Exploring the current state of application of self-healing concrete

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Abstract. As the durability requirements of the construction industry increase, the vulnerability of traditional concrete structures to environmental erosion and the difficulty of repairing cracks due to external forces are becoming more and more obvious. To prolong the life of concrete structures, reduce maintenance costs and improve safety, the investigation of the performance of new material self-repairing concrete has arisen. This paper adopts the classification method of intrinsic self-repair and extrinsic self-repair to compare and analyze the five common types of self-repairing concrete at this stage. The analysis shows that different types of self-repairing concrete have their different advantages and applicable conditions, but there are also certain limitations. For example, osmotic crystallization self-repairing concrete is suitable for concrete structures in wet or moisture-containing environments. Microbial self-repairing concrete is more suitable for environments with suitable temperature and humidity to ensure the activity of repairing microorganisms and repairing effect. This paper can provide a theoretical basis for the future application of self-repairing concrete and promote the sustainable development of the construction industry.

Keywords: Osmotic crystallization self-repair; Microbial self-repair; Electrodeposition self-repair; Capsule-based self-repair; Shape memory alloy self-repair.

1. Introduction

Concrete, one of the most used as well as widely used structural materials in construction, plays a vital role in a range of building projects due to its affordability, excellent compressive and durability properties, and abundance of resources. However, its physical and structural properties also bring some disadvantages. For example, its weak resistance to tensile forces and low modulus of elasticity make concrete susceptible to cracking during construction and use. Especially when used under the influence of external loads and exposure to the environment, the frequency of cracks increases. This seriously affects the safety and durability of concrete materials, while reducing the permeability of the structure and frost resistance, resulting in premature destruction of buildings and structures, causing great harm. Therefore, in order to avoid further deterioration of concrete, repairing cracks becomes an efficient measure.

Traditional crack treatment methods include filling, transposition, etc., however, these traditional methods can substantially increase the cost, consume labor, and have poor repair results. The relevant report listed the development and application of self-healing concrete materials as an encouraging project [1]. In this context, self-healing concrete materials have gradually become the focus of research due to their ability to heal cracks automatically.

Self-repairing concrete is a new type of intelligent material with the ability of self-detection, self-perception, and self-healing, it can mimic the self-healing characteristics of living organisms and automatically repair concrete cracks, thus extending the service life of concrete structures and reducing maintenance costs. Research by Feng Rongand others has shown the mainstream ways of concrete self-repair, there are self-repair systems based on cementitious materials, microbial self-repair system, and microencapsulated self-repair system [2] . These innovative repair technologies have great advantages and have far-reaching research value and significance for solving concrete crack problems in engineering. According to the research of Chen Jing, a variety of concrete crack self-repairing technologies and their progress are reviewed from the perspective of classification according to the repair principle, emphasizing the importance of self-repairing technologies in promoting the green development of the concrete industry [3].

In this paper, based on the summary of concrete self-repair research and results in China and abroad in recent years [4], a new perspective is proposed to divide the common types of self-repairing concrete into intrinsic self-repairing as well as extrinsic stimulation of two different types of self-repairing to summarize and analyze the advantages and disadvantages so as to put forward proposals to promote the practical application of this technology to achieve the sustainable development of construction materials. Intrinsic self-healing is a method that relies on the chemical reaction or physical action within the concrete to realize the repair of cracks. Extrinsic self-healing is a method that requires external stimuli such as electric field, temperature change or mechanical rupture to trigger the repair process.

2. Intrinsic self-healing

The following section describes the two main methods of osmotic crystallization self-repair as well as microbial self-repair.

2.1. Osmotic crystallization self-repair

Osmotic crystallization self-repair is a process in which, in concrete, ion exchange, diffusion penetration, and chemical reaction occur to form hydrated calcium silicate, which closes pores and repairs cracks. The chemical reaction mechanism of osmotic crystallization self-repairing concrete can be expressed by the chemical formula Ca (OH) 2+SiO2+H2O→CaSiO3·nH2O.

When concrete cracks, moisture penetrates into the cracks and calcium ions (Ca^{2+}) produced by cement hydration undergo ion exchange with specific anions such as sulfate or chloride ions. At the same time, the calcium ions move through the concrete by diffusion and osmosis, creating an environment with a high concentration of calcium ions that react with water and silicate ions to form calcium-hydrated silicate ($CaSiO_3$-nH_2O). The hydrated calcium silicate produced by the reaction is a hydrate that acts as a filler for cracks and pores, thus enhancing the structural integrity of concrete [5].

At present, the development and application of osmotic crystallization cementitious materials are relatively mature, and their repair effect is durable and stable. However, there are limitations in the environmental dependence and repair width of the osmotic crystallization self-repair technology, such as the repair effect is not obvious for cracks with a width greater than 0.4 mm [6].

2.2. Microbial self-repair

Microbial self-repair is a type of method that utilizes the metabolism of microorganisms (e.g., bacteria and fungi) themselves to repair concrete. The core of this technology lies in the fact that microorganisms provide reactants for the mineralization reaction during the self-repair process, and at the same time provide the initial attachment points required for the crystallization of healing compounds such as calcium carbonate, which is the growth point of mineral crystals i.e., the location where the mineral crystal gel is formed in the mineralized matrix. Based on strain characteristics, they are further categorized into aerobically induced precipitation type and anaerobically induced precipitation type. Qian Chunxiang [7] and others showed that under sufficient oxygen conditions, aerobic microorganisms can convert two organic calcium compounds, calcium formate and calcium lactate, into calcite through their own metabolism, and at the same time produce a large amount of carbon dioxide, a process that helps calcium hydroxide in the cementitious materials react with carbon dioxide to form calcium carbonate precipitation for self-healing effects. Another example is that anaerobic microorganisms are able to produce urease during metabolism, and urease hydrolyzes urea and produces ammonia and carbon dioxide, which increases the pH value of the solution. In an alkaline environment, when carbonate ions encounter calcium ions, they can cause calcium ions to be deposited in the form of calcium carbonate, which can repair the cracks.

Zhang Liqiu [8] et al. To investigate the influence of different factors on the effect of microbial repair of concrete cracks such as crack width, crack angle and PH value of bacterial solution. Using Bacillus pasteurus as the strain, two kinds of bacterial solutions with pH values of 7 and 8 were prepared, and concrete specimens with different fissure widths (0.25mm, 0.5mm, 1.0mm, 1.5mm) and fissure angles (70°, 80°, 90°) were prefabricated for the experiments. It was found that the repair effect of concrete fissures was affected by both fissure width and angle, in which the fissure width had a more significant effect on the repair effect. It was also concluded that a fissure angle of 90°, a fissure width of 0.5 mm, and a pH value of 8 of the bacterial solution were the optimal environments for the repair of concrete fissures.

3. Extrinsic self-healing

The following section describes three methods: electrodepositional self-repair, capsule-based self-repair, and shape memory alloy self-repair.

3.1. Electrodeposition self-repair

Electrodeposition self-repair is a technique that utilizes electrochemical principles to repair cracks in materials by applying an electric current to promote the deposition of insoluble compounds (e.g., magnesium oxide, calcium carbonate, etc.) on the cracks and surfaces of the concrete, thereby healing the cracks. This method is particularly suitable for the repair of metallic materials and some conductive polymer materials. There are many factors affecting the repair effect of electrodeposition on concrete cracks, the main factors include the type of precipitates produced by electrolysis, current strength, the concentration of electrolyte in the environmental solution, the morphology of cracks on the surface of the concrete and so on. The cations in the electrolyte solution play a decisive role in the type of precipitate formed as well as the deposition effect, and it has been shown that zinc sulfate and magnesium sulfate solutions produce better results in the electrodeposition process. That is, these specific cations, i.e., Zn^{2+} in zinc sulfate solution and Mg^{2+} provided by magnesium sulfate solution, can effectively promote the formation of the desired precipitates, which improves the effect of electrodeposition to repair concrete cracks.

The electrodepositional self-repair method can efficiently prevent and repair the deterioration of concrete components caused by chloride ion erosion or carbonation, so this method is widely used in repairing the cracks of seaport concrete structures and hydraulic concrete structures. In other words, by using the steel bar as the cathode setting the anode, and utilizing the minerals in water or seawater as the electrolyte, an electric field is applied to generate inorganic compounds, such as ZnO, $CaCO_3$, and $Mg(OH)_2$, on the surface layer of the concrete and in the cracks through the electrodeposition reaction. These newly generated inorganic compounds can fill the cracks and improve the compactness of the concrete while preventing the penetration of other harmful substances to repair the cracks and enhance the durability of the structure. However, the electrodeposition method is mainly applicable to materials with good electrical conductivity and is sensitive to crack depth and ambient temperature, which limits its wide application in practical engineering.

3.2. Capsule-based self-repair

Microencapsulated repair is a technology that allows for self-repair by embedding microcapsules containing repair agents in the concrete material. Microcapsules usually consist of a shell and a core. The wall materials of the capsule shell are commonly polyurethane, urea-formaldehyde resin and silica gel, which effectively protect the repair agent inside until it is released when repair is required. The release of microcapsules is triggered by a variety of mechanisms, including, for example, mechanical rupture triggered by crack expansion, temperature change triggered, pH change triggered, and ion triggered.

When the microcapsule ruptures, the restorative agent (which can be liquid or solid, and commonly includes epoxy resins, waxes, metal ion solutions, etc.) reacts with water or other substances in the material, and the resulting product of the reaction is used to fill the crack, thereby restoring the integrity of the material. Most microcapsules are triggered physically, meaning that the capsule wall material undergoes only physical changes to release the repair material. Other microcapsules are triggered by chemical means, i.e., the capsule wall material is affected by humidity, air, and other conditions and undergoes chemical changes to release the repair material. However, at this stage, the yield and storage stability of microcapsules are relatively low and the cost is relatively high, and these drawbacks also bring some limitations to this technology [9].

3.3. Shape memory alloy self-repair

Shape memory alloy (SMA) is a smart material with a unique shape memory effect. Its crystal structure changes when subjected to mechanical stress or temperature changes, and it can “remember” its initial shape and return to its original shape when conditions are restored. As shown in Fig. 1:

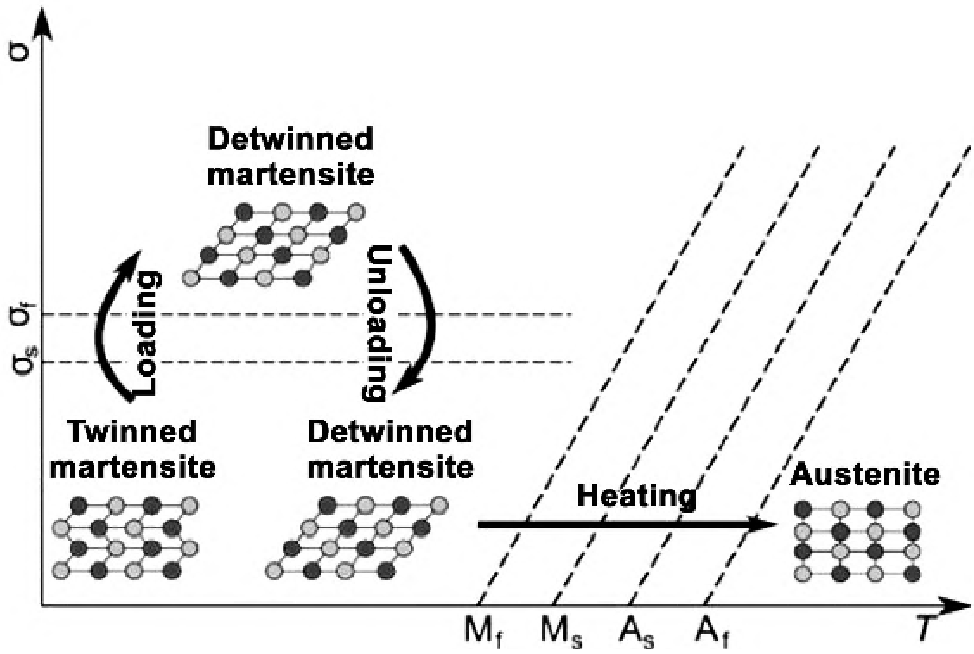

Fig 1. Shape memory effect of SMA [10].

According to current research, two main methods are usually used to repair concrete cracks. The first method is the implanted SMA wire method, in which shape memory alloy wires are embedded in concrete members and the restoring stress of the shape memory alloy wires is triggered by changing the environmental conditions, such as the temperature; the second method is the prestressing tendon method, in which shape memory alloys are added in the preparation of the prestressing tendons, and these prestressing tendons are then subsequently used to construct the concrete members. Regardless of that method, with the generation and expansion of concrete cracks, the strain of SMA at the concrete cracks will increase and the resistance value will be raised, and the change of cracks can be monitored in real time by monitoring the change of the resistance value about the strain of SMA and the width of the cracks, and at the same time, by raising the temperature, the shape memory effect of SMA can be stimulated to generate the restoring stress as high as 600-800 MPa to compress the cracks to make closed. In addition, this property of SMA can play a self-adjusting role in concrete structures. That is to say, SMA can automatically adjust its internal stress distribution according to the structural stress and environmental changes, thus effectively preventing the further development of cracks, prolonging the service life of concrete structures, and improving durability and safety.

4. Suggestion

In summary, today's domestic and international research has been carried out a variety of concrete crack self-repair technologies, and has made good progress. Each technology has its own advantages and shortcomings, for the osmotic crystallization self-repairing concrete, this way to obtain raw materials is relatively simple and the preparation process is not complex, but needs to have a water environment to have the effect, and the width of cracks greater than 0.4mm repair effect is not obvious, so it is suitable for wet or water-containing environments in the concrete structure. Microbial self-repairing concrete has the advantages of environmental friendliness and high durability. However, it is more suitable for concrete environments with suitable temperature and humidity and compatible with repairing microorganisms because it requires complex technology and many influencing factors. Self-repair by electrodeposition is suitable for harbor concrete structures and hydraulic concrete structures because it is low-cost and environmentally friendly, and it can effectively prevent concrete elements from being attacked by chlorine ions, etc. However, it is not suitable for larger cracks. However, it is less efficient for larger cracks. Capsule-based self-repairing concrete is used in areas such as protective coatings, aerospace and marine coatings because this type of concrete does not require additional manual testing and has high corrosion resistance, but if the cracks do not extend to the location of the microcapsules, these capsules can appear to be unable to rupture to release the repairing agent, which in turn restricts the repairing ability. As for the shape memory alloy self-repairing concrete, it can improve the seismic performance technology of the structure, but there are also limitations such as higher costs and complex processes. However, no matter what kind of technology there is a common problem - most of the research is still stagnant in the laboratory stage, and not really applied in real engineering projects [11,12].

Therefore, because of the above problems, in future research of self-repairing concrete, the shortcomings and deficiencies of different repair materials should be addressed, and a stable and reliable repair material suitable for use should be developed through experiments. And systematic research and analysis to develop the selection mode and method of self-repair technology. The strength and durability of self-repaired concrete should be monitored and rated comprehensively and systematically, so that it can play a more efficient role in a wide range of applications, and ultimately promote the development of the concrete industry in a green and sustainable direction.

5. Conclusion

This paper examines the research progress of concrete crack self-repair technology at the present stage at home and abroad. This paper compares and analyzes five kinds of self-repairing concrete from two perspectives: the intrinsic self-repairing method and the extrinsic self-repairing method. And this paper analyzes in detail the mechanism and research results of each type of repair technology and discusses the application of different repair technologies in the self-repair process. It is found that although various self-repairing techniques show certain repair effects under laboratory conditions, most of them still face problems such as high cost, complicated operation and difficulty to be applied in large-scale engineering.

Future research on self-repairing concrete technology should focus on improving repair efficiency, reducing the cost, simplifying the process to reduce its limitations and increasing the practicality of the project. The development of self-repairing concrete technology is of great significance to extend the life of engineering structures, and at the same time, it is in line with the national environmental policy and has a positive effect on promoting the concrete industry to the green and sustainable direction. Therefore, the exploration and research of self-repairing concrete technology should be further deepened.

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