Introduction of Self-Healing Concrete and Different Methods of Its Scientific Implementation

Davoud Beheshtizadeh, Davood Jafari

Abstract**—**Concrete, with its unique properties and advantages, has gained widespread and increasing use in the construction industry, particularly in a country's infrastructure. However, concrete exhibits certain defects, most notably the presence of micro-cracks that occur after the setting process, leading to increased costs for infrastructure repair and maintenance. As a result, self-healing concretes have garnered attention in various countries in recent years. These concretes employ different mechanisms for repair, including physical, chemical, biological, and combined approaches, each with its own subsets and implementation methods. Certain mechanisms hold significant importance, leading to specialized production methods. Given the novelty of this subject in Iran, there is limited knowledge or, in some cases, a complete lack of understanding. This paper presents various self-healing concrete mechanisms and the advantages, disadvantages, and application scope of each method.

Keywords**—**Micro-cracks, self-healing concrete, microcapsules, concrete, cement, self-sensitive.

I. Introduction: Problems of Concrete and Repair of Concrete in Infrastructure in Iran

IN the present century, concrete and concrete products have a special place in construction and the use of concrete is increasing day by day; and in this regard, the concrete mix design and consequently the type of concrete is changing and goes towards specific applications, and any type of concrete with special materials used in its mix design acquires its unique properties for its specific performance. Anti-radiation concrete, ultra-lightweight concrete, high strength concrete and other types are the examples of this variety. In addition to possessing favorable properties, concrete also exhibits negative characteristics that researchers strive to mitigate through the incorporation of special materials or the implementation of alternative production methods. One of these shortcomings is the weak tensile property of concrete, but this is not the only negative feature of concrete and the emergence of cracks after setting the concrete is among the important disadvantages that strongly affects the mechanical strength of concrete. Concrete structures are prone to cracking [1], which are caused by different factors. Considering the extremely proper properties of concrete, including ductility, high compressive strength and good fire resistance, this product cannot be ignored, and on the other hand, the cost of repair and maintenance of concrete structures, because of cracks in the passage of time, is very high and time-consuming. Therefore, researchers are actively seeking more cost-effective and efficient methods for concrete repair. In this regard, efforts have been made to enhance the resilience of concrete against detrimental factors through the incorporation of various materials into the concrete mixture. Additionally, some researchers are exploring the potential of self-healing methods for concrete.

The concrete used in infrastructure is often of a special type of high resistance concrete, and when damaged, incurs high repair costs, as stated in the article by Gara and Manson about the cost of concrete repairs: "It is estimated that the total cost pf repairing inter-state and highway system of the country will be 1 trillion and about 3.6 trillion for the repair of all the infrastructure of the country" [2].

The maintenance costs of concrete structures and even detecting defects are high, and sometimes timely detection is impossible. We consider, for example, a highway or dam structure that must be inspected daily by special equipment to detect defects that are not visible on the concrete surface, which requires a high amount of time and precision and is not practical. So, using simpler solutions such as using defective sensitive materials in concrete, and then self-repairing systems, can reduce many of these costs. Also, the inability to detect cracks in time due to the invisibility of internal cracks or small cracks causes the cracks to spread, and until they appear on the surface and do not spread, it will not be possible to observe and carry out repairs. In this case, the cracks will increase and the structure will suffer serious problems. Thus, finding various methods to improve the quality of concrete during construction and preventing premature destruction of concrete during operation has been studied, and beyond that, special methods for self-repair of concrete have been proposed [3].

In self-repairing concretes, before the detection of concrete defect by the eye, the repair mechanism occurs spontaneously and the concrete repairs itself. Therefore, there was a state of sensitivity to defects in this type of concrete, which after cracking autogenous healing occurs. As mentioned in scientific sources, this mechanism is very useful for small cracks before expansion and cracks with an approximate width of less than 3 mm are easily repaired. Different types of these self-repair systems are offered, each of which has its own disadvantages and advantages depending on the climate, place of use, application and cost. Considering that this type of concrete is new in the world and Iran, more and more comprehensive studies should be done, especially more laboratory studies.

Therefore, this paper, by describing and familiarizing the reader with self-repair concrete, discusses the types of methods used and some details. Finally, in the conclusion section, Table I is presented that describes the advantages and disadvantages

Eng. Davoud Beheshtizadeh, PhD. Student in Civil Engineering, Islamic Azad University - Tabriz Branch, Iran (e-mail: davoudbz@yahoo.com).

Eng. Davood Jafari, M.Sc. Student, is Independent Researcher.

of each method.

It is necessary to pay attention to the fact that in Iran, due to lack of proper supervision, lack of clear and explicit laws regarding the construction of concrete for important infrastructure, as well as non-compliance with standards in full, the country's infrastructure is severely deteriorating and no effective effort has been taken to improve the quality of concretes. As well, inflation and the government's inability to pay for repairs have posed a major challenge to the government. Therefore, more appropriate solutions may be helpful and may reduce maintenance costs during operation.

II. Research Literature: Effects of Microcracks, Traditional Methods of Concrete Repair, Research on Self-healing Concretes

Before explaining the traditional methods of concrete repair, here we will introduce the types of cracks and the effect of fine cracks, because the type and manner of their formation is effective on how to use self-repair methods.

A. Effects of Microcracks on Concrete

Microcracks appear on the surface of concrete structures sometime after use, and by the penetration of damaging factors such as carbon dioxide, water and chlorine ions into the concrete, they will damage both the concrete and rebar. There are several factors than cause microcracks. Microcracks will be formed due to shrinkage and thermal changes at an early age or due to structural loads and environmental actions during operation [3]. It can also occur due to alternating periods of ice and thawing. Certain types of concrete are more prone to cracking agents and, if left untreated, can lead to concrete flakiness, such as high-strength concretes (HSC). One of the major ways to crack concrete is through plastic shrinkage, where cracks due to plastic shrinkage occur when concrete loses water [2]. Another way that can usually cause cracks is longitudinal expansion, where in very hot environments, the concrete begins to expand [2]. Fig. 1 is a complete list of the types of cracks in concrete.

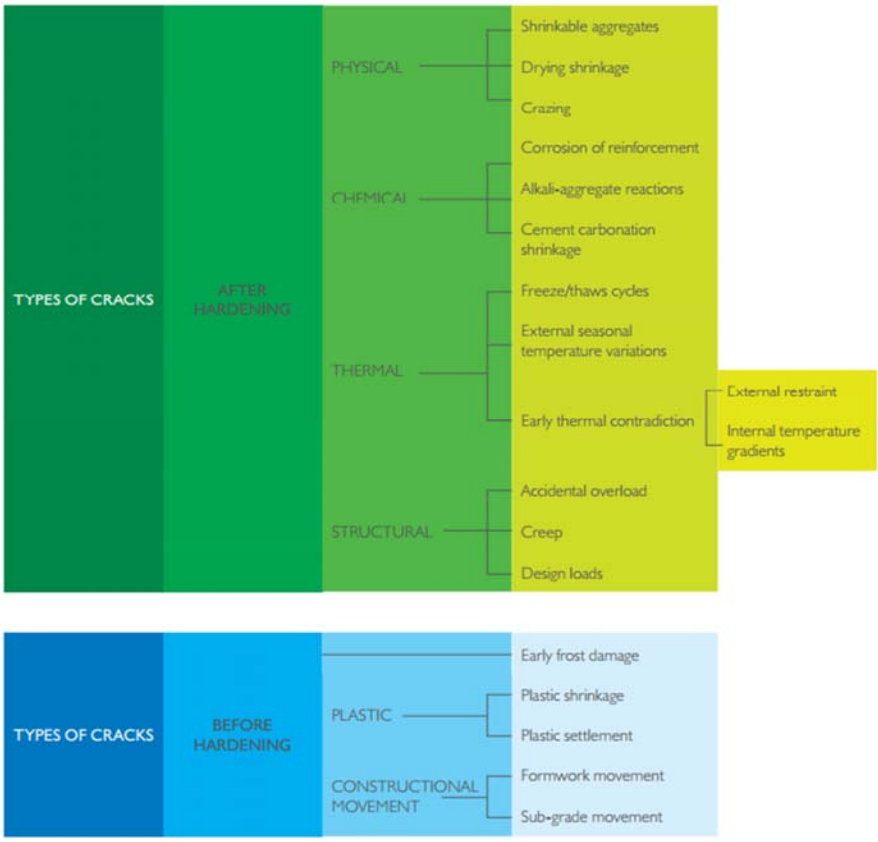

Fig. 1 Types of cracks in concrete before and after setting [4]

Before the invention of self-healing methods, there were other methods for repairing concrete, which were very time consuming and are still used today; self-healing methods also use some of past methods' properties and repair materials. These include structural epoxies, resins, epoxy mortars and other methods of mixing and local repair. It should be noted that not all of these methods are old due to the presence of cracks in the deep layers of permanent concrete.

B. Research Literature on New Methods of Concrete Healing

In their article, Wang et al. [5] summarize experimental research methods and the results of different types of self-repairing concrete in recent years based on a variety of mechanisms, including deep penetrating concrete crystals, self-repairing based on shape reminder alloys, biological and microbial, and finally, point out the problems and defects in the self-healing of concrete. In addition to explaining the uses and advantages of concrete, Li [7] deals with the disadvantages of concrete, especially cracks, and examines ways to reduce and repair concrete, and analyzes them for future development in a specific category and pays more attention to the ionic mechanism. The next article reviews the self-healing method of concrete based solely on the bacterial and partial methods. This article, written by Al-tabbaa [8] also points to different bacteria and their feeding methods that affect the properties of concrete. In their review article, Amiri and Sardroud [1] examine the self-healing processes in concrete and collects the materials with a holistic view.

III. Types of Healing Mechanisms

A. Two General Mechanisms of Self-Healing

The main property of self-healing concretes is the protection of concrete against cracking, protection of rebar, prevention of harmful substances reaching the rebar and depth of concrete by:

a) Materials inside concrete and mix design (autogenous healing) or
b) Materials outside of concrete that are applied to its surface (autonomous healing).

All restorative mechanisms are a subset of the two general mechanisms above, and its subsequent subdivisions include a variety of physical, chemical, synthetic, or biological mechanisms.[3]

1. Autogenous Healing

This type of healing is based on the elements in the cement that has not been hydrated, and this healing occurs both physically and chemically. Self-healing is achieved through two (chemical mechanisms):

a) Continued hydration of unreacted cement particles,
b) Deposition of calcium carbonate ($CaCO_2$) from the carbonation of calcium hydroxide [3].

In the second stage, crystallization is seen around the crack. In this type of healing, the presence of moisture in the vicinity of ordinary concrete is necessary for self-healing and other materials are not added to the concrete mixing plan from the beginning, and only the cement grains are not hydrated. After the exposure of these elements in the vicinity of moisture that have appeared in the new crack, self-healing occurs. The basis of the self-healing capacity of concrete is mainly due to the entry of air and moisture into the crack, under which the fully hydrated condition of the part of the cement particles that is not hydrated occurs [5].

In this method, sometimes flakiness and inflammation of the surface occurs and the substrate undergoes self-healing in the presence of high humidity (physical mechanism). At an early age, CSH formation predominates in autogenous healing due to hydration of unreacted cement particles on crack surfaces. In the later stages, due to the lack of hydrated cement grains, recovery occurs with calcium carbonate deposition [3]. In this type of repair, the crystal grows on the cracked surface, which causes the crack to close.

This type of self-healing is uncontrolled and is done spontaneously, and from the beginning the concrete structure is not made in this way with the intention of self-healing, but it occurs due to cracking, the presence of water and non-hydrated cement agent. Some initial cracks in concrete can close spontaneously if present in the right conditions (humidity) [6]. While this process will take place slowly without external factors and may not take place in any condition and in all parts of the concrete, so the healing itself either does not take place or is incomplete and slow or will not always occur. Three conditions have to meet for autogenous healing: 1) continuous water supply, 2) the presence of cementitious minerals to participate in the reactions, and 3) limited crack width [16]. For this type of reaction, the conditions must be ideal and under a specific PH of water. This process is time consuming to form crystals. The chemical reactions of calcium carbonate and the increase of crystals in the crack process proceed as follows [3]:

$$H_2O+CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3 \Leftrightarrow 2H^+ + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \Leftrightarrow CaCO_3 \quad (pH_{water} > 8)$$

$$Ca^{2+} + HCO_3 \Leftrightarrow CaCO_3 + H^+ (7.5 < pH_{water} < 8)$$

Fig. 2 Advanced status for self-healing concrete [7]

The drawbacks of this method:

- Lack of self-healing control,
- Length of repair time [7],
- The need for the presence of moisture to perform the healing process,
- Lack of self-healing elements always and everywhere and non-healing of cracks all over the concrete (healing is done randomly).

2. Autonomous Healing

Autonomous healing is based on adding materials to the mixing plan for concrete healing. This method is much more effective than the autogenous healing method, because it is more controllable and the elements in the concrete are used for self-healing intentionally and during operation [3]. This method is divided into four categories: physical, chemical, biological, and combined. This method is very suitable as it heals microcracks and also internal and invisible microcracks automatically [3]. In this mechanism, self-healing agents are stored in containers or distributed in the form of a vascular network or in the form of microcapsules separately [3].

Before explaining the types of autonomous self-healing mechanisms, its applications, advantages and disadvantages will be mentioned, and in the conclusions section, each will be reviewed separately and in comparison, with the other again.

a. Applications of Autonomous Self-healing Concrete

Due to the advantages and disadvantages that will follow, these concretes can be used in all concrete buildings. However, due to the high cost of using this technology, it is currently not affordable for ordinary buildings and is mostly used for more important buildings and infrastructure. If this type of concrete is not used to build infrastructure, which in addition to being self-healing, is also sensitive to cracks and has the ability to react quickly when the first small cracks are formed, ordinary concrete should be regularly inspected and examined. Therefore, in addition to healing, the cost of examining is high, and even the methods of detecting small internal cracks require special equipment that requires money and time. Moreover, because this infrastructure is very important and is mainly serving its users in public places, repairs in the usual and traditional ways of these concretes require the closure of part or all of the structure or infrastructure activity, which causes service disruption. For example, studies have shown that highway repairs waste passengers' time and disrupt traffic, in addition to the costs they incur to governments for repair.

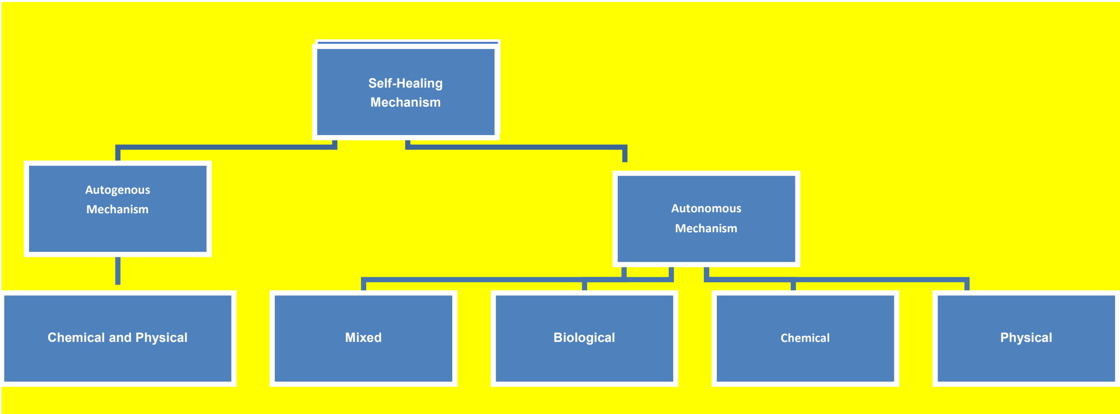

Fig. 3 Classification of self-healing mechanisms

The most important applications of autonomous self-healing concrete:

- ❖ Public buildings,
- ❖ Used in old buildings for restoration purpose,
- ❖ Military uses,
- ❖ Used in underground projects such as subways,
- ❖ Coastal and offshore structures,
- ❖ Projects in the field of sustainable development: These concretes have been evaluated with long stability and this will reduce pollution and will be environmentally friendly,
- ❖ Environments with tough weather factors and sudden sharp changes during the day and night (desert and polar regions),
- ❖ Use in infrastructure projects that have a long life, such a: Bridges, tunnels, water reserve resources, roads, hospitals and other service centers.

b. Advantages

- ❖ Possibility of self-healing of concrete and its cracks,
- ❖ Increasing of concrete life,
- ❖ Reducing the cost of repairing of concrete structures,
- ❖ Reducing the cost of maintaining concrete structures,
- ❖ Preventing the flakiness and increase of cracking,
- ❖ Preventing the rusting of reinforcements inside concrete,
- ❖ Prevent adverse factors from reaching the rebar,
- ❖ Increasing the stability and durability of the structure and preventing its destruction,
- ❖ Improving mechanical properties in concrete such as increasing compressive and flexural strength compared to conventional concrete.

c. Disadvantages

- ❖ High and extra costs of self-healing concrete,

Therefore, the best self-healing method should be used based on the following:

- – Paying attention to the speed of healing required for concrete (time is an important factor in self-healing, and the age of concrete should be consistent with the method chosen for self-healing),

d. Case Studies of Self-healing Concrete Execution Methods Outside the Laboratory Environment

- ❖ Water canal in Ecuador,
- ❖ Parking lot of 2000 square meters in the Netherlands,
- ❖ Repairs of tunnel built in 1930 and healed by these modern methods.

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B. Autonomous Self-Healing Mechanisms

As mentioned, in the process of making this type of concrete, special materials are added before concreting so that the concrete can heal itself after creating small internal and surface cracks. There are various mechanisms of self-healing concrete technology, which are divided into four sub-categories: physical process, chemical process, biological process and multiple (combined) process. In most of these processes, the self-healing process is activated after the crack occurs.

1. Physical Mechanisms

These mechanisms only physically heal the concrete and do not react chemically with the concrete molecules. The type of healing is by adding agents to the concrete, which after cracking, these agents are activated and prevent the spread of cracks in the concrete, and so-called cracks are closed in the concrete. This mechanism is divided into four sub-categories, which are:

- ❖ Flow networks (vascular)
- ❖ Shape memory alloys (SMA)
- ❖ Microcapsules (filled with adhesive liquid)

In microencapsulation mechanisms and vascular flow network, the release of healing factors is done in concrete, while in the SMA system, the repair process is different and will be examined in the following.

1. Vascular System

The vascular network system consists of a thin network of fragile tubes filled with healing material and connected to an external reservoir that continuously supplies the healing material [3]. These pipes are very brittle and break with the slightest impact and crack. That is, a fracture occurs in the crack area. This network is planted all over the concrete and then concreting is done and all the pipes are connected to each other. This is because, when part of the network breaks as a result of a crack and the healing material is released into the concrete, the adjacent network can serve the cracks that occur in the previous scope. When a crack breaks part of the pipe, the healing material is released in the concrete. While this system has excess healing potential and high reproducibility, the fragile network of brittle pipes is not practical for industrial use due to the need for excessive protection against breakage during molding [14]. One type of this network is fed from outside the concrete and is injected into the concrete from time to time by a pump of healing materials.

2. Shape Memory Alloys

Shape memory alloys (SMA) are alloys that that reshape and are able to regain their former shape after thermal changes. This is a new type of metal-based material that has been developed in recent decades and is associated with obvious phase change, good shape memory, ultra-elastic properties, good mechanical properties, corrosion resistance and biocompatibility, and high damping properties [5]. This alloy is made with different elements, each of which has unique properties, so that in choosing the amount and type of alloy used, care must be taken. Memory alloys can be examined in two ways: a state that is under stress or load and endures a lot of stress, in which case the product temperature is low, this state is called martensite. The second case is the condition in which the load is lifted, in which case the alloy can be heated to return to the original state. This state is called deformation or austenite. The effect of SMA is due to the plastic deformation of the material, which is in the state of martensite, a hard and brittle metal, at low temperatures, and returns to the main phase after heating the material by removing the external load [5]. With regard to the fact that concrete has poor tensile properties, this material is used as wires in the lower part and under the tensile stress of concrete, and in case of cracks in the mentioned part, self-healing is done using this SMA property.

This self-healing is different from other types of self-healing and improves the properties of stretched concrete only during cracking, but has little role in repairing cracks. Beams reinforced with SMA in the critical stress zone return to their original state under certain conditions after removing additional load and the depth of the cracks decreases. SMA can be made of two ribbed and plain rebars and placed in concrete. The simple or ribbed rebar produced from this product behaves differently in concrete. The presence of longitudinal treads has special effects on mechanical and self-healing properties in SMA concrete structures. Previous research has shown that SMA rebars can be used to replace traditional prestressed cables [15]. The use of wires or SMA rebars due to the high cost of this product has not made it suitable for all types of concrete products. Moreover, sufficient and real-scale research and examining the negative effects of it in specific conditions has not been done which has caused the behavior of this concrete be still unknown [11].

3. Microcapsules

Among the various self-healing systems that have been developed so far, the use of microcapsules has received considerable attention due to the way they are used [8]. One way to achieve self-dealing is to add microcapsules containing healing agents in the mixing process [8]. In this method, the material is protected in spherical or tubular microcapsules and is mixed with concrete raw material during concrete construction. These microcapsules are typically dispersed in concrete mortar and paste and open when cracks spread in the concrete. After the shell is torn, healing agents are released into the crack by capillary force or gravity [3]. The microencapsulation process is when particles of gases, solids, and liquids, about 1 micron in size, are placed in a shell, removing them from the environment and protecting them [2]. The type of core material is very different and can be one-component, two-component chemical adhesives or specific bacteria that are further elaborated in the biological section. It can also contain substances that hydrate the cement in the cracks and form crystals in the crack area. These substances can be calcium silicate or some viscous liquids such as hydroxide. Healing agents react with materials in the cement environment, chemicals in the host mixture, or with other encapsulated materials to close the crack surface [3]. Cracking activates the microcapsule and causes it to rupture. After activating (and cracking), the shell releases the healing agent and the crack is healed [8]. It should be noted that the type of shell material is also very different and in different ways protects this coating from material or releases the core material in concrete. Here are four main ways of rupturing microcapsules:

- ❖ Mechanical rupture (due to cracking),
- ❖ Rupture due to porous changes,
- ❖ Thermal decomposition,
- ❖ Rupture due to phase changes and pH changes in pH sensitive materials.

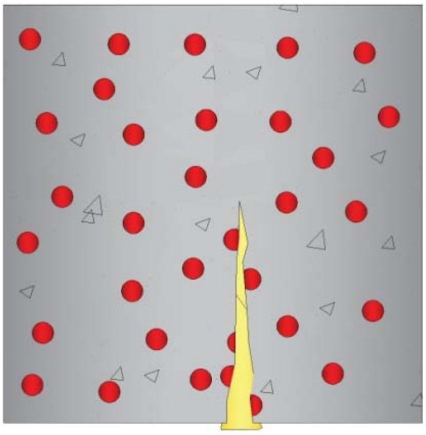

Fig. 4 Concept photo of mechanical rupture of microcapsules

One of the advantages of this method is the possibility of operating this method. Moreover, an additional advantage of this method is the activation of a self-sensing system, where healing agents are released within the crack zone. This method utilizes specially designed capsules that are able to trigger the healing process without the need for external energy. Even if the capsule's outer shell is bulky due to the substantial volume of the internal material, the healing process can still be effectively initiated [9]. That is, the shell is destroyed by the crack or the factors that change after the crack is created, and the agent leaks out. In the article by Das et al. [10], several distinct benefits of encapsulation are mentioned, including:

A) Effective protection of the encapsulated active ingredients against spoilage.
B) The ability to control the release rate of the ingredients, thereby enhancing their effectiveness.

It should be noted that the release rate control or uniform dispersion rate is not the same and these two are different. Another advantage of this method is the possibility of repairing internal cracks that cannot be seen and even external cracks that cannot be seen with the naked eye. In addition, the full penetration of materials in the depth of cracks due to the presence of healing factors in concrete is a prominent feature of this method that not only heals the surface of the concrete, but also the healing agents enter deep into the concrete.

Several disadvantages of the capsule-based self-healing method include the non-uniform dispersion of the capsules and the complex production process [16]. This discussion about dual capsules becomes very important, and if the second factor is not in the desired range, the crack will not be healed. In terms of reproducibility, these capsules will only be used once [9]. In the explanation of this section, it can be said that if microcapsules are used in a certain area and the crack is healed, this area will no longer have a healing agent, and traditional methods of healing should be used for the repeated crack of this area.

4. Disadvantages of Physical Mechanism

Among the major disadvantages of physical mechanisms of Self-Healing Concrete can be listed the following.

- High price,
- Less impact,
- Not applicable for large projects

These are expressed in general; and for all methods in this mechanism, we cannot list all the disadvantages.

2. Chemical Mechanisms

In this type of mechanism, the connections between the chemical elements cause the concrete to heal. One method of chemical mechanism of autogenous healing type was previously elaborated on. Here, we discuss chemical reactions from the set of autonomous healing. This mechanism can be examined in three sub-categories, which are:

- Self-healing with sediment crystallization,
- Self-healing with electrolytic sediments,
- Other chemical reactions.

a. Self-healing with Crystallization of Sediment

This method can be considered as a type of autogenous healing method that is utilized in a controlled manner to heal concrete. It relies on active chemicals that react with water and deposit unstable ions within the concrete. Specifically, unstable calcium ions are introduced into water and placed within the cracks of the concrete. When these ions encounter anhydrous cement and cement gel, they lose their instability. As a result, sediment forms in the cracks, effectively closing them and preventing further crack propagation.

b. Electrolytic Deposition

Electrochemical or electrolytic deposition is the same as cathodic protection that is also used in Iran to protect oil pipes. This method can be used in piers and water structures. In this method, a negative electrode and a positive electrode are required. The rebar acts as an anode and a rod outside the concrete is used as a cathode. This type of healing can be used for reinforced concrete. A direct current (DC) is used to connect the anode and cathode. Deposition of adsorbed cathodes to the anode in the cracks heals the concrete. It should be noted here that the type of cathode and the solution used to move the material to the anode are important [12].

One of the advantages of this method is its wide applicability, as it has been successfully used to repair various structures. Additionally, this method is considered cost-effective compared to other repair methods. This type of healing requires special conditions; it means that the concrete must be of reinforced type and the possibility of communication between the anode and the cathode be created by a special solution. This method is performed in special environmental conditions.

c. Other Types of Chemical Reactions

Some other types of chemical reactions that cause concrete to heal are:

- Use of sodium silicate,
- Use of calcium hydroxide,
- Adding special materials to prevent rebar rust,
- Adding special factors and substances that increase the volume of hydration after the initial hydration.

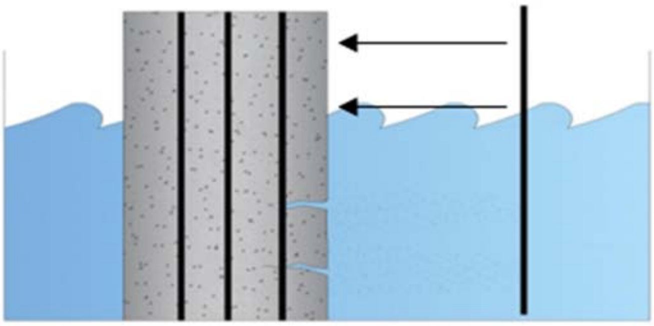

Fig. 5 Concept photo showing particles entering the concrete crack and approaching the anode in aqueous structures

d. Main Factors Involved in Chemical Mechanism

Each of the following factors affects the speed or quality of concrete healing:

A) The amount of moisture available can affect both the quality of healing and the speed of healing, and reports indicate that pilot samples [7] placed in water have effectively healed themselves.

B) The width of the cracks is effective in healing concrete. If the healing process begins in the early traditions of cracking, the cracks are smaller and the healing is done properly, and tests have shown that cracks with a width of 0.3 mm are completely healed, while cracks wider than 0.3 mm wide may not be healed. Also, the width of these cracks is related to the speed of healing, so that cracks with a width of 0.1 mm are completely healed after 200 hours, and cracks between 0.15 and 0.3 mm are reduced after 7 days, and completely healed after 33 days.

C) Hydrations with longer duration can work better in self-healing.

D) Pressure of appropriate loads on the cracks can improve its self-healing ability.

E) The higher rate of water to cement increases the number of non-hydrated cement particles, which in turn can be effective for subsequent hydration during cracking and produce calcium carbonate, which is a key healing factor in concrete.

F) In addition to all of the above, the timing of concrete cracking is important. The initial cracks, after setting the concrete, have more particles than non-hydrated cement, which makes these factors have a high ability in self-healing of the concrete being hydrated.

e. Disadvantages of Chemical Mechanism

❖ Self-healing reactions in the chemical method take a long time,
❖ For better results, ideal conditions for these processes and special curing conditions with water are needed,
❖ The need for active chemicals is felt in some cases.

3. Biological Mechanism

In this method, bacteria and biological agents resistant to alkaline conditions are used in concrete for healing. These bacteria are added to concrete in different ways, which can be done by microencapsulation methods, placement on polyvinyl alcohol fiber, vascular transfer, and placement of bacteria in the porous space of the aggregate or bacterial spray. With regard to the fact that these methods have already been fully explained, only the specific points of this method will be stated here. This method is referred to as Microbiologically Induced Calcite Precipitation (MICP), which involves stimulating microorganisms to induce the precipitation of calcite ($CaCO_3$). Specifically, certain bacteria such as *Sporosarcina pasteurii* and *Bacillus pasteurii*, along with nutrient sources, are introduced into the concrete to facilitate the healing process [13].

Disadvantages of Biological Mechanism

❖ The survival time of bacteria under certain conditions.
❖ Proper nutrition of bacteria is a challenge,
❖ High costs do not make it feasible.

IV. Conclusion

In conclusion, this paper provides an overview of various self-healing mechanisms and categorizes them in a comprehensive manner. Here, the advantages and disadvantages of each method are compared in Table I, offering a concise summary of their characteristics.

TABLE I
COMPARISON BETWEEN TWO GENERAL SELF-HEALING MECHANISMS

Autogenous Healing		Autonomous Healing
1. No need for additives	Advantages	1. Possibility of self-repairing concrete and its cracks
2. Perform healing without extra cost		2. Increase in the life of concrete
		3. Reduction in the maintenance cost of concrete structures
		4. Reduction in the cost of repairing concrete structures
		5. Preventing flakiness and increase in cracking
		6. Preventing rusting of reinforcements inside concrete
		7. Preventing undesirable factors from reaching the rebar
		8. Increase in the stability and durability of the structure and preventing its destruction
		9. Improving mechanical properties in concrete such as increasing compressive and flexural strength
1. Lack of control over the self-healing process	Disadvantages	1. Increasing the cost of concrete production
2. Prolonged healing time		
3. The need for the presence of moisture to perform the healing process		
4. Lack of self-healing elements always and everywhere (accidental healing)		

TABLE II
COMPARISON BETWEEN THREE INDEPENDENT SELF-HEALING MECHANISMS

	Physical	Chemical	Biological
Advantage	1. High speed of healing 2. Crack detection and crack healing even internal type 3. Reproducibility of some methods 4. Variety of mechanism and possibility of application in dry climates if appropriate feasibility study	1. High quality healing 2. Low cost of some operations 3. Performed in specific climates	1. High speed of healing 2. High quality healing 3. Crack detection and crack healing even internal type
Disadvantage	1. High price 2. Less effects 3. Not applicable for large projects	1. Long duration of self-healing reactions 2. Need ideal conditions 3. Need for special curing conditions (water) 4. Requires active chemicals in some cases	1. Limited time for bacteria to survive 2. The need for proper nutrition 3. High costs 4. Strict production conditions of products 5. Lack of uniform self-healing element 6. Not repeating healing in one area

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