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Research Status of Self-healing Concrete

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Abstract. Through collecting, sorting and analyzing the domestic and foreign references of self-healing concrete research, this paper has summarized the experimental research methods and results of different types of self-healing concrete in recent years, and expounded the mechanism of its action. Self-healing concrete types include self-healing concrete based on concrete itself, self-healing concrete based on permeable crystal repair technology, self-healing concrete based on shape memory alloy, self-healing concrete based on bionic self-repair and self-healing concrete based on microbial. Finally, the existing problems of self-healing concrete are put forward, and the shortcomings of self-healing concrete need to be further strengthened.

1. Introduction

Concrete structure is the most important civil engineering structure. Since it appeared, engineering and technical personnel have continued to conduct research, and concrete materials have been developed in the direction of high strength, high performance and versatility, and the structure has become more complicated and larger. But concrete, as a brittle material, has a very low tensile strength. During construction or during use, cracks may occur in the structure due to the nature of the material itself, the construction method, environmental conditions and load effects, and even cracks that are clearly visible to the naked eye may occur.

There are many ways to deal with concrete structures that have cracks. Epoxy resin reinforcing grouting is a method that is widely used at present. It has strong bonding force, small shrinkage after curing, high mechanical strength, heat resistance and stability. However, these repair methods are mostly used in the case of wide cracks, and the autonomy is poor. It is difficult to repair very small cracks or micro cracks inside the structure. In this context, along with the development of modern science and technology, people began to have great interest in the new technology of concrete self-healing to repair cracks. The research on self-healing concrete has become one of the research hotspots for processing and controlling cracks. After the concrete has cracked, it can self-repair without the influence of external human disturbance. And then the process of healing the crack is called self-healing of concrete.

2.Research status of different types of self-healing concrete

2.1 Self-healing concrete based on concrete itself

Based on the repair capacity of the concrete itself, it is mainly because moisture and air enter the structure through cracks, and a part of the unhydrated cement particles undergo further hydration. The precipitates condense and accumulate, eventually blocking the cracks. However, it should be pointed out that this naturally occurring crystallization aggregation self-repairing concrete generally has a low strength recovery rate, and the concrete under different conditions is highly different.

Gao et al. conducted a self-healing performance test on the crack of the reinforced concrete pool wall[1]. The results show that the crack width of the concrete slab in the environment in contact with the water gradually decreases. The self-healing properties of cracks are related to the composition of the concrete, the age of the damage, the degree of damage, the environmental conditions such as the temperature and humidity during self-healing, and the healing time. Finally, it was found that the cracks of the concrete tested can heal 0.1mm in a short-term in a still water environment. It is suggested that the crack width limit of basically intact tank and the degree of minor damage can be increased by 0.1mm.

Fang et al. studied the mesostructure of cement-based materials in crack-hardened cement pastes, mortars and concrete specimens[2]. The results show that the infiltration process of cement-based materials leads to the dissolution of calcium ions in the hardened cement paste. When the penetration rate is small, the crack surface of cement-based material is rough and easy to adhere to $CaCO_3$ crystal, the calcium ion may combine with CO_3^{2-} dissolved in water to form $CaCO_3$ crystal. It is one of the reasons for the self-healing of concrete cracks.

Yao et al. studied the natural healing phenomenon of damaged concrete of different ages after the same curing period[3]. The damage degree of concrete bauxite after compression and cracking was characterized by the change of ultrasonic velocity, and the relationship between concrete damage and healing condition was established. The results show that there is a damage threshold for concrete materials. When the damage of concrete is lower than the damage threshold, the self-healing rate increases with the increase of the damage amount. when the concrete damage exceeds the damage threshold, the self-healing rate decreases with the increase of the damage amount.

Schlangen et al. used the self-repairing principle of the concrete structure to make self-healing contrast tests of different widths. The result is that the narrower cracks are more easily healed by the inherent self-repair of concrete[4].

However, it should be pointed out that this natural crystallization accumulation has a certain effect on the crack repair of concrete, but the self-repaired concrete has a low strength recovery rate, and the number of unhydrated particles in the concrete is limited. At the same time, the self-healing effects of different concretes based on their own materials vary greatly. In a drier environment, the self-healing effect may be very small, so in actual engineering, it is unrealistic to play a large role in controlling cracks according to such self-healing phenomenon.

2.2 Self-healing concrete based on permeable crystal repair technology

The infiltration crystallization repair technology mainly incorporates cement-based permeable crystalline waterproof material, referred to as CCCW（Cementitious Capillary Crystalline Waterproofing Materials）. It is usually made of Portland cement or ordinary Portland cement, quartz sand, etc., and is made by injecting active chemicals. Because of the presence of active chemicals, self-healing and performance are stronger than cement hydration. The key active chemical is composed of a variety of components, including active anion catalysts, pozzolans, surfactants, early strength agents, water reducing agents, and the like. The living anionic catalyst is inert when it is dried, and has good solubility and permeability in the presence of water. Its main function is to effectively catalyze the hydration reaction of cement, promote the action of Ca^{2+} and SiO_3^{2-} provided by cement base, gather and fill the crack to achieve self-healing repair. When the water is cut off, the catalytic reaction is stopped, the catalyst remains therein, and after the crack occurs again, water can enter, and the self-healing repair can be achieved twice.

Tittelboom et al. carried out an experimental study on full-size concrete beams (150 mm ×250 mm ×3000 mm), and superabsorbent polymers (SAPS) was added to the concrete[5]. The study stressed that because SAPS needs to react with water, the main areas of application of this approach are water retaining structures such as swimming pools, tunnels and under-ground structures, where you have shrinkage cracks. These structures have a better healing effect after the addition of SAPS.

Shi et al. rely on the deep foundation pit project of a square project in Hangzhou to compare and analyze the technical and economic benefits of infiltration crystallization self-healing concrete and traditional deep foundation pit materials[6]. An alternative to self-healing waterproof concrete has been obtained, which can save nearly 700,000 yuan. In particular, it has the effect of reducing cracks in the plastic state and the curing stage, and the function of automatically repairing cracks (width ≤ 0.6 mm) in the presence of water will save the owner about 10% of the maintenance cost in the latter stage.

Liu et al. studied the effect of Canadian XYPEX penetrating crystalline materials on the self-healing properties of concrete[7]. By analyzing the characteristics of self-healing products under different cracking time, curing mode and crack width, it is concluded that curing mode has influence on self-healing products. The microstructure is loose under dry conditions, and the number of crystals and gels formed is small. More crystals are formed in a humid environment, and the structure is more dense. The larger the crack width, the larger the size of the self-healing product produced, and the larger the number, but at a larger crack width, even a lot of self-healing products are not enough to offset the large effect of the crack width itself. From micro-viewing, the self-healing products are criss-crossed and distributed in a spatial network, blocking cracks and pores. Not only played a role in repair, but also effectively played a waterproof role.

Liu et al. examined the self-healing ability of XYPEX blending agent in concrete through six groups of concrete impermeability experiments of different ages[8]. It was found that the XYPEX blending agent can form crystals by utilizing the migration of moisture in the cement hydration, blocking the permeation passages generated by the damage in the concrete, thereby improving the self-healing ability of the concrete. After the XYPEX blending agent is added, the self-healing ability at early age is stronger than that in the later stage. Mainly because the hydration of XYPEX admixture in concrete is directly related to the migration of water, the activity of XYPEX admixture can only be activated during the process of water migration, and there is more free water in the early age concrete which is not involved in cement hydration.

Of course, in addition to the use of permeable crystalline materials, the pore structure of the concrete members and the overall porosity, crack size, and many other factors that may not be considered affect the self-repairing effect. The self-healing properties of concrete based on infiltration crystallization repair technology are not effective when the crack width is greater than 0.6 mm. According to the research results of the predecessors, it is not difficult to find that the self-healing performance based on the infiltration crystallization repair technology is still open to question for the cracking of concrete in dry area.

2.3 Self-healing concrete based on shape memory alloy

Shape Memory Alloys, referred to as SMA. It is a new type of metal functional material developed in recent decades, with obvious phase change phenomenon, excellent shape memory and superelastic properties, good mechanical properties, corrosion resistance and biocompatibility, and high damping properties. The shape memory effect of SMA refers to the plastic deformation generated in the low temperature martensite state, and can be completely restored to the original parent phase state by heating after the external load is removed. Under certain constraints, the SMA will generate a large recovery stress when it recovers. In recent years, the SMA material is combined with concrete to improve the mechanical properties of the concrete members and control their deformation and cracks by using the good physical and mechanical properties of the SMA.

Eunsoo Choi et al. studied the use of SMA materials for the circumferential restraint of concrete columns and carried out uniaxial stress experiments[9]. The analysis of the test data showed that the external SMA wire did not significantly improve the bending resistance of the concrete column, but it increased the ductility of the column. The effect is obvious, and this is very advantageous for Earthquake resistance.

Tao et al. test pre-buried the pre-stretched SMA wire in a crack-prone area of the concrete while placing the fiber in the area[10]. When the concrete appears cracks in the working range beyond the allowable range, the microprocessor will issue a command based on the signal picked up by the fiber to electrically heat the SMA wire at the crack, causing it to shrink and deform, causing the crack to close or restrict further crack propagation.

For the specimens in which the shape memory alloy is embedded in the concrete structure, the presence of the longitudinal ribs has a certain influence on the mechanical properties and self-repairing properties of the SMA concrete structure. Yan et al. conducted a comparative analysis of SMA concrete specimens and SMA concrete specimens with tensile reinforcement[11]. They found that the reinforcement in the tension zone can improve the bearing capacity of the beam; the SMA rib is energized by the test piece after unloading, and the recovery force of the shape memory alloy causes the deflection of the beam to recover and the crack width to decrease. However, the magnitude of the recovery is smaller than that of the SMA concrete specimen of the same configuration. This result is consistent with the intuitive imagination, and it is obvious that the deformation of the tensile reinforcement inhibits the shrinkage of the memory alloy.

Previous investigations have explored the use of shape memory alloy (SMA) bars to replace traditional pre-stressing tendons [12-15]. Whilst these materials have been shown to be effective at providing pre-stress in concrete elements, their relatively high cost makes their use unviable for all but the most specialized of applications. Jefferson presents an original crack-closure system [16]. The system involves the incorporation of unbonded pre-oriented polymer tendons in cementitious beams. At low stress level, it is feasible to use oriented shrinkable polymer tendons to achieve fracture closure.

At present, there are many researches on shape memory alloys. Although there are good results, there are still some deficiencies in the research work on SMA concrete. At present, the study generally uses alloy wire with a small cross-sectional area, and there are few applications in large-scale concrete structures. There is little research on the bonding properties of SMA and concrete, and this work should be strengthened. This is the key to working together with SMA. In order to make SMA concrete structures widely used in engineering, it is necessary to establish corresponding theoretical formulas and corresponding rules to guide the design of structures to ensure the rationality of its structural structure.

2.4 Self-healing concrete based on bionic self-repair

Self-healing is one of the important characteristics of biological tissues. For example, when some tissues of humans are scratched, internal blood vessels rupture, blood, white blood cells and phagocytic cells ooze out from blood vessels, blood and some proteins undergo a series of complex biochemistry. The reaction is converted into solid fibrin, which causes the exudate near the wound to solidify to form a clot, which blocks the wound and protects it. Inspired by this self-healing behavior, people began to add some microcapsules or glass tubes containing repairing agents to the concrete. When the concrete structure is damaged, the internal glass tube or capsule structure will be broken, and the repairing agent inside will be released. Then automatically penetrates into the damaged area for repair.

Araújo proposed an innovative method that makes it easier to assess the survival rate of capsules during concrete agitation [17]. Using this method to calculate the capsule with a wall thickness of 0.7 mm after surface treatment, it cannot break in the mixing process of concrete, and can be broke in time with a small crack width (116 μm), so that the adhesive flows out and the crack is healed. The results also showed that cracked concrete beams with mixed-in capsules (glass or PMMA) filled with water-repellent agent showed higher resistance against chloride ingress compared to plain cracked concrete beams.

Perez studied the self-healing properties of two new additives to enhance concrete, epoxy-containing silica microcapsules and amine-functionalized nanosilica[18]. Through analysis, the additives had good dispersibility and stability in the cementing material, but the addition of the healing system reduced the compressive strength of paste, and the higher the content of the additives, the lower the strength.

Zhao et al. embedded a liquid core glass fiber containing a acetal polymer solution in a cement-based composite material reinforced with steel wire short fibers[19]. Next, the layers were poured, solidified and watered for 4 days, and then subjected to a bending test. When the structure is cracked and the external force is removed, it is found that some of the liquid core fibers are broken, and the repairing agent inside penetrates into the crack, and the crack is filled and solidified soon. In addition, Zhao also pointed out that when injecting the repair agent into the glass fiber, there should be a certain pressure, which is conducive to the spread of the repair agent.

In addition, there is a tube-based self-repair in which the repair agent is placed in isolation into a hollow tube that connects the inside and the outside of the concrete structure, and the tube like a biological tissue generally passes through the concrete. Lark et al. used a cyanoacrylate adhesive that reacted with air and put it into a glass tube[20]. After the concrete cracked, the pipe also ruptured, and the repair agent in the pipe flowed out, repairing the crack. When the crack is wide, the repair agent in the tube is exhausted, and the crack can be healed by transporting an additional repair agent to the damaged portion through the tube inside and outside the connecting structure.

The most critical of this self-healing concrete based on bionic self-healing is how to control the time to release the repair agent and how to determine the reasonable distribution of the fiber tube or capsule in the concrete. First, the fiber tube or capsule must be matched with the elastic modulus and stiffness of the concrete to ensure simultaneous cracking with the concrete. At the same time, whether it is factory prefabricated or cast-in-place concrete, it is necessary to ensure that the container remains intact during production. In addition, the repair agent container arranged in the system should not be too much or too little, and must satisfy certain repair effects without affecting the strength and macroscopic performance of the concrete. In short, to be widely used in practice, the research is still insufficient.

2.5 self-healing concrete based on microbial

While most healing agents are chemically based, more recently the possible application of bacteria as self-healing agent has also been considered. The principle of microbial self-healing concrete technology is to use the mineralization reaction of microorganisms to form gelling substances. The researchers first discovered in the oil exploitation project that the rock crack can be repaired by microorganisms, and the repairing effect can still be carried out after the microorganisms become dead bodies. After this phenomenon was discovered, the microbial self-healing technology was applied to geotechnical engineering and cultural relics restoration projects, and the application in concrete crack repair engineering was gradually deepened. In a number of published studies the potential of calcite precipitating bacteria for concrete or limestone surface remediation or durability improvement was investigated[5,18,21,22].

Wiktor et al. added a special new biochemical self-healing agent to the porous expanded clay granules[23]. The use of two-component bio-chemical agent can increase the self-healing capacity of concrete by more than one time. Analysis of the reasons there are two points: direct $CaCO_3$ precipitation through metabolic conversion of calcium lactate and indirect formation due to reaction of metabolically produced CO_2 molecules with $Ca(OH)_2$ minerals present in the concrete matrix leading to additional $CaCO_3$ precipitation.

Recently, Jonkers et al. developed a two-component self-healing system that is composed of bacterial spores, which after germination catalyze the metabolic conversion of organic compounds (the second component) to calcium carbonate[24]. This study revealed that the setting time was delayed with the increase in the replacement percentage of bio admixture, and with the increase of the concentration of bio admixture, the compressive strength and workability were improved. However, Jonkers also observed that the functionality of bacterial mineral production of directly(unprotected) incorporated two-component healing agent was limited to young (1–7 days old) concrete specimens[25]. It was hypothesized that the majority of incorporated spores apparently become crushed or inactivated by high alkalinity in aged specimens, resulting not only in loss of viability but also in decreased mineral-forming capacity.

At present, the self-healing concrete based on bacteria is still in the experimental research stage. Before the actual application, several problems need to be solved, such as the cost of the new types of self-healing concrete based on bacteria and the bacteria still have activity and repair function within several decades after pouring. In additional, since the type of microbial mineralization reaction products is largely dominated by the environment, the key points of this technology are the selection of microorganisms, the protection of microorganisms, the concentration of calcium ions, the concentration of inorganic carbon, and the Mineralized environment pH value, etc.

3. Current problems in self-healing concrete research

The experimental research on the self-repairing of concrete cracks by researchers at home and abroad has effectively promoted the development of intelligent concrete. However, most of these self-healing methods are only carried out in the laboratory environment, and it is difficult to apply them to actual projects. In addition to the deficiencies mentioned above for specific types of self-healing concrete, there are several problems with self-healing concrete.

1) Combined with various researches, the self-healing properties of almost all self-healing concrete have certain requirements on the width, and only small cracks can self-heal.

2) There are few studies on the performance of concrete after self-healing. Most of the research is concentrated in the field of materials. Whether it is the use of its own strength healing agent or the catalytic healing agent that catalyzes the healing of concrete base materials, the change of mechanical properties such as concrete strength and elastic modulus after crack repair is still unclear.

3) A unified assessment method for the self-healing effect of concrete has not been established. For example, set the fracture healing rate, healing speed, multiple healing ability, mechanical properties after healing and other indicators. If there is not a good evaluation method, it is impossible to judge the quality of the self-healing effect, and the normal use of the structure cannot be guaranteed, and the self-healing concrete loses its application value.

4. Conclusion

The crack treatment of concrete structures is a research hotspot and has caused long-term problems for the development of the engineering community. At present, the research on self-healing concrete technology at home and abroad has been carried out in a variety of ways, and good progress has been made in different research directions, but most of the research is in a state of theoretical feasibility and laboratory feasibility. There are few proposals for projects that can make use of a large amount of self-healing concrete. Many key issues need to be addressed, such as the compatibility of new materials with concrete matrices, the optimal choice of materials to be incorporated, and the optimal choice of blending amounts, long-term work stability of repair materials, reliability of multiple repairs, and inspection standards for repair effects. At the same time, due to the non-uniformity and randomness of cracks in the concrete matrix, it is difficult to determine the actual repair effect in the experiment.

Although many key technologies are still in the state of research, in the general trend of green buildings and green materials, self-healing concrete technology has great potential, which can save the high cost of artificial repair, improve the service life of concrete materials and further ensure the safety and durability of the building. The technology from the self-healing concrete will be an important part of intelligent buildings and green buildings in the future.

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