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INVESTIGATION OF THE TRIGGER MECHANISM OF SELF-HEALING OF CONCRETE BY MICROGRANULES

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Abstract

Introduction. Concrete, as a traditional building material, was first developed by the British civil engineer John Smeaton in the 18th century. In 1894, the Frenchman Joseph Monier first injected concrete into molds with steel bars, giving birth to reinforced concrete structures. Since then, concrete has been used to protect steel bars and improve the load-bearing capacity and safety of structures. However, concrete has a fatal flaw in its resistance to tension, so the repair of concrete as a branch of concrete materials has received widespread attention from both academic and engineering communities in the past decade. **Methods.** The addition of encapsulated millimeter particle units during the concrete mixing phase has been proven to be an effective implementation of autonomous concrete repair. In the development of self-healing concrete, the encapsulation unit and trigger design are important factors that determine the work performance of self-healing units and the overall repair efficiency of concrete. **Results.** This article describes the passive and active trigger in two directions, further explaining the main triggering mechanism of concrete self-healing and the corresponding repair mechanism, as well as compares and analyzes the technical characteristics and application range of various self-healing triggering mechanisms, providing a reference for future product development.

Keywords: microgranules; self-healing mechanism; trigger mechanism.

Introduction

Concrete is widely used in the construction industry worldwide due to its high bearing capacity, compressive strength, durability, and low production cost. However, the low tensile strength and cracking issues are two inherent defects that are difficult to avoid in concrete materials. The tensile strength of concrete can be effectively enhanced by adding reinforcement, but there is currently no fundamental method to inhibit crack formation. Although crack formation and development are the only signs of damage and failure in concrete structures, the causes of concrete cracking are complex, with common factors including plastic shrinkage, thermal stress, settlement, drying shrinkage, weathering, rebar corrosion, and load application (S and S, 2023). If these cracks are not effectively prevented and repaired, they may cause durability and reliability issues in concrete structures (Sun et al., 2020). Therefore, necessary repair measures are of great significance in extending the service life of concrete structures. Traditional repair methods for concrete cracking, such as filling and sealing, and low-pressure grouting, although have a certain positive effect on extending the service life of concrete, also have many shortcomings. Firstly, the service life of the filling material is usually limited and requires regular inspections and maintenance. Secondly, the timeliness of manual repairs may pose safety hazards for the use of concrete structures. In addition, from an economic perspective, the inspection and maintenance of concrete buildings or structures also consume a large amount of manpower and resources, and the related maintenance costs increase significantly with the extension of service life.

In response to the cracking issues of concrete materials, researchers have explored the use of additives in the cement matrix to delay concrete cracking (Sakir et al., 2020) and started using supplementary cementitious materials such as silica fume, granulated blast furnace slag, fly ash, metakaolin, limestone powder, and rice husk ash to replace part of the cement matrix, thereby reducing early-age cracking in concrete. In recent years, nanomaterials such as carbon nanotubes have also been used to improve the performance of concrete. Carbon nanotubes can bridge micro-cracks in concrete and strengthen the interface transition zone between aggregate and cement paste, to some extent delaying the development of micro-cracks (Lan et al., 2022). However, these modified methods still cannot fundamentally address the issue of reduced durability and safety of concrete structures after cracking. Therefore, endowing concrete with the ability to autonomously detect and heal cracks from a material design perspective undoubtedly has important scientific and social value in enhancing the durability and structural toughness of concrete materials.

In the past twenty years, the innovative concept of self-healing concrete has been the subject of in-

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depth research, with experts and scholars in the relevant field having conducted extensive work on the design of self-healing methods and self-healing units applicable to concrete (Van Tittelboom and De Belie, 2013). In fact, concrete itself has the ability to self-heal cracks, as unhydrated cement particles further hydrate and repair microcracks under the combined action of water and carbon dioxide (Van Tittelboom et al., 2012). However, natural healing is only effective in microcracks of limited scale, and has minimal effect on cracks wider than 200 microns. In order to enhance the self-healing capacity of concrete, researchers have developed autonomous repair techniques based on externally added self-healing units (Wu et al., 2012).

According to whether the self-healing process is based on the chemical reaction of concrete's own binder or on the release of repair substances from externally added self-healing units, researchers generally classify concrete self-healing methods into two categories: autogenous self-healing and autonomous self-healing. The self-healing of concrete cracks mainly depends on one or more of the following mechanisms:

1) the formation of calcium carbonate precipitation from calcium hydroxide in cement;
2) settling of debris and loose cement particles caused by water flow;
3) rehydration of unhydrated cementitious particles;
4) further swelling of hydrated cementitious matrix.

It can be seen that the main triggering conditions for self-healing are the presence of special environments containing water and air. Researchers have also attempted to promote the speed and efficiency of autogenous self-healing through various additives. For example, the use of superabsorbent polymers (SAP) (Lee et al., 2010; Snoeck et al., 2012; Park and Choi, 2018; Wu et al., 2021a) or other internal water-retaining substances (Qian et al., 2010) to provide a water source for unhydrated binders, thereby promoting the further hydration and precipitation of unhydrated products to repair cracks, or by directly adding related minerals to the cement matrix to accelerate secondary hydration and recrystallization (Sisomphon et al., 2013; Marchon et al., 2018; Vehmas et al., 2018; Chandra Sekhara Reddy and Ravitheja, 2019). Compared to autogenous self-healing, autonomous self-healing of concrete cracks mainly relies on adding self-healing units containing repair substances such as biological, organic or inorganic materials to the cement matrix, and based on certain triggering mechanisms, controlled release of repair substances in the self-healing units to achieve active repair of concrete cracks. In order to improve the triggering efficiency and repair efficiency of self-healing units, researchers have designed a series of self-healing units with different triggering mechanisms according to various factors and environmental variables associated with concrete degradation. In addition to using concrete cracking as the triggering mechanism for self-healing units, special ions, pH values, light energy, heat energy, and other environmental factors have also been used as triggering mechanisms to design functional units for concrete self-healing (Mauser et al., 2004; Bédard et al., 2010; Broaders et al., 2011; Kost and Langer, 2001; Kim et al., 2013; Dong et al., 2015). For example, in the marine environment, concrete is susceptible to chloride ion damage, leading to rebar corrosion, so researchers have used chloride ion concentration as a triggering mechanism to guide the repair of concrete degradation problems by self-healing units (Xiong et al., 2015; Liang et al., 2018). Recently, emerging triggering mechanisms such as magnetic fields, electric fields, microwaves, and ultrasonic waves have also been designed and used to control the release of repair functions in self-healing units (Dubinsky et al., 2008; Klibanov et al., 2010; Yim et al., 2012; Wan et al., 2021).

The self-healing ability of concrete is not generated out of thin air, and even the occurrence of self-healing in concrete itself requires environmental factors such as water and carbon dioxide as triggering conditions. When designing repair units suitable for self-healing concrete, the design of the self-healing triggering mechanism will directly affect the actual effect of its repair function and the overall repair efficiency of the concrete, due to the different types of repair agents, the physicochemical environment within the concrete, and the repair targets. Therefore, the selection of the self-healing unit triggering mechanism is a crucial part of the self-healing concrete system. Although there are many different design methods and corresponding triggering mechanism types for existing self-healing units, there is a lack of overall understanding and systematic comparative research on the triggering performance of various self-healing units under different triggering mechanisms and the repair efficiency of concrete, which greatly affects the systematic advancement of self-healing concrete research and hinders the practical application of self-healing concrete in engineering. In response to these issues, this paper systematically summarizes the main types of existing self-healing concrete and the basic principles of the corresponding triggering mechanisms; compares the differences in triggering efficiency and triggering conditions among various triggering mechanisms; and summarizes the repair effects of different triggering mechanisms, repair agent types, and repair conditions on concrete cracks. Based on the comparison, this paper also discusses in detail the evaluation methods for the applicability and efficiency of self-healing triggering mechanisms, with the aim of providing guidance for future research on self-healing concrete and the design of its self-healing mechanism.

Methods

Self-repair triggering methods

The internal deterioration characteristics of concrete (e.g. matrix cracking, pH, ion concentration) as well as external service environment changes (e.g. loading, temperature, light, magnetic field, microwave and ultrasonic waves) are often used by researchers as triggering conditions for self-healing concrete repair units. Depending on whether the triggering of the self-repair behavior of concrete requires human control and intervention, the triggering mechanisms for self-healing concrete can be divided into passive triggering and active triggering. The following is an introduction to these two types of triggering mechanisms, respectively.

Passive triggering mechanisms mainly include crack triggering, environmental triggering, ion triggering, and other triggering methods. The working mechanism is that when negative factors affecting the stability or durability of concrete structures reach the design threshold, the factor will act as a trigger to activate the repair function of self-repair units in the concrete, and the repair agent in the self-repair unit will subsequently repair the concrete.

The working mechanism of crack-triggered self-healing concrete can be summarized as follows: the stress at the crack tip caused by the expansion of micro-cracks damages the repair agent carrier and provides a release channel for the repair material. Since the release of the repair agent occurs almost simultaneously with the crack propagation, the repair behavior under the crack triggering mechanism responds very quickly to deteriorating factors, and the curing action of the repair agent can quickly stop the further expansion of the crack. Although the principle of the crack trigger mechanism is simple, the triggering efficiency of this mechanism is influenced by many factors, including: crack width; bond strength between the repair unit and the concrete matrix; material properties of the repair unit, etc.

Previous studies have shown that crack width greatly affects the repair results (Van Tittelboom et al., 2016). A crack width exceeding the repair threshold value will significantly weaken the repair effect, while a width which is too narrow may fail to trigger the self-repair behavior (Sinha et al., 2022). In addition, the properties of the repair agent carrier (self-repair unit) are closely related to the triggering efficiency of crack triggering. The morphology and surface physical characteristics (roughness) and chemical characteristics (chemical functional groups) of the repair unit are important factors affecting the bond strength between the encapsulant and the concrete matrix (Apolinário de Oliveira et al., 2021). Fig. 1 shows the triggering situation of two different-shaped self-repair units in the concrete matrix. To increase the surface roughness of the encapsulant, Araújo et al. (2018) prepared five different surface roughness capsules through polishing, the addition of a sand layer, and other methods. Compared with the untreated group, the capsules after surface treatment had a higher triggering rate when passing through cracks. Feng et al. (2020) successfully ruptured microcapsules containing repairing agent powder as the cracks passed by, by encapsulating the capsules with quartz sand particles to increase their surface roughness.

Shape memory alloys (SMAs) are metallic materials that can “remember” their original shape. The shape memory effect and superelasticity are the two main properties of SMAs, and they are also the theoretical basis for the application of SMAs in self-healing concrete structures (Wool, 2008). The working mechanism of SMA in self-healing concrete can be summarized as follows: SMA, with pre-stress applied, generates compressive stress on the crack surface when triggered by external stress on the concrete, forcing the crack to close and inhibiting its propagation, restoring the deflection and deformation of the concrete structure components. There are two common methods for applying SMAs to self-healing concrete. One method is to externally reinforce SMA materials onto concrete components, and the other is to incorporate SMA materials as self-healing units into concrete structures, as shown in Fig. 2.

In existing research, the feasibility of using SMAs for self-healing concrete has been thoroughly demonstrated. Sakai et al. (2003) tested SMAs to reinforce concrete beams and found that small

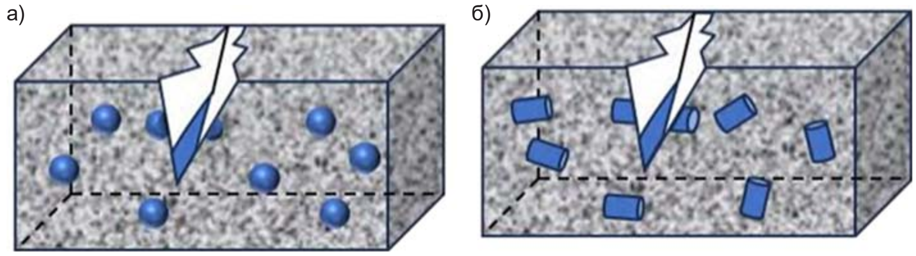

Fig. 1. Cracking induced autonomous self-healing in (a) concrete spherical capsules; (b) cylindrical capsules. (Apolinário de Oliveira et al., 2021)

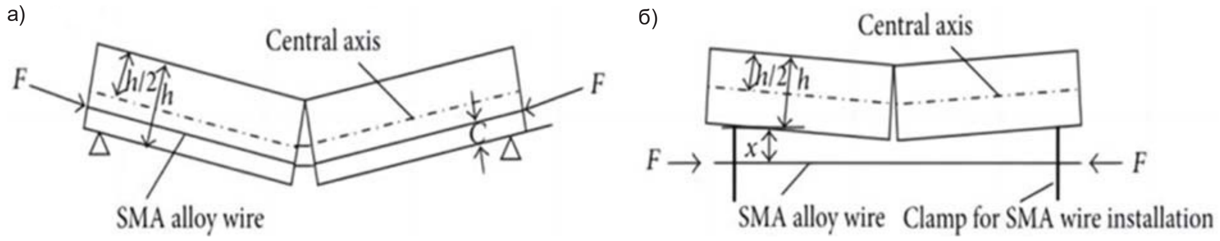

Fig. 2. Application methods of two SMA alloys in self-healing concrete (a) interpolation method and (b) external connection method

cracks almost completely closed after unloading. Sun et al. (2013) embedded SMAs into concrete beams and effectively repaired cracks with widths of up to 0.4 mm. However, due to the uneven distribution of SMAs, not all cracks can be effectively repaired by SMAs alone, leading to uneven repair areas. To address this, researchers have combined SMAs with other self-healing materials to design a new composite material consisting of Engineered Cementitious Composite (ECC) and SMA fibers to address this issue. Experimental results showed that, compared to concrete specimens, SMA-ECC specimens not only had significantly improved strength and ductility, but also effectively reduced the number and width of cracks, demonstrating promising crack repair capabilities. Bonilla et al. (2018) evaluated the self-healing effect of concrete beams reinforced with calcium nitrate microcapsules and SMAs. The experimental results showed that the addition of microcapsules significantly enhanced the self-healing capacity in the presence of SMAs. The ionic trigger method is mainly used in capsule-type self-healing units, often using ions harmful to concrete structures as the trigger for the self-healing unit. By setting up an ion-sensitive trigger unit inside the encapsulated repair agent shell (capsule), it can react with the corresponding harmful ions after they enter the concrete, creating a channel for the internal repair agent to be released from the encapsulated shell, achieving the active repair of concrete degradation.

It is generally believed that the corrosion of steel reinforcement is the main cause of durability problems in reinforced concrete structures, and chloride ions are one of the factors causing premature corrosion of steel reinforcement. Chloride ions (Cl^-) can reach the transition zone between steel and concrete through micro / nano channels in the concrete matrix. When the Cl^- concentration exceeds a threshold, the protective passivation layer on the steel surface will be destroyed, leading to corrosion. Since chloride ion erosion of concrete has already occurred before cracks appear and may cause a certain degree of damage to the structural durability, using crack triggering alone as the trigger mechanism for self-healing has a certain lag. The advantage of the ion trigger mechanism is that the trigger unit can respond to concrete degradation issues before cracks develop, avoiding damage to the structural stability during the cracking period of concrete components.

Researchers have been exploring the use of Cl as a trigger for self-healing mechanism design and its application in the self-healing of concrete in marine environments. Liang et al. (2018) synthesized microcapsules with an ion-responsive shell consisting of multiple ionic liquids (Cpil). Fig. 3 shows the mechanism of action of this ion-triggered microcapsule. In water containing Cl, the PF_6 functional group in the capsule shell can exchange with Cl, transforming the hydrophobic polymeric ionic liquid (PIL) on the outer shell of the microcapsule into a hydrophilic channel. At this time, the $Ca(OH)_2$ healing agent encapsulated in the capsule can be released through the hydrophilic channel, chemically binding with Cl to effectively reduce chloride ion erosion. Another research approach is to use response materials containing metal ions (such as Ag^+, Pb^{2+}) on the self-healing unit, which can react with Cl upon encountering it to produce precipitation, providing a pathway for the overflow of the repair agent inside the capsule. Xiong

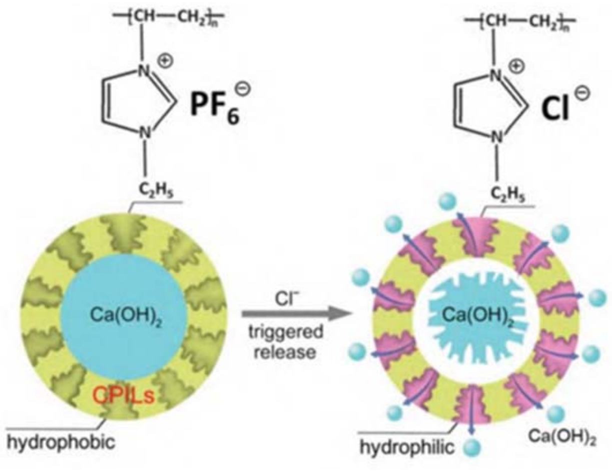

Fig. 3. Schematic diagram of $Ca(OH)_2$ release from Cl^- induced microcapsules (Liang et al., 2018)

et al. (2015) developed a novel capsule-based self-repair system that intelligently responds to chloride ions. The system uses silver alginate hydrogel as the matrix material for the capsule, epoxy resin as the repair agent, and the concentration of chloride ions as the trigger for self-repair. When the silver alginate hydrogel comes into contact with dissolved chloride ions, the silver ions can quickly react with the chloride ions to form silver chloride precipitation, leading to the rupture of the capsule and the release of the repair agent inside.

During the service life of concrete, the internal temperature, humidity, and pH value will continue to change with age, and these changes are closely related to issues such as concrete cracking, rebar corrosion, and strength degradation. Therefore, researchers have attempted to use these environmental factors as triggering conditions for self-healing, in the design of self-healing triggering mechanisms.

The pH trigger uses changes in the concrete's internal pH as the triggering condition for self-healing (Matsuda et al., 2019). The pH trigger is mainly applied in encapsulated self-healing materials, where the encapsulation shell contains a large amount of weak alkali or weak polyacid. When cracking or aging issues cause a change in the pH inside the cement, the weak alkali or weak polyacid undergo protonation or deprotonation under the influence of pH. This process causes the charged groups to repel each other, leading to the expansion and rupture of the encapsulation shell. Commonly used pH-sensitive polymers include polyacrylic acid (PAA), polyvinyl alcohol (PVA), polymethacrylic acid (PMAA), poly-N-vinylpyrrolidone (PVP), polyallylamine hydrochloride (PAH), polycaprolactone (PCL), and polyethylene glycol (PEG) (Snoeck and N, 2016). Matsuda et al. (2016) synthesized pH-triggered microcapsules with ester chains as the shell, which have the ability to hydrolyze under alkaline and acidic conditions and form an oxide layer on steel substrates. He et al. (2015) prepared ethyl cellulose (EC) / calcium hydroxide microcapsules. The EC shell of the microcapsule is pH-sensitive and can be triggered by the changing pH value inside the concrete and release calcium hydroxide to adjust the environmental pH. Dong et al. (2015) prepared a microcapsule system with polystyrene resin (PS) / sodium monofluorophosphate (Na_2PO_3F, MFP), and found that the triggering efficiency increases as the environmental pH decreases, as shown in Fig. 4, which displays microcapsules under different pH conditions. Kim et al. (2020) synthesized pH-sensitive microcapsules containing $NaNO_2$ corrosion inhibitor using the water-in-oil-in-water (W/O/W) double-emulsion method. They placed the synthesized pH-sensitive capsules in deionized water (pH 6.8), carbonate / bicarbonate buffer solution (CBS, pH 9.1), and simulated concrete pore solution (SCPS, pH 12.6) and observed the release process. The results show that the higher the pH, the faster the release rate of the self-healing capsules.

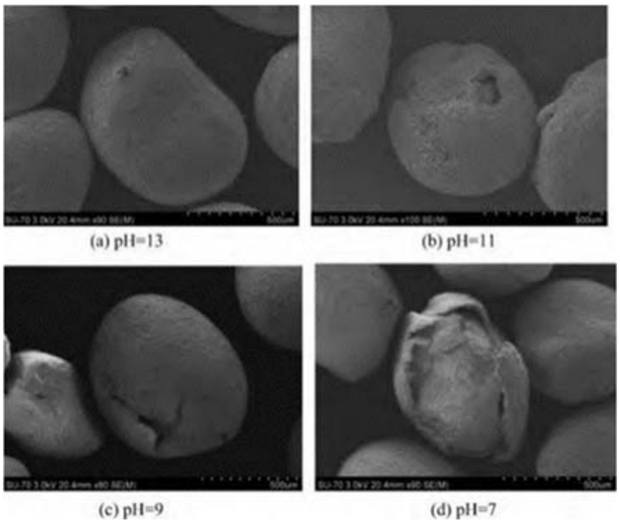
(a) pH=13
(b) pH=11
(c) pH=9
(d) pH=7

Fig. 4. Scanning electron microscope image of microcapsules after soaking in different pH solutions for the same time (Dong et al., 2015)

Ultrasonic waves have the characteristics of directional accuracy, strong penetration, and concentrated energy, and are widely used as a non-destructive testing method in the fields of medicine, biology, and engineering. Previously, Klibanov et al. (2010) used the unique cavitation and acoustic streaming effects of ultrasonic waves to trigger and target the delivery of drug-carrying microbubbles, laying a scientific and technological foundation for using ultrasonic waves as the triggering mechanism for self-healing concrete. The mature application of ultrasonic transducers in non-destructive testing of concrete structures also proving the harmlessness of ultrasonic waves to concrete structures (Yim et al., 2012). As a non-destructive triggering method, ultrasonic triggering can achieve the goal of targeted self-healing of concrete by stimulating the self-healing units before significant deterioration of the concrete occurs.

The mechanism of ultrasonic triggering is as follows (Nodehi et al., 2022): Under the mechanical vibration caused by the propagation and reflection of ultrasonic waves, the gas enclosed in the capsules of the repair agent or the environmental medium (i.e., the pore solution of the cementitious material) constantly escapes outward and generates microbubbles. Under the action of mechanical vibration, these microbubbles undergo a series of dynamic processes such as movement, expansion, and rupture. The instantaneous high pressure of up to about 100 MPa generated after the rupture of the bubbles will cause damage to the microcapsule wall, thereby releasing the repair agent (Fig. 5). Compared to traditional

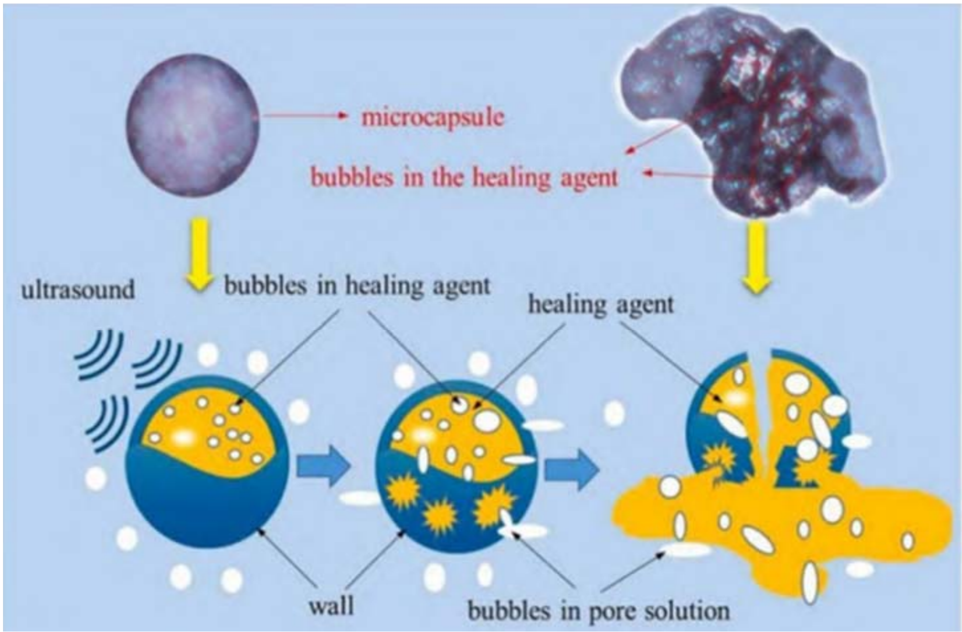

Fig. 5. Mechanism of ultrasound-induced rupture of microcapsules (Xu et al., 2018)

mechanical triggering methods, ultrasonic triggering not only has higher triggering efficiency but is also controllable, reducing the impact of defects such as cracks on concrete to a minimum. Xu et al. (2018) demonstrated through experiments that ultrasonic waves can effectively improve the triggering and release efficiency of UF / E microcapsules in cement mortars. In contrast, the efficiency of traditional crack triggering is generally lower, with only a small percentage of microcapsules rupturing.

Among the available self-healing triggering mechanisms, magnetic field triggering offers the possibility of precise control and on-demand release, and therefore has particular advantages. During the triggering process, the magnetic particles in the healing unit will shake, flip or gather under the low-frequency magnetic field, thereby disrupting the surrounding material structure and releasing the healing components in the healing unit. In addition, the heat generated by the magnetic and metallic materials under the action of high-frequency magnetic fields, through magnetic and inductive heating effects, can also cause the self-healing units to rupture and trigger the healing behavior. The electromagnetic controlled release microcapsules designed by Li et al. (2020) were prepared by melt-polycondensation method, and under the electromagnetic field, the mortar containing microcapsules could recover to 91.4 % of its initial compressive strength, nearly twice as high as under room temperature conditions. The main mechanism is that under the electromagnetic field environment, nano-Fe_3O_4 induces temperature rise, causing the paraffin to melt, leading to the release of the encapsulated healing agent toluene diisocyanate (TDI).

It is worth noting that water in concrete will evaporate and diffuse at temperatures exceeding 100 °C, and at temperatures exceeding 180 °C, concrete will undergo micro-scale dehydration and collapse (Hager, 2013). Prolonged action of the magnetic field trigger will cause the overall temperature of the concrete structure to rise, affecting the durability of the concrete specimens over the long term. In order to better utilize the magnetic triggering mechanism without compromising the overall stability of the concrete structure, Loiseau et al. (2016) proposed a magnetic triggering encapsulation system (Explosive Raspberries). This system consists of an induction heating core and temperature-sensitive bursting microcapsules, which can release their contents in a matter of seconds without causing global heating of the main structure. Fig. 6 shows the complete triggering process of this system. One of the main advantages of the Explosive Raspberries concept, compared to traditional thermal triggering encapsulation systems, is the spatial control of the heat generation process. When a high-frequency alternating magnetic field is applied, heat is generated only in the vicinity of the cast steel particles. Induction heat is not applied to the entire matrix, but directly to the microcapsules in close contact with the heat source, thus having the potential to be applied as a magnetic field-triggered self-healing unit in concrete.

Microwave radiation heating is the result of the interaction between polar molecules in the material and the microwave electromagnetic field. It is widely used due to its non-contact, selectivity, and cleanliness. Gorin et al. (2006) previously confirmed that nanosilver particles can be used to improve

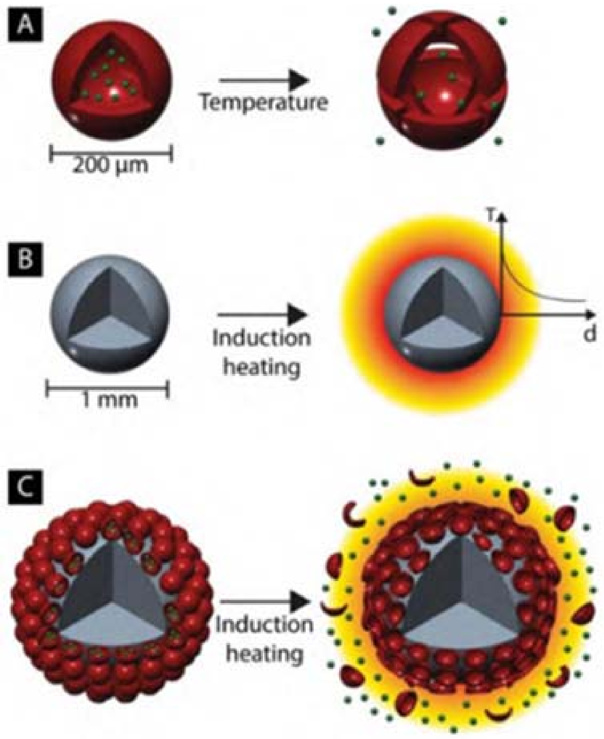

Fig. 6. Working principle of magnetic trigger blasting system (Loiseau et al., 2016)

the efficiency of microwave radiation damage. Nowadays, various microwave sensitizers, such as Au, Ag, and Fe_2O_3NPs, as well as MoS_2 nanosheets and nanodiamonds, have been used for remote microwave-induced drug release. The working mechanism is that microwave-sensitive particles embedded in the capsule shell will cause local heating damage to the outer shell under microwave radiation. Table 1 summarizes the advantages and disadvantages of the various triggering methods mentioned above.

Trigger efficiency evaluation method

The self-healing trigger efficiency is one of the important factors determining the self-healing performance of concrete. Below is the summary and introduction of existing evaluation methods for self-healing trigger efficiency.

The methods for evaluating the trigger efficiency of self-healing in experiments can be divided into two categories: direct observation and indirect evaluation. The direct observation method uses optical microscopy, scanning electron microscopy (SEM), environmental scanning electron microscopy (ESEM), and other micro-imaging technologies to evaluate the triggering of self-healing units by observing the profile or fracture of the sample,

Table 1. **Self-repair trigger mechanism**

Trigger Mechanism	Trigger Methods	Advantages	Disadvantages	Reference
Passive Trigger	Crack Triggering	The triggering method is simple and direct, able to react quickly to cracks and promptly repair them. It has relatively low application requirements for concrete environments and can function in complex conditions.	The triggering efficiency is low, and it cannot prevent the generation of cracks, only take remedial measures for existing cracks.	(Van Tittelboom et al., 2016; Araújo et al., 2018; Feng et al., 2020; Apolinário de Oliveira et al., 2021; Sinha et al., 2022)
	Stress Triggering	It responds positively to the destructive load and can improve the concrete's resistance to tensile damage.	The repair behavior is not repeatable, and the repair effect is limited.	(Sakai et al., 2003; Wool, 2008; Sun et al., 2013; Bonilla et al., 2018)
	Ion Triggering	Ions can diffuse through micro-nano voids in the concrete matrix and trigger self-healing function without needing to go through concrete cracks, making the triggering method more intelligent.	Special ions are usually only present in specific environments, so their use as a triggering mechanism is limited.	(Xiong et al., 2015; Liang et al. 2018)
	pH Triggering	It can self-adjust trigger based on the internal environment of the concrete, able to actively repair extremely small micro-cracks in concrete.	pH triggering is based on changes in the pH value of the concrete matrix, with a single triggering condition, and is easily influenced by additives.	(He et al., 2015; Matsuda et al., 2016; Snoeck and N, 2016; Matsuda et al., 2019; Kim et al., 2020)
Active Trigger	Ultrasound Triggering	Accurate direction, strong penetration, concentrated energy	May increase the porosity of the structure, with adverse effects on durability.	(Klibanov et al., 2010; Yim et al., 2012; Xu et al., 2018; Nodehi et al., 2022)
	Magnetic Field Triggering	Efficient, and triggering does not adversely affect the concrete substrate	Triggering equipment is complex and expensive.	(Hager, 2013; Loiseau et al., 2016; Li et al., 2020)
	Microwave Triggering	High triggering efficiency, low cost, can be manuall y controlled and environmentally friendly	May cause overheating of repair units or the substrate, with adverse effects on structural stability.	(Gorin et al., 2006)

which is the most direct experimental observation method. Hu et al. (2018) judged the trigger efficiency by directly observing the rupture of macrocapsules after pre-compression of the test block. For microcapsules at the micron or even nanometer level, their rupture cannot be directly observed by the naked eye, so the morphology of the microcapsules within the crack surface can be analyzed by observing them under a microscope to determine the triggering situation. Xu et al. (2021) proposed to judge the triggering situation based on changes in microcapsule morphology. The specific method is to observe the SEM image of the area where the microcapsules are located in the cement paste, as shown in Fig. 7. If the core material of the microcapsule is completely released but the shell is still embedded in the cement paste, it indicates complete triggering and good bonding between the microcapsule shell and the cementitious material. Lv et al. (2020) used ESEM to study the crack surface of the microcapsules embedded in the cement paste, observed the fracture of the microcapsules in the cement paste specimen, and judged their trigger efficiency based on the morphological appearance of the encapsulant.

New imaging technologies have been widely used in the detection of trigger efficiency of self-healing materials, and the visualization of the release process of the repair agent using imaging technology has also been proven feasible. The main techniques involved include X-ray computed tomography imaging technology, neutron computed tomography imaging technology, and digital image correlation technology. Mihashi et al. (2000) used X-ray imaging technology to characterize the self-healing ability of intelligent concrete containing urea-formaldehyde resin microcapsules (UFF) developed by them.

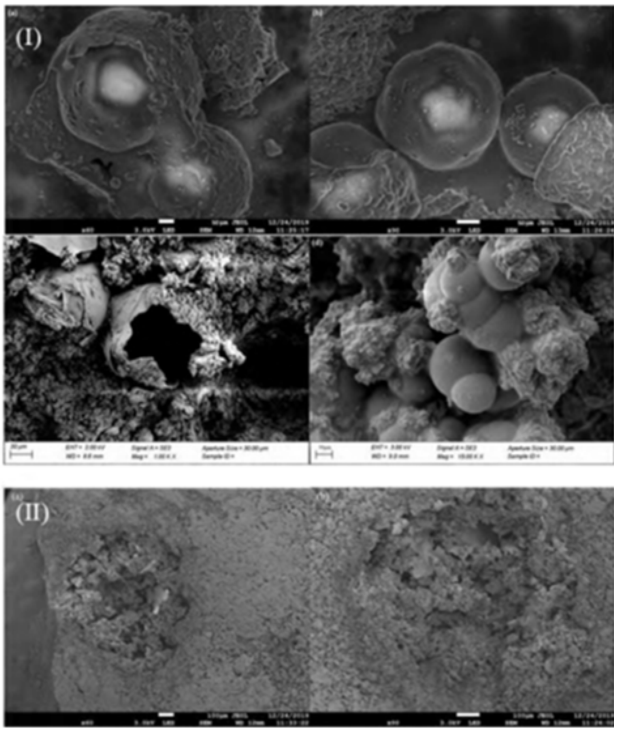

Fig. 7. SEM images of microcapsules after crack triggering. and ultrasonic triggering (II) in a cement specimen (Xu et al., 2021)

Direct observation method has certain limitations. When the volume of repair units is small and the quantity is large (Dong et al., 2016), it is difficult to accurately characterize the triggering of repair units through direct observation. The degree of crack healing, mechanical property restoration rate, durability characteristics, and other performance recovery of self-healing concrete are closely related to the triggering efficiency of the repair units. Therefore, for micro-nano-level self-healing triggering units, their triggering efficiency can be indirectly characterized by the degree of concrete performance recovery after their triggering.

Due to the large number and small volume of self-healing units in self-healing concrete, it is often difficult to statistically record the triggering of all self-healing units using experimental observation and counting methods. Compared to experimental verification, using numerical simulation to evaluate and analyze the triggering of self-healing is often more comprehensive and accurate (Jefferson et al., 2018). Research on the triggering efficiency of self-healing using computer simulation analysis mainly falls into two categories: direct and indirect methods. The direct method involves modeling to directly study the response probability of the repair agent encapsulant under the triggering mechanism. The indirect method characterizes the triggering efficiency by simulating the recovery of concrete performance after repair.

Selection of Triggering Mechanisms

Given the complex application environment of concrete and the different performance recovery requirements after deterioration, selecting suitable and efficient self-healing triggering mechanisms for self-healing concrete is particularly important. Due to the lack of systematic summary and evaluation of existing self-healing triggering mechanisms in current research, this paper has identified three criteria for selecting self-healing triggering mechanisms: triggering efficiency, repair objectives, and constraints. Based on these criteria, Table 2 compares the triggering rates of triggering units under different triggering mechanisms and clarifies the applicability and limitations of each triggering mechanism, providing a reference for relevant researchers.

The effectiveness of self-healing in concrete largely depends on the triggering of self-healing units. The response of triggering units to triggering conditions, or triggering efficiency, is the basis for evaluating the triggering situation.

Table 2. **Comparison of different triggering mechanisms in terms of triggering efficiency, repair targets, and limitations**

Trigger Unit	Triggering Method	Triggering Rate	Performance Recovery			Applicable Environment	Reference
			Mechanical	Durability	Corrosion Resistance		
Gelatin Capsule	Crack-triggered	95 % success rate in capsule rupture	√	√	—	Lighting environment	(Lv et al., 2020)
Poly(methyl methacrylate) (PMMA) based macrocapsules		100 % rupture when a 0.3 mm thick wall intersects a crack with an average width > 69 μm	√	√	—	—	(Araújo et al., 2018)
Polyacrylamide (PAM) hydrogel capsules		Triggering rate up to 90 % in simulated pore solution	√	√	—	Humid environment (RH > 95 %)	(Gao et al., 2022)
Polyethylene glycol (PEG) based macrocapsules		—	√	√	—	Water environment	(Yuan et al., 2017)
Polyethylene (PE) based macrocapsules containing TiO_2		100 % rupture when the crack width is > 20 mm	—	√	—	Lighting environment Water environment	(Wu et al., 2021b)
Ethylene-vinyl acetate (EVA) polymer		—	√	—	—	Water environment	(Xu et al., 2020)
Ethyl cellulose (EC) based microcapsules	pH-triggered	—	—	—	√	Water environment	(Thimmareddy and Theja, 2018)
Polyvinyl alcohol (PVA) based microcapsules		Over 80 % successful capsule release	—	—	√	Water environment	(Li et al., 2021)
Crosslinked poly(ionic liquid) based microcapsules	Ionic-triggered	—	—	—	√	Ocean environment	(Liang et al., 2018)
Nano Fe_2O_3 and paraffin-based microcapsules	Electromagnetic-triggered	100 % release rate of microcapsules in an electromagnetic field environment with an output voltage of 600 V and a frequency of 124 kHz	—	√	√	Electricity environment	(Li et al., 2020)
Microcapsules composed of graphite, paraffin, and polyethylene wax (PEW)	Microwave-triggered	—	√	√	√	Electricity environment	(Vijay et al., 2017)

When triggering units are randomly and uniformly distributed in the specimen, the triggering mechanism under a pH trigger has a higher triggering efficiency compared to a single crack triggering mode. Ress et al. (2020) synthesized pH-triggered microcapsules using resin as the encapsulation material through the water-in-oil-in-water (W/O/W) double emulsion method, and fitted their release kinetics to a power-law model, with results showing a release efficiency of over 80 %. Furthermore, for the self-healing mechanism triggered by cracks, improving the interface bonding strength between the capsule surface and the concrete matrix can also enhance the triggering efficiency of self-healing units. Lv et al. (2020) used an alkyl coupling agent [3-(2-aminoethylamino) propyltrimethoxysilane (KH792)] to increase the crack triggering rate of phenol-formaldehyde (PPF) microcapsules. SEM observation of the fractured surface of the test block revealed a significantly higher triggering rate for the surface-modified microcapsules compared to the untreated control group, reaching up to 63 %, while the triggering rate of the unmodified microcapsules was only 22 %.

Some new triggering mechanisms have surpassed traditional mechanical triggers in triggering efficiency and overall performance recovery. Ultrasonic triggering is an efficient, controllable, and environmentally friendly self-healing triggering mechanism, and extensive research has confirmed its feasibility for application in microcapsule self-healing concrete. Xu et al. (2021) found that specimens triggered by ultrasonic waves achieved a strength recovery rate 2–4 times higher than mechanically triggered samples. Morphological observations further indicated that ultrasonic waves have a better triggering effect on microcapsules. Similarly, electromagnetic triggering also has high efficiency and precision, as Li et al. (2020) achieved a triggering efficiency of 100 % by placing microcapsules constructed with nano-Fe_3O_4 and paraffin in an environment with an output voltage of 600V and a field frequency of 124 kHz. It can be seen that the triggering efficiency, application scenarios, and material preparation costs of different triggering mechanisms vary, and therefore the appropriate triggering mechanism should be chosen based on specific requirements.

Due to the different service environments of concrete structures, the potential degradation issues and repair targets may vary. Therefore, it is crucial to understand the performance restoration of concrete after repair under different triggering mechanisms when designing and applying self-healing mechanisms for concrete. Crack-triggered self-healing concrete mainly addresses cracking and the durability of structures after cracking. Alghamri et al. (2016) immersed healing agents into lightweight aggregates (LWA) under negative pressure, and encapsulated them with polyvinyl alcohol (PVA) to obtain self-healing coarse aggregates. Cracked specimens containing self-healing coarse aggregates showed a maximum crack repair width of 0.135 mm after 28 days of water curing, and the average sorptivity index of the repaired specimen was very close to that of the uncracked specimen. Rais and Khan (2021) studied the use of recycled aggregates (RAC) as the carrier for self-healing bacteria, inducing $CaCO_3$ precipitation as a strategy for crack self-repair. After 56 days of curing, the maximum crack repair width in the self-healing concrete with cracked bacterial colonies reached 0.63mm, and the change in the permeability coefficient (Rk) ranged from 143 % to 181 %.

pH-triggered and ion-triggered self-healing mechanisms mainly target concrete degradation caused by steel reinforcement corrosion. Liang et al. (2018) studied the anti-corrosion effect of chloride ion-triggered self-healing microcapsules on steel reinforcement in concrete in a marine environment. It was found that the addition of microcapsules effectively slowed down the rate of steel reinforcement corrosion after measuring the mass loss rate of different groups of steel reinforcement. Ress et al. (2020), in order to verify the protective effect of pH-triggered resin microcapsules against steel reinforcement corrosion, set up a three-electrode system to test the changes in the corrosion potential and corrosion current of different groups using a potentiostat. The results showed that in the experimental group containing microcapsules, the degree of steel reinforcement corrosion was much lower than in the control group.

The restoration of mechanical strength is also one of the main parameters to consider when selecting a concrete self-repair mechanism. Wan et al. (2021) compared the strength recovery rates of specimens containing microwave-triggered microcapsules and blank control specimens. Due to the combined effect of the repairing agent released by the microcapsules and the heat generated by microwave activation, the strength recovery rate of the specimens containing microcapsules was significantly higher than that of the control specimens after the same microwave time. Li et al. (2020) designed electromagnetic-triggered self-healing microcapsules incorporated into mortar, effectively improving the compressive strength recovery rate of pre-damaged specimens.

For encapsulated self-healing concrete, the triggering method and the type of healing agent jointly determine its applicable range. Bédard and Liang (Bédard et al., 2010, Liang et al., 2018) developed a chlorine ion-triggered self-healing microcapsule, which is only suitable for concrete structures in coastal or marine environments due to the need for chlorine ions to trigger the process, and may not function in environments without chlorine ions. Wu et al. (2021b) developed a CaO-$NaAlO_2$ healing agent that requires an environment rich in chloride ions and sulfate ions to effectively carry out the repair work. Zhou et al. (2022) designed a photocatalytic self-healing material by adding photocatalyst TiO_2 to the capsule shell. However, its application environment not only requires sufficient light but also ample water as a medium for the internal healing agent to react.

Water-oxygen-triggered self-healing concrete is usually only applicable in areas with abundant rainfall or in structures such as dams and underground water pipelines. Roig-Flores et al. (2015) studied the self-healing of concrete with crystalline admixtures in different environments and found that cracks can only be repaired when they are in direct contact with water, with a repair rate of 0 % in laboratory conditions or under humidity. Chandra Sekhara

(Thimmareddy and Theja, 2018) found that the higher the water content in the environment, the better the mechanical performance recovery of concrete containing crystalline admixtures (CA). When submerged in water, the strength recovery of CA concrete reached a maximum value of 95 %.

In order to meet the metabolic needs of bacteria, the healing process of bacteria-based self-healing concrete must involve water and air. Zhang et al. (2021) found that to harness the repairing ability of bacteria-based self-healing concrete, cracked samples need to be cured in water for 28 days. Other scientists (Rais and Khan, 2021; Xu et al., 2021) developed a microbiological self-healing mechanism based on artificial aggregates and ceramic particles, which also requires water curing to achieve crack repair. Feng et al. (2020) kept cracked samples in a standard curing room and continuously sprayed calcium lactate-containing tap water onto the cracked area during the curing stage to provide an appropriate ionic environment for crack repair. Compared to passive triggering methods, active triggering mechanisms are less restricted by the environment, but they present issues such as complex operation, expensive equipment, and higher preparation costs during application. Furthermore, some active triggering methods may have adverse effects on concrete structures. Xu et al. (2021) found that prolonged use of ultrasonic waves or high-frequency ultrasonic waves may increase the porosity of concrete structures, thereby reducing their durability and service life (Table 2).

Conclusion

In the past twenty years, the concrete self-healing technology has seen rapid development, as well as the design and development of self-healing mechanisms. In order to further promote the research and development of self-healing technology and its widespread application in civil engineering, this article provides a detailed summary of the relevant triggering mechanisms for concrete self-healing and systematically reviews existing methods for evaluating self-healing triggering efficiency. Subsequently, based on triggering rate, repair targets, and limiting conditions, the article summarizes the important factors that influence the selection of self-healing mechanisms in order to provide a more rational basis for researchers in related fields to design and practice self-healing concrete.

The selection of self-healing mechanisms should take into account the service life, scope of application, repair targets, preparation costs, and the impact on the concrete’s inherent properties. Ideally, the chosen self-healing mechanism should ensure that it has no significant impact on the working and mechanical performance of concrete, which is a necessary condition for the engineering application of self-healing technology. Furthermore, the durability and resistance of the self-healing mechanism within the concrete are also important factors in determining the potential practical application of this technology in engineering, as the self-healing units will be sealed within the concrete for an extended period. Lastly, the simplification of the preparation process and control of preparation costs are also important directions for future research of this technology, while ensuring the triggering efficiency and repair effectiveness of the self-healing mechanism.

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ИССЛЕДОВАНИЕ МЕХАНИЗМА ЗАПУСКА САМОВОССТАНОВЛЕНИЯ БЕТОНА МИКРОГРАНУЛАМИ

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Аннотация

Введение. Бетон как традиционный строительный материал был впервые разработан британским инженером-строителем Джоном Смитоном в XVIII веке. В 1894 году француз Жозеф Монье впервые ввел бетон в формы со стальными стержнями, положив начало железобетонным конструкциям. С тех пор бетон используется для защиты стальных стержней и повышения несущей способности и безопасности конструкций. Однако бетон имеет фатальный недостаток в своей устойчивости к растяжению, поэтому ремонт бетона как отрасль бетонных материалов в последнее десятилетие получил широкое внимание как со стороны академического, так и инженерного сообщества. **Методы.** Добавление инкапсулированных миллиметровых частиц на этапе перемешивания бетонной смеси доказало свою эффективность в реализации автономного восстановления бетона. При разработке самовосстанавливающегося бетона конструкция инкапсулированных частиц и механизма запуска является важным фактором, определяющим работоспособность самовосстанавливающихся элементов и общую эффективность восстановления бетона. **Результаты.** В данной статье описываются пассивные и активные механизмы запуска в двух направлениях, подробно объясняется основной механизм запуска самовосстановления бетона и соответствующий механизм восстановления, а также проводится сравнение и анализ технических характеристик и области применения различных механизмов запуска самовосстановления, что служит ориентиром для будущей разработки продукции.

Ключевые слова: микрогранулы; механизм самовосстановления; механизм запуска.