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SELF-HEALING CONCRETE- A NOVEL APPROACH FOR CIVIL ENGINEERING

JAGMEET SINGH, JASPAL SINGH & MANPREET KAUR

Department of Civil Engineering, Punjab Agricultural University, Punjab, India

ABSTRACT

Concrete structures often suffer from cracking that leads to much earlier deterioration than designed service life. Repairs can be particularly time consuming and expensive because it is often very difficult to gain access to the structure to make repairs, especially if they are underground. In particular, the utilization of self-healing technologies has high potential as a new repair method for cracked concrete. Self-healing is a natural process of crack repair that can occur in concrete in the presence of moisture. Self-healing character of concrete can be accelerating using different materials like mineral admixture, bacteria and fibers. Mineral admixtures have been deployed as an approach for self-healing of concrete cracks by reducing the water permeability after concrete damage. Mineral admixture (Expansive agents and geo-materials) swell in the presence of water and fills the cracks. Fibers in concrete recover the mechanical properties of concrete as a result of self-healing of concrete and helps to controlled tight crack width. Bacteria additive self-healing approach utilizes bacteria that induce precipitation of calcium carbonate as a result of carbonate generation by bacteria metabolism in a high calcium environment. The precipitation of calcium carbonate fills the larger cracks. Self-healing concrete has significant implications in extending service life of building by reducing its repairing and repairing costs. Thus, self-healing concrete could be a major enabling technology towards sustainable civil infrastructure.

KEYWORDS: Bacteria, Concrete, Fibers, Mineral Admixture, Self-Healing

INTRODUCTION

Concrete structures often suffer from cracking that leads to much earlier deterioration than design services life. Tiny cracks on the surface of the concrete make the whole structure vulnerable because water seeps in to degrade the concrete and corrode the steel reinforcement, greatly reducing the lifespan of a structure. Concrete can withstand compressive forces very well but not tensile forces. When it is subjected to tension it starts to crack, which is why it is reinforced with steel; to withstand the tensile forces. Structures built in a high water environment, such as underground basements and marine structures, are particularly vulnerable to corrosion of steel reinforcement. Repair of conventional concrete structures usually involves applying a concrete mortar which is bonded to the damaged surface. Repairs can be particularly time consuming and expensive because it is often very difficult to gain access to the structure to make repairs, especially if they are underground. In particular, the utilization of self-healing technologies has high potential as a new repair method for cracked concrete under the water leakage of underground civil infrastructure such as tunnels (Ahn and Kishi 2009). The action of self-healing was first discovered by the French Academy of Science in 1836. Although, the idea remains a novelty in practice, it has attracted a significant amount of attention in the research community. Many different approaches to functionalizing concrete to posse self- healing ability have been investigated. Review on healing of cracks can be found for example in Lauer and Slate (1956) and Jacobsen et al (1998). Given the damage in concrete is dominated by cracks; much attention has been given to self-repair of cracks. In a few cases, field trials have been launched. These studies hold promise to the feasibility of future civil infrastructure smart enough to detect its own damage and undergo repair by itself. Thus self-healing concrete has significant impactions in extending services life, and reducing economic, social and environmental costs of civil infrastructure. That is, self-healing concrete could be a major enabling technology towards sustainable civil infrastructure. The present paper reviewed the different self-healing techniques in concrete.

SELF-HEALING APPROACHE IN CONCRETE

Self-healing is a natural process of crack repair that can occur in concrete in the presence of moisture. The deposition of calcium carbonate is said to occur as the results of the following reactions (Edvarden 1999).

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + HCO_3^{2-} \quad (1)$$

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

$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + H^+ (7.5 < pH_{water} > 8) \quad (3)$$

The dissolved CO_2 ion and the calcium ion Ca^{2+} in water combine with each other to produce calcium carbonate crystal, and the resulting calcium carbonate crystallization is precipitated on the crack surface. As a result, the crack width is gradually reduced and ultimately the cracks close. Lauer and Slate (1956) reported a study of the nature of the self-healing action and studied the effect conditions of curing on healing. They emphasized that the presence of water as the curing medium was essential to obtain the maximum healing strength. Dhir et al (1973) studies the influence of age and mix proportions on the self-healing of mortars. They concluded that the rate of healing decreased with age within the test rate 7-120 days and that the percentage of recovery in strength was greater for the mixes with higher cement contents. Reinhardt and Jooss (2003) reported a series of permeability tests with the constant temperature at 20, 50, and 80^0C. They showed that the higher temperature favors a faster self-healing process. Self-healing character of concrete can be accelerating using different materials like mineral admixture, bacteria and fibers.

SELF- HEALING CONCRETE USING FIBERS

Self-healing properties of Fiber Reinforced Cementations Composites (FRCC) concrete are better than self-healing properties of plain concrete. Hannant and Keer (1983) carried out an experimental study on the recovery of elastic modulus and tensile strength of thin FRCC sheets under tension. W/C was 0.34 using ordinary Portland cement mortar containing fine silica sand of 150 to 300 micrometers and reinforced with a polypropylene network. The specimens were 1.2 mm in thickness and 30 mm in width. The study concluded that specimens containing about 22 cracks of the average width of 7 micrometers showed almost complete recovery of elastic modulus but only about 50% recovery of tensile strength after curing of seven months to two years in natural weathering conditions. Grey (1984) examined self-healing of the interfacial bond strength between steel fiber and mortar by means of a pulling-out test on single fibers embedded in water-cured specimens. The test results indicated that the extent of the interfacial bond healing was greater than that observed for the compressive strength of the plain mortar. Li et al (1998) carried out experimental studies on the self-healing capability of Engineered Cementitious Composites (ECC) and concluded that cementitious materials with inherently tight crack widths are conducive to self-healing and that self-healing can distinctly recover the stiffness of cracked ECC, a fact established through resonance frequency measurement. Yang et al (2005) investigated self-healing of ECC subjected to wetting and drying cycles. They used a mix proportion of water-binder ratio of 0.25 including a large amount of fly ash and 2% PVA fiber by volume fraction. The ECC material subjected to tensile load exhibited multiple cracking in which the crack width was between 60 and 80 micrometers on average. It was found that the resonance frequency could recover 76% to 100% of the initial value and that the tensile strain after self-healing could recover 1.8% to 3.1% for specimens pre-loaded to high levels of strain between 2% and 3%.

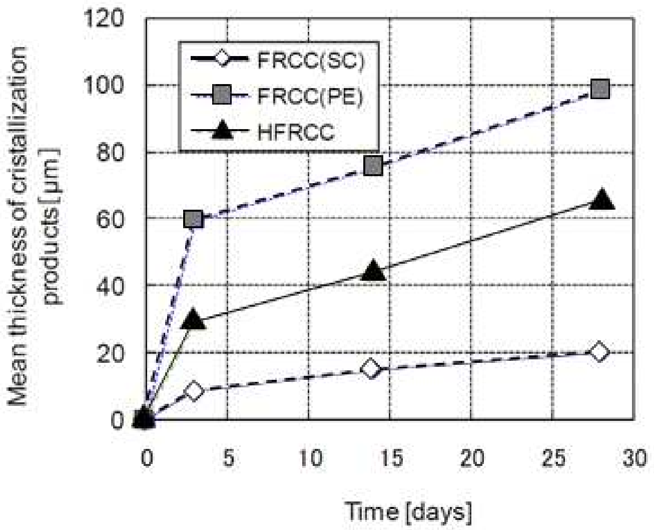
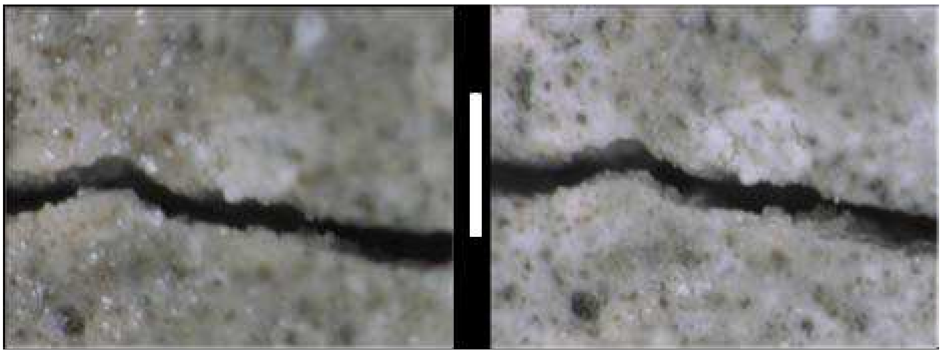


Figure 1: Time Dependence of Mean Thickness of Crystallization Products Attached to the Crack Surface (Homma et al 2009)

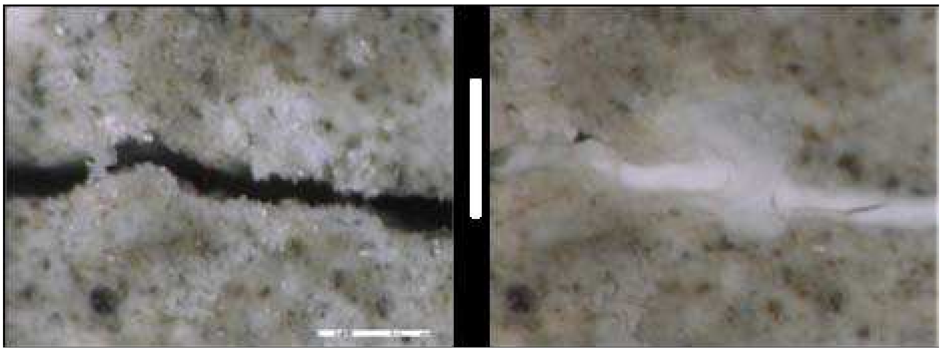
Homma et al (2008, 2009) investigated the self-healing capability of FRCC by microscope observation, water permeability test, tension test and back- scattered electron image analysis. They prepared specimens with water/binder ratio of 0.45, containing three different types of fiber (i.e. steel cord 0.75 vol.%: SC, polyethylene fiber 1.5 vol.%: PE, and hybrid type including both of these two fibers: 0.75 vol.% & 0.75 vol.% for a total of 1.5 vol.%: PE+SC). It was found that lots of very fine PE Fibers Bridge over the crack and those crystallization products of calcium carbonate examined with Raman spectroscopy become easily attached to the PE fibers. As a result, in the case of PE, the mean thickness of the crystallization products attached to the crack surface increased much faster compared with the other fibers (Figure 1). Herbert and Li (2011) reported the results of an experimental study on the self-healing behavior of ECC under natural environmental conditions. They concluded that self-healing was not as robust as that observed in some experimental results carried out under controlled laboratory conditions, though the self-healing in the natural environment was promising.

SELF-HEALING CONCRETE USING MINERAL ADMIXTURE

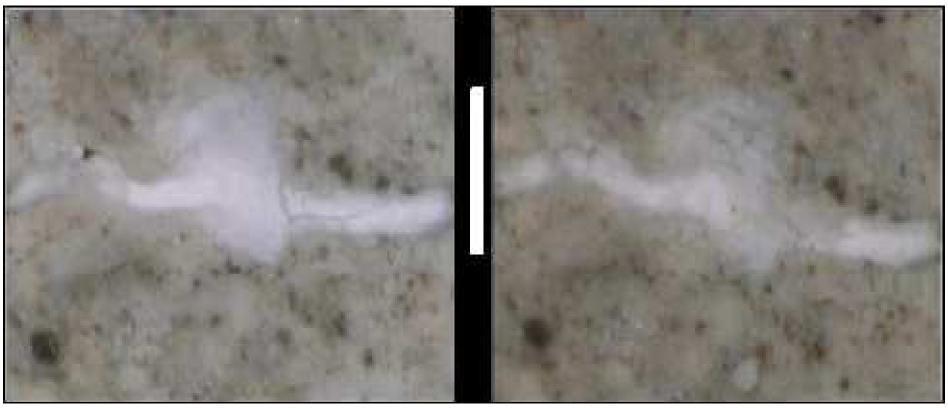
Mineral admixtures have been deployed as an approach for self-healing of concrete cracks by reducing the water permeability after concrete damage. Kishi et al (2007) demonstrated the use of a tailored mix of expansive agents, swelling geo-material (mainly silicon dioxide and sodium aluminum silicate hydroxide) and various types of carbonate as partial (10% by weight) cement replacement, and found that the healing action can be effective for cracks up to 0.22mm in water permeability test in concrete with normal w/c ratio. The healing process of the cracked three-component system at different curing ages is shown in Figure 2 (Ahn and Kishi 2010). The combined effect of geo-materials swelling upon rehydration and expansive agent expansion in the crack were suggested as the mechanisms leading to effective healing. Calcium-sulfur-aluminates (CSA) have been utilized as an expansive agent for self-sealing (Sisomphon and Copuroglu 2011). Van Tittel boom and De Belie (2009) investigated the effect of blast furnace slag (BFS) and concluded that increased self healing can be achieved by both increasing the ratio of BFS and also reducing the water to binder ratio. Self-healing behavior of pre-cracked SHCC (strain hardening cementitious composites) made with local waste materials (blast furnace slag and limestone powder was investigated by Qian (2009). They concluded that Self-healing behavior in SHCC heavily depends on the availability of un-hydrated cement and other supplementary cementitious materials. Low water/cementitious material ratio and high percentage of cementitious material appear to promote self-healing behavior. Ahn and Kishi (2010) developed self-healing concrete using geo-materials which was available for practical application. They concluded that self-healing capability was significantly affected by alumina-silicate materials and various modified calcium composite materials mainly due to the swelling effect, expansion effect and re-crystallization. This approach requires the supply of water or at least moisture, but since most infrastructures are exposed to rain or underground water, usually this is an easily satisfy able requirement.



(a) 3 Days **(b) 7 days**



(c) 14 Days **(d) 28 days**



(e) 40 days **(f) 200 days**

Figure 2: The Healing Process of the Cracked Three-Component System at Different Curing Ages (Ahn and Kishi 2010)

SELF- HEALING CONCRETE USING BACTERIA

The bacteria additive self-healing approach utilizes bacteria that induce precipitation of calcium carbonate as a result of carbonate generation by bacteria metabolism in a high calcium environment (Figure 3). The specific bacteria chosen must be able to withstand the high alkalinity of cement and the internal compressive pressure as microstructure continuously densities with cement hydration. A nutrient must also be available to feed the bacteria. For example, Wiktor and Jonkers (2011) encapsulated spores of Bacillus pseudofirmus and Bacillus cohnii, calcium lactate and yeast extract in porous expanded clay particles up to 4mm in size. Evidence of self- healing was based on visual observation of calcium carbonate precipitates on the cracked surfaces after 100 days of immersion in water. A technique based on the application of mineral producing bacteria has been developed in several laboratories. Ramachandran et al (2001) published a paper describing an innovative biotechnology utilizing microbiologically induced mineral precipitation for concrete remediation. Cracks filled with bacteria and sand demonstrated a significant increase in compressive strength and stiffness when compared with crack without cells. Van Tittelboom et al (2010) investigated the use of a biological repair technique in which ureolytic bacteria are able to precipitate $CaCO_3$ in their micro-environment by conversion of urea into ammonium and carbonate. It was shown that cracks were filled completely by protecting bacteria in silica gel against the high pH in concrete, though pure bacteria cultures were not able to bridge the cracks.

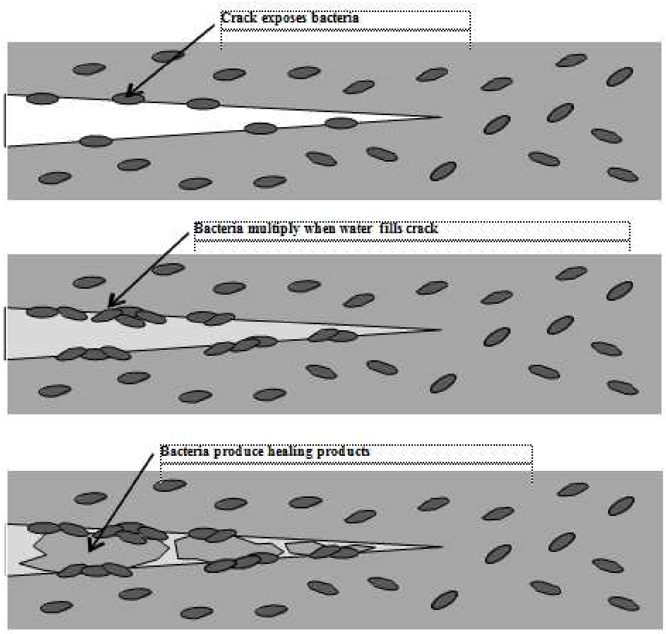


Figure 3: Bacteria Additive Self-Healing Approach (Victor and Herbert 2012)

In order to substantially increase the lifetime and associated functionality of concrete incorporated bacteria, Jonkers (2010, 2011) immobilized both bacteria spores and a simultaneously needed organic bio-mineral pre- cursor compound (calcium lactate) by applying a vacuum technique in porous expanded clay particles prior to addition to the concrete mixture. The particle size was 1 to 4 mm and the shape was spherical. Environmental SEM revealed that efficient healing of cracks occurred in the bacteria specimen in which large (50 to 100 micrometers) calcium-carbonate-based self-healing products were created. Tests also showed that bacterial spore viability increased from two to more than six months, though this duration is still much shorter than the usual lifetime of buildings and infrastructures.

CONCLUSIONS

In this paper self-healing technique of concrete using three different materials are discussed. Mineral admixtures have been deployed as an approach for self-healing of concrete cracks by reducing the water permeability after concrete damage. Mineral admixture (Expansive agents and geo-materials) swell in the presence of water and fills the cracks. Fibers in concrete recover the mechanical properties of concrete as a result of self-healing of concrete and helps to controlled tight crack width. Bacteria additive self-healing approach utilizes bacteria that induce precipitation of calcium carbonate as a result of carbonate generation by bacteria metabolism in a high calcium environment. The precipitation of calcium carbonate fills the larger cracks.

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