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Self-healing concrete: a potential smart material to apply for underground construction

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ABSTRACT

The crack of the concrete in underground constructions is generally difficult to detect and repair and consequently causes structural deterioration. Smart concrete with self-healing ability to autonomously repair micro cracks is a potential smart material to apply for underground constructions with sustainable development proposes. This paper reviews healing materials, the self-healing process, and the mixing method of self-healing concretes using bacteria, mineral admixtures, and fibers. The bacteria such as Bacillus sphaericus, Bacillus megaterium, Bacillus subtilis, Bacillus pasteurii, and Bacillus subtilis can produce a calcareous product for healing exterior cracks through microbial metabolic processes. As micro cracks are formed in the smart concrete, the bacteria spores contact nutrients and water and generate Calcium Carbonate ($CaCO_3$). The addition of mineral admixtures based on silica including fly ash and granulated blast furnace slag (GGBS) heals the inner cracks through Calcium silicate hydrate (CSH) gels – hydration reaction products. Other minerals such as expansive materials, geo-materials, crystals, and chemical additives change their forms or volumes to close cracks. Fibers including steel, carbon, PVA, PE, and carbon fibers are utilized to develop self-healing concretes based on controlling the crack width. The addition of fibers generates multiple micro-cracks, decreases the crack width, and enhances autogenous crack healing. Besides, healing agents can be easily dispersed into self-healing concretes by using the dry mixing, the wet mixing, or the latter mixing. Hence, all smart concretes with self-healing ability demonstrate potential and suitable characteristics for underground constructions. A combination method of fibers and bacteria or mineral admixtures can be applied for better sealing crack and durability enhancement of underground concrete structures.

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1. Introduction

The generation and propagation of cracks in the concrete can cause a decrease in the durability of structure, prone to the corrosion of steel reinforcing bars, and consequently resulted in structural deterioration. To reduce the cost of maintenance and repair for concrete structures, the smart concrete with self-healing ability has been investigated (Chahal et al., 2012; Huang et al., 2014; Xu & Wang, 2018; Chandra Sekhara Reddy & Ravitheja, 2019; Kanellopoulos et al., 2015; Fan et al., 2018). Especially, to repair concrete cracks in dangerous and difficult conditions of underground concrete structures, self-healing characteristics of smart concretes is the potential method.

Self-healing concrete, which impresses to heal the cracks without the involvement of humans, was made according to the two main approaches including natural and artificial approaches (Manvith Kumar Reddy et al., 2020). Nature healing mechanism is based on an autogenous healing process, which is due to chemical reactions and water involvement (Figure 1). The artificial approach is based on adding healing agents such as bacteria, mineral admixture, or fibers to improve the healing crack process.

This study reviews the work done previously on self-healing concrete by using mineral admixture, bacteria, and fibers as healing agents to understand self-healing materials, methods, healing process, and their potential application to underground concrete structures.

2. Review of the literature on self-healing concrete, its healing process, and its self-healing methods

2.1. Self-healing concrete with bacteria

In this type of smart concrete, bacteria biologically produced a calcareous product for healing cracks on the exterior of concretes. According to Far Eastern Federal University (FEFU) (Vladivostok, Russia), bacteria can live in concrete for 200 years. Bacteria including Bacillus sphaericus, Bacillus megaterium, Bacillus subtilis, Bacillus pasteurii, Bacillus sphaericus, and Bacillus subtilis was generally in forms of species, calcium lactate, nitrogen, bacillus, and phosphorous (Yatish Reddy et al., 2020). They can be directly dispersed into concrete or encapsulated to protect the bacterial spores.

As cracks were generated in smart concretes, the bacteria spores contact nutrients and water and consequently germinate (Kumar Jogi & Vara Lakshmi, 2020). Then, the bacteria activated and nourished the calcium lactate ($C_6H_{10}CaO_6$). The soluble calcium lactate ($Ca(C_3H_5O_2)_2$) was converted into calcareously impenetrable according to Eq. (1) as the bacteria consumed oxygen. Thus, Calcium Carbonate ($CaCO_3$) was formed through microbial metabolic processes and indirectly through autogenous curative processes. Hence, cracks were filled by the calcium carbonate precipitation. Figure 2 illustrates the healing crack process of smart concrete with bacteria while Figure 3 presents the generating process of calcium carbonate.

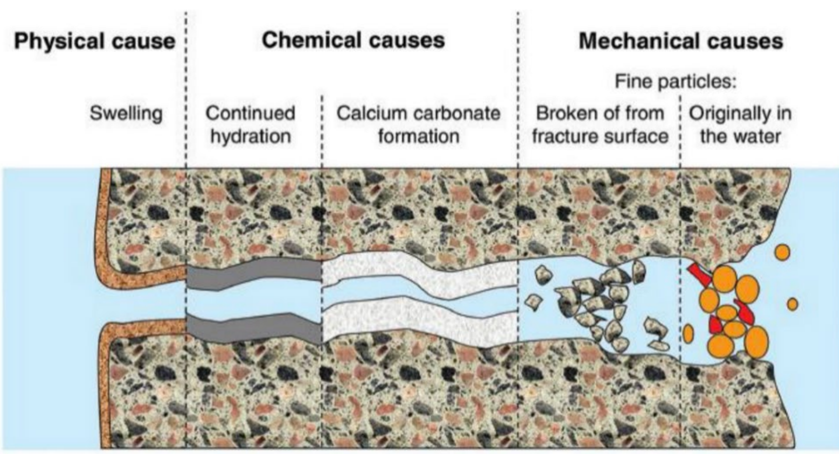

Figure 1. The autogenous healing concrete mechanisms (Ivanor, 1974; Zhang et al., 2020).

$$Ca(C_3H_5O_2)_2 + 7O_2 = CaCO_3 + 5CO_2 + 5H_2O \quad (1)$$

2.2. Self-healing concrete with mineral admixtures

In this type of smart concrete, to improve the self-healing process, mineral admixtures such as fly ash, granulated blast furnace slag (GGBS), carbonated steel slag, expansive materials, geo-materials, crystals, and chemical additives were used. In addition, they are easily incorporated into concrete mixtures. Figure 4 illustrates the self-healing method based on mineral admixtures.

As silica-based minerals including GGBS and fly ash (often high content in concrete mixtures) contact water, the hydration reaction produced C-S-H gel, which seals cracks (Van Tittelboom et al., 2012). However, the hydration reaction process was time-consuming.

The addition of crystalline admixtures and expansive additives to the concrete can heal the inner cracks of the specimen. The crystalline admixtures would be more useful in hydraulic structures like water tanks, dams, etc. (Manvith Kumar Reddy et al., 2020). As the concrete was exposed to water, the crystalline admixture formed into the needle-like structure, closed the cracks, and consequently reduced the permeability. Many researchers reported that there is an increase in the mechanical properties and a decrease in the water permeability of concrete by the addition of these admixtures. Besides, the chemical expansive additives swiftly increase their volume to seal cracks (Zhang et al., 2020).

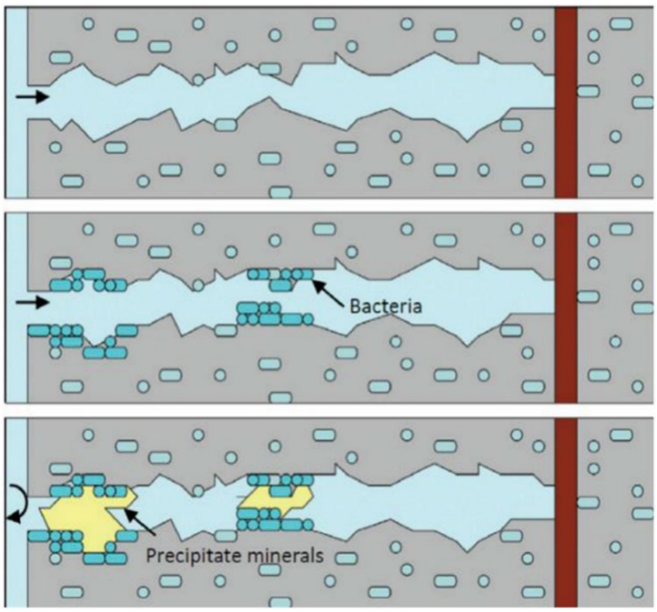

Figure 2. Crack-healing process by concrete-immobilized bacteria (Jonkers, 2007).

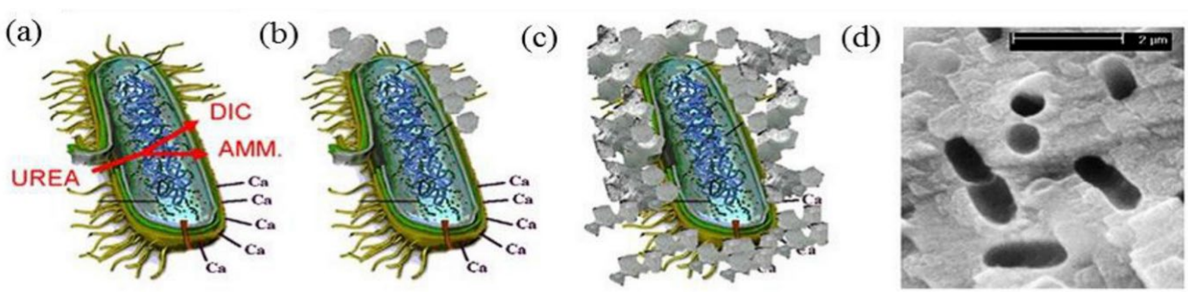

Figure 3. Process of carbonate precipitation during ureolytic: (a) bacteria convert urea into carbon and dissolved inorganic ammonium; (b) precipitation of $CaCO_3$ on the bacterial cell wall; (c) encapsulated the whole cell; (d) bacterial cells and carbonate precipitation (Zhang et al., 2020).

However, the self-healing capability of smart concrete containing mineral admixtures has been limited and the crack width cannot be properly sealed if it exceeds a particular critical value. (Yang et al., 2009). For engineered cementitious composites (ECC), Yang et al. (2009) mentioned that crack width should be controlled below 150 μm to achieve better self-healing performance. Curing conditions also significantly influence self-healing behavior. Continuous water curing produced higher density microstructure and permeability resistance of concretes in comparison with freeze-thaw cycles and continuous air (Sahmaran et al., 2013).

2.3. Self-healing concrete with fibers

In this type of smart concrete, fibers such as steel, PVA, PE, PP, and carbon fibers decreased crack width in concretes and consequently enhanced autogenous healing characteristics. Figure 5 demonstrates two mechanisms of self-healing concrete with fibers. The addition of fibers significantly improved the tensile resistance of concrete and produced multi-micro cracks. As a result, self-healing effectiveness was increased because fewer healing chemicals are required to fill in the micro cracks. (Şahmaran et al., 2015). In addition, fibers bridging cracks can help to attach crystallization products, which improve self-healing (Homma et al., 2009; Kan & Shi, 2012). Nishiwaki et al., 2014 mentioned that Fiber-reinforced concretes produced good self-healing properties when crack width was less than 0.1 mm. Moreover, Homma et al., 2009 reported that the water permeability of self-healing concrete with fibers clearly decreased.

2.4. Mixing and dispersion methods

According to healing agents, the mixing methods of self-healing concretes can be divided into dry mixing, wet mixing, and latter mixing, as illustrated in Figure 6 (Zhang et al., 2020).

Self-healing concrete with bacteria was often mixed using the wet mixing method (Reddy et al., 2020). Firstly, bacterias can be directly mixed with water. Then, cement, additive, and aggregates were added into mixtures. Besides, bacterias could be firstly prepared into encapsulation, which is to protect bacterial spores prior to mixing with water. Then, the bacterial encapsulation can be dispersed into self-healing concrete using the latter mixing method (Figure 6).

Mineral admixtures were normally

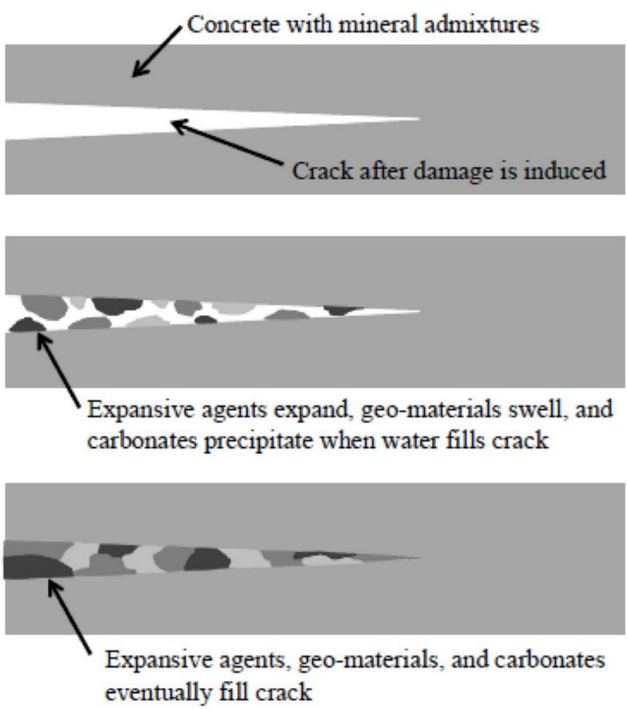

Figure 4. Self-healing process of smart concretes with mineral admixtures (Li & Herbert, 2012).

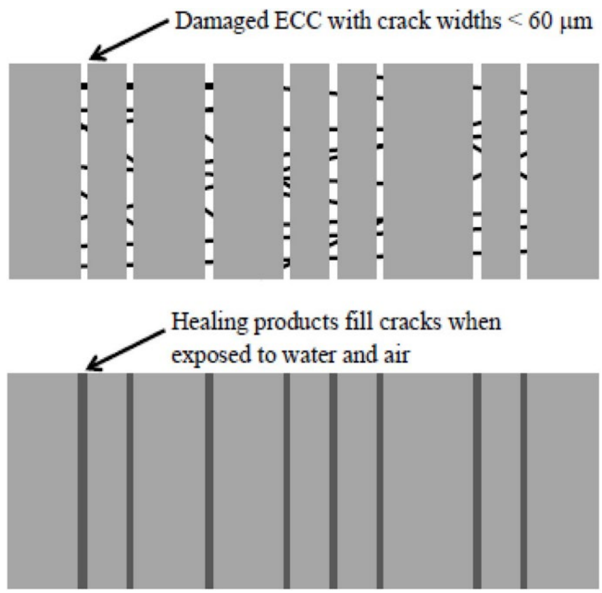

Figure 5. Self-healing process of the smart concrete with fibers by autonomously tight crack width (Li & Herbert, 2012).

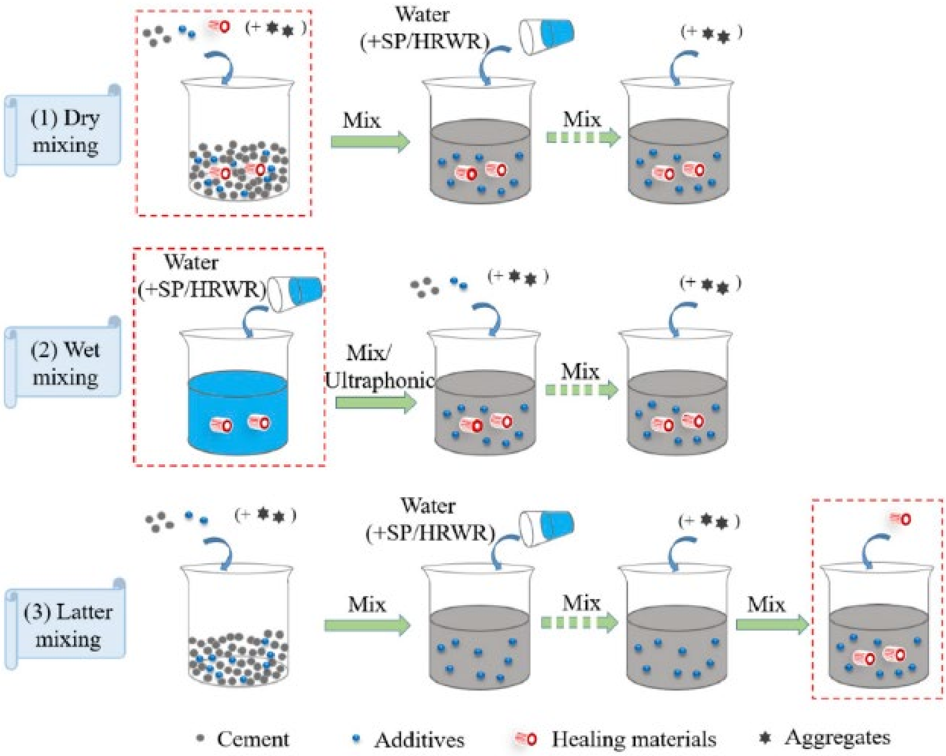

Figure 6. Mixing methods for the self-healing concrete (Zhang et al., 2020).

dispersed into the self-healing concrete by using the dry mixing method. Mineral admixtures (fly ash, GGBS, geo-materials, crystals, expansive materials, and chemical additives) were dry mixed with cement, additive, and aggregates. Then, water and/or superplasticizer were added to the mixture.

Self-healing concretes with fibers were generally mixed using the later mixing method. Firstly, cement, additive, and aggregates were dried mixed. Then, water and/or supper plasticizer were slowly put into the mixture. As the mixture presented suitable workability, which is determined based on the flow table test, for fiber distribution, fibers were manually added into the mixture.

3. Discussion of self-healing concrete for underground construction

Cracks of underground concrete structures may occur owing to material shrinkage, steel corrosion, extreme force, and ground movement. The generation and propagation of cracks are difficult to detect and maintain for underground constructions. Thus, smart concrete with self-healing crack ability is potential to apply for these structures. In addition, self-healing concrete has several advantages including a lower rate of degradation, a longer service life, a decrease in the frequency of repairs and maintenance, and a lower overall life cycle cost of concrete structures (Li & Herbert, 2012).

The self-healing concrete with a bacterial encapsulation approach based on the biological processes for crack healing can be highly efficient and attractive. It is potential to apply for certain types of structures such as underground constructions. Recently, Wang et al. (2019) applied self-healing concretes using microencapsulate for a tunnel engineering project in the Qianhai area, China (Figure 7). They suggested that using self-healing concrete based on microcapsules is promising and feasible to increase the durability of concrete constructions (Wang et al., 2019).

As mineral admixtures in self-healing concretes were exposed to water, they were effectively activated. Thus, for underground structure in wet condition, the self-healing concrete containing mineral admixtures has been highly convincing.

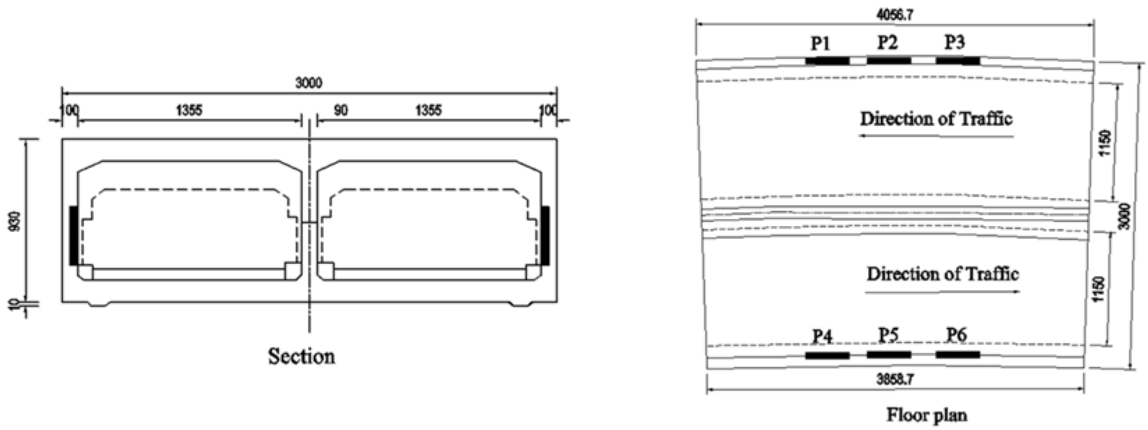

Figure 7. Precast self-healing concrete slab using in the tunnel (Wang et al., 2019).

The self-healing concrete with fibers or self-healing with self-controlled micro-crack approach shows promise for underground construction. The compressive and tensile strengths of SHFRCs were clearly higher than conventional concretes. The economic cost of SHFRCs is currently higher (E.g. ECC cost was two to three times) than that of conventional concrete. However, the higher initial cost of SHFRCs could be offset because they have a lower life-cycle maintenance cost and significantly higher tensile resistance.

4. Conclusion

The cracks in the underground concrete constructions are not easy to detect and repair owing to their dangerous and difficult conditions. The self-healing concrete is a potential material to apply for underground construction. This study reviewed the mechanism, the healing process, and the mixing method for self-healing concretes with three healing agents including bacterias, mineral admixtures, and fibers.

For underground concrete constructions, the use of self-healing concrete with bacteria based on biological processes for crack repair can be significantly effective and appealing. Calcium Carbonate ($CaCO_3$), filling cracks, is created both directly by microbial metabolic processes and indirectly by autogenous curative processes.

The self-healing concrete containing mineral admixtures is more useful in underground constructions with wet conditions. As crystalline admixtures (fly ash, GGBS, geo-materials, crystals, expansive materials, and chemical additives (often with high content)) were exposed to water, hydration reaction generated C-S-H gel, which seals cracks.

The self-healing concrete with fibers based on controlling crack width of the strain hardening fiber reinforced concretes with multiple micro-cracks is also suitable for underground constructions even highly initial cost. The addition of fibers enhanced the strength of concretes as well as decreased crack widths, which require less healing product for fill cracks. Moreover, fibers bridging cracks also help to attach crystallization products, which improve self-healing.

It can be interested in investigating combinations of the different approaches for further enhancements in the self-healing concrete of underground constructions. In the future, highly robust self-healing can be attained by combining bacteria and/or mineral additives in SHFRC with multiple micro-crack width control. The tensile ductility of SHFRC also can produce durability and resiliency enhancements for underground constructions.

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Contribution of authors

Viet Huy Le - methodology, writing original draft and supervision; Nhan Thi Pham - writing - reviewing and editing (preparing the content about self-healing concrete with bacteria); Anh Ngoc Pham - writing - reviewing and editing (preparing the content about self-healing concrete with mineral admixture); Tien Manh Le - writing - reviewing and editing (preparing the content about self-healing concrete with fibers). All authors are legally responsible for such information.

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