca^{2+} + HCO_3^{-} \leftrightarrow CaCO_3 + H^{+} \ (7.5 < \text{pH water} < 8)$$

The location of the $CaCO_3$ crystals depends on the temperature, the pH value, the CO_2 partial pressure, the saturation index of calcite and the concentration of Ca^{2+} and CO_3^{2-} ions in the solution.

Two major types of self-healing products were distinguished, one crystal-like consisting of portlandite/calcite and the other gel-like primarily made of calcium silicate hydrate (CS-H). The amount of formed portlandite was higher (~ 80%) than CS-H (< 15%) in comparison with the surrounding binder matrix. It was observed that the self-healing process tends to slow down after approximately 300 hours.

The physio-chemical principles behind the autogenous self-healing are still not completely understood. Often, only the surface cracks are evaluated, therefore the results regarding products of self-healing can be misleading. In general, the causes of autogenous self-healing can be divided into three main groups: physical, chemical and mechanical. The physical causes consist of swelling of the cement matrix. Chemical causes, most often mentioned in the literature, are the continued hydration of cement particles and formation of calcium carbonate. The mechanical causes include filling of the cracks with fine particles originating from the broken surface of concrete or transported with water inside the crack.

2.2.3 Factors Affecting the Autogenous Self-Healing Concrete

The necessary conditions for autogenous healing in concrete are:

- **Age of Concrete:** At an early stage of concrete, the hydration products formed by the hydration of calcium silicates into C-S-H calcium silicate hydrate take the role of a self-healing process. In the later stage, the main products involved in self-healing are calcium carbonates formed by carbon-di-oxide in water and calcium in concrete.
- **Internal Stress:** Impelled compressive stress makes the cracked face come into contact. It is found that the concrete specimens cured under some amount of compressive stress healed much better than those cured under no compressive stress.
- **Curing Period:** The process of curing can recover the strength of concrete. But, highly humid conditions are not enough to trigger the healing process in concrete.
- **Moisture Content:** Water accelerates the hydration of unhydrated cement particles and increases the dissolution of calcium hydroxide from the concrete matrix near the crack surface.
- **Crack Width:** Spontaneous or autogenous healing is the most efficient for tiny cracks of less than 0.3 mm in width. We need to enhance the process for more significant cracks using additional materials or autonomous healing.

3. SCOPE OF SELF-HEALING CONCRETE

Self-healing concrete has promising applications in various construction scenarios, offering enhanced durability and reduced maintenance costs. Here are some detailed applications of self-healing concrete:

- **Infrastructure and Buildings**
  Bridges and Highways
  Self-healing concrete can significantly benefit critical infrastructure like bridges and highways. These structures are often exposed to harsh environmental conditions and heavy loads, leading to the development of cracks over time. The autonomous healing properties of concrete can help mitigate the impact of these cracks, improving the overall longevity and safety of the infrastructure.
  Commercial and Residential Buildings
  Self-healing concrete is also applicable in commercial and residential construction. It can reduce the need for frequent maintenance and repairs in structures, contributing to sustainable and cost-effective building practices.
- **Underground Structures**
  Tunnels and Subway Systems
  The underground environment poses unique challenges to concrete structures, including exposure to moisture and aggressive chemicals. Self-healing concrete can address these challenges by autonomously repairing cracks, preventing the deterioration of tunnel structures and subway systems.
  Sewer Systems
  Self-healing concrete is beneficial in sewer systems where exposure to corrosive elements can lead to cracks. The ability to autonomously repair cracks helps maintain the structural integrity of sewer pipes, reducing the risk of leaks and associated environmental hazards.

- **Marine Structures**
  Harbors and Ports
  Concrete structures in marine environments are susceptible to deterioration due to exposure to saltwater. Self-healing concrete can actively combat the effects of saltwater intrusion by sealing cracks and preventing further damage, making it a valuable solution for harbor and port infrastructure.
  Offshore Platforms
  Offshore structures face challenging conditions, including corrosive saltwater and dynamic loads. Self-healing concrete contributes to the longevity of offshore platforms by addressing cracks and maintaining structural integrity in these demanding environments.
- **Historical Preservation**
  Self-healing concrete can be employed in the restoration and preservation of historical structures. By mitigating the impact of cracks and reducing the need for frequent repairs, it helps protect the cultural heritage embodied in these structures.
- **Nuclear Facilities**
  In nuclear facilities where radiation exposure and harsh conditions are prevalent, self-healing concrete can play a crucial role in maintaining the integrity of structures. It provides an additional layer of protection against potential radiation-induced damage.
- **Environmentally Sensitive Areas**
  In areas with ecological sensitivity, such as wildlife reserves or natural parks, self-healing concrete minimizes the environmental impact associated with traditional repair methods. This aligns with sustainable construction practices by reducing the need for disruptive maintenance activities.

4. CURRENT RESEARCH PRACTICES

There is a lot of full-scale outdoor testing of self-healing concrete structures. A small structure or part of a structure will be built with self-healing material and observed over two to four years. Structures will be fitted with some panels of self-healing concrete and others with conventional concrete so that the behavior of the two can be compared. Cracks will be made in the concrete that are much larger than the ones that have healed up in the laboratory to determine how well and fast they heal over time.

The research will test two systems. The first technique will see bacteria and nutrients applied to the structure as a self-healing mortar, which can be used to repair largescale damage. The second technique will be seeing the bacteria and food nutrients dissolved into a liquid that is sprayed onto the surface of the concrete form where it can seep into the cracks. Laboratory tests are being carried out to accelerate the ageing process of self-healing concrete. The tests will subject the concrete to extreme environments to simulate changing seasons and extreme temperature cycles, wetter periods and dryer periods.

5. CHALLENGES

- Self-healing concrete heals or recover only small cracks. But it fails to recover the larger cracks or structural damage remains a challenge for many existing self-healing technologies.
- Test results which was obtained in the laboratory varies or maybe different when applied in real world conditions.
- Durability of self-healing concrete is not fully understood and ability of these materials to sustain Autonomous Healing over extended period is a subject of ongoing investigation.
- The cost-effectiveness of implementing self-healing concrete on a large scale is not economical as the production and incorporation of healing agents can contribute to increased material costs, and the overall economic feasibility of self-healing technologies needs further evaluation.
- Self-healing mechanisms may change the mechanical properties of concrete such as strength, stiffness and other properties of concrete which is a major concern in Structure design.
- Use of self-healing concrete in the existing structures is a major concern and requires thoughtful planning and execution.

6. CONCLUSION

- Self-Healing concrete is classified into types based on the mechanisms involved as Autonomous Healing Concrete and Autogenous Healing Concrete.
- The Autonomous self-healing concrete can be enhanced and improved by using Bacterial Autonomous Healing Capsule-Based Autonomous Healing, Fungi spore Autonomous Healing and Carbon Nanotube Autonomous Healing.

- Autogenous healing in concrete can be enhanced and improved by using fiber in Autogenous-Healing of Concrete, Shrinkable Polymers in Autogenous-Healing of Concrete and Mineral Admixture in Autogenous Healing of Concrete.
- By using the bacteria on concrete, the maintenance cost is reduced because the crack heal itself and it is studied that the maintenance cost is almost zero.
- Using bacteria in concrete make concrete more durable and the compressive and flexural strength of concrete is increased little bit.
- The bacteria are difficult to cultivate because the bacteria cannot survive any weather condition and the cost of the bacteria is high.
- By using the bacteria in concrete, the chance of reinforced bar in concrete gets corrode is reduced.
- From the cost point of view, we can only use this concrete where the chance of water enter through the cracks is high that is in marine structure and water retaining structure.

7. REFRENCES

1. Ghosh SK, editor. Self-healing materials: fundamentals, design strategies, and applications. John Wiley & Sons; 2009 Aug 4.
2. S. Van der Zwaag (Ed.), (2007) Self Healing Materials–an Alternative Approach to 20 Centuries of Materials Science, Springer, Dordrecht, The Netherlands.
3. M. Nosonovsky, B. Bhushan, (2009) Thermodynamics of surface degradation, self-organization, and selfhealing for biomimetic surfaces, Phil. Trans. R. Soc. A. 367: 1607–1627.
4. M. Nosonovsky, R. Amano, J. M. Lucci, P. K. Rohatgi, (2009) Physical chemistry of selforganization and self-healing in metals, Phys. Chem. Chem. Phys, 11 :9530–9536.
5. B. Van Belleghem, N. De Belie, J. Dewanckele, V. Cnudde, Analysis and visualization of water uptake in cracked and healed mortar by water absorption tests and X-ray radiography, in: Concr. Repair, Rehabil. Retrofit. IV, CRC Press, 2015: pp. 12–13. https://doi.org/10.1201/b18972-8
6. S. K. Ghosh (Ed.), (2009) Self-Healing Materials: Fundamentals, Design Strategies, and Applications, Wiley WCH, GmbH.
7. K. van Breugel (2007) Is There a market for selfhealing cement-based materials. In: Proceedings of the first international conference on self-healing materials, Noordwijkaan zee, the Netherlands.
8. W. Zhong, W. Yao, (2008) Influence of damage degree on Self-healing of Concrete. Construction and Building Materials, 22: 1137-1142
9. S. Van der Zwaag (Ed.), (2007) Self Healing Materials–an Alternative Approach to 20 Centuries of Materials Science, Springer, Dordrecht, The Netherlands.
10. M. Nosonovsky, R. Amano, J. M. Lucci, P. K. Rohatgi, (2009) Physical chemistry of selforganization and self-healing in metals, Phys. Chem. Chem. Phys, 11 :9530–9536.
11. Palin, D., Wiktor, V. & Jonkers, H.M., A bacteria-based self-healing cementitious composite for application in low-temperature marine environments. Biomimetics, 2(4), pp. 13, 2017. https://doi.org/10.3390/biomimetics2030013.
12. Tang, W., Kardani, O. & Cui, H., Robust evaluation of self-healing efficiency in cementitious materials – A review. Construction and Building Materials, 2015. https://doi.org/10.1016/j.conbuildmat.2015.02.054.
13. Malinskii, Y.M.; Prokopenko, V.V.; Ivanova, N.A.; Kargin, V.A. Investigation of self-healing of cracks in polymers. Polym. Mech. 1970, 2, 271–275.
14. Ferrara, L.; Van Mullem, T.; Alonso, M.C.; Antonaci, P.; Borg, R.P.; Cuenca, E.; Jefferson, A.; Ng, P.L.; Peled, A.; Roig-Flores, M.; et al. Experimental characterization of the self-healing capacity of cement based materials and its effects on the material performance: A state of the art report by COST Action SARCOS WG2. Constr. Build. Mater. 2018, 167, 115–142.
15. Jacobsen, S.; Sellevold, E.J. Self healing of high strength concrete after deterioration by freeze/thaw. Cem. Concr. Res. 1996, 26, 55–62.
16. Kumar Jogi, P.; Vara Lakshmi, T.V.S. Self healing concrete based on different bacteria: A review. Mater. Today Proc. 2020, 43, 1246–1252.
17. Wiktor, V.; Jonkers, H.M. Quantification of crack-healing in novel bacteria-based self-healing concrete. Cem. Concr. Compos. 2011, 33, 763–770.
18. Huang, H.; Ye, G.; Qian, C.; Schlangen, E. Self-healing in cementitious materials: Materials, methods and service conditions. Mater. Des. 2016, 92, 499–511.
19. De Belie, N.; Gruyaert, E.; Al-Tabbaa, A.; Antonaci, P.; Baera, C.; Bajare, D.; Darquennes, A.; Davies, R.; Ferrara, L.; Jefferson, T.; et al. A Review of Self-Healing Concrete for Damage Management of Structures. Adv. Mater. Interfaces 2018, 5, 1800074.
20. Bacteria-based self-healing concrete H. M. Jonkers1.
21. Bharanedharan G1 , Logesh S2 , Nishok A.V.K "Studies on Self-Healing Sustainable Concrete Using Bacterial Carbonate Precipitate", International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13,

22. G. Mohan Ganesh, A.S. Santhi, “self-healing bacterial concrete by replacing fine aggregate with rice husk”,International Journal of Civil Engineering and Technology (IJCIET) Volume 8, Issue 9, September 2017, pp. 539–545
23. Bio-Based Self-Healing Concrete: From Research to Field Application Eirini Tziviloglou, Kim Van Tittelboom, Damian Palin, Jianyun Wang, M. Guadalupe Sierra-Beltra´n, Yusuf C¸ agatay Ers¸an, Rene´e Mors, Virginie Wiktor, Henk M. Jonkers, Erik Schlangen, and Nele De Belie
24. Seifan M., Samani A.K., Berenjian A. Bioconcrete: Next generation of self-healing concrete. Appl. Microbiol. Biotechnol. 2016;100:2591–2602. doi: 10.1007/s00253-016-7316-z.
25. Development of a bacteria-based self healing concrete Henk M. Jonkers & Erik Schlangen Delft University of Technology, Faculty of Civil Engineering and GeoSciences/Microlab, Delft, The Netherlands
26. Interactions of Fungi with Concrete: Significant Importance for Bio-Based Self-Healing Concrete Jing Luo1 , Xiaobo Chen2 , Jada Crump3 , Hui Zhou2 , David G. Davies4 , Guangwen Zhou2,3 , Ning Zhang1,5* , Congrui Jin2,3* .
27. Jonkers HM, Schlangen E. Development of a bacteria-based self healing concrete. Proc Int FIB Symp 2008 - Tailor Made Concr Struct New Solut our Soc. 2008;(May 2008):109. doi:10.1201/9781439828410.ch72
28. Pappupreethi K, Ammakunnoth R, Magudeaswaran P. Bacterial concrete: A review.
29. Khattab IM, Shekha H, Abdi MA. Study on Self-healing Concrete types – A review. Sustain Struct Mater An Int J. 2019;2(1):76-87.
30. Murari K, Kaur I. A review of self-healing bacterial concrete. Lect Notes Civ Eng. 2019;21 LNCE(June 2020):432-437.
31. Morsali S, Yucel Isildar G, Hamed Zar gari Z, Tahni A. The application of bacteria as a main factor in self-healing concrete technology. J Build Pathol Rehabil. 2019.