The Effectiveness of Self-Healing Agents on the Properties of Fresh and Hardened Concrete

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Abstract

The use of self-healing agents in the production of concrete has garnered great interest in the research community worldwide. This is mainly because existing concrete has several limitations in terms of strength, ductility, durability and resistance to cracking. To overcome this problem, bio-concrete is used for self-healing and additional value-added features such as high durability, increased strength and lower water absorption capacity. Concrete structures are very susceptible to cracking and repairs. This makes the maintenance of concrete structures due to cracking difficult and costly. As a possible solution to this problem, this study investigates the introduction of self-healing materials in concrete.

Keywords—self-healing, fresh and hardened properties, durability

1. INTRODUCTION

Concrete has become a major component in the construction industry and the most widely used building material in the construction industry due to its durability, cost effectiveness and high compressive strength. Concrete consists of a mixture of fine and coarse aggregates, cement and also water. The chemical compound of cement is combined with water which form a new compound that will provide concrete with durability and shear strength. The purpose of mixing aggregates into cement is to maintain dimension stability and to increase compressive strength [1].

Although cement has the capability to resist chemical attacks, weathering action and abrasion by maintaining its engineering properties, it is not immune to problems such as cracking [1]. Cracking may grow wider in concrete and cause the durability of the concrete to decrease due to the ingress of sulphate and chlorides and this leads to corrosion in the reinforcement. When the reinforcement corrodes, the structure will be damaged and may even collapse. The solution to
overcome these problems is to incorporate self-healing agents in the production of concrete. Self-healing approaches have been adopted over the last decade and have shown promising results for concrete structures.

Self-healing concrete is defined as concrete that possesses self-healing agents. When cracks occur during its life cycle, self-healing concrete will automatically heal the concrete structure. However, autogenously healing is only effective when water is available and is limited to small cracks. According to previous research, bacterial-induced Calcium Carbonate (Calcite) precipitation has been proposed as an alternative to heal cracks in concrete structures [2].

2. PREVIOUS RESEARCHERS’ PERSPECTIVES

Based on the literature review, self-healing concrete can be described in many different ways. Every researcher has his or her own explanation and perspective about self-healing concrete. Previous research studies on self-healing concrete are summarised in Table 1.

<table>
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<tr>
<th>No.</th>
<th>Perspective towards self-healing concrete</th>
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<tr>
<td>1.</td>
<td>Gradual degradation occurs until the moment where first repair is urgently needed. The concrete durability after the self-healing process is always the point of concern. The second repair is likely to be needed 10 to 15 years later.</td>
<td>Van Breugel, (2007)</td>
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<td>2.</td>
<td>The entry of moisture and other harmful chemicals into the concrete structure may result in the decrement of strength and service life. The durability of concrete often decreases due to the entry of sulphates and chlorides.</td>
<td>Rama Mohan Rao, P., (2016)</td>
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<td>3.</td>
<td>Self-healing is defined when a crack occurs in the concrete. The concrete material is able to repair cracks without human intervention.</td>
<td>Tomoya Nishiwaki, (2006)</td>
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<td>4.</td>
<td>A perfect self-healing system should be able to sense the damages or cracks which can set off the release of the healing agent. Self-healing techniques are good approaches for the rehabilitation of micro-cracks in concrete.</td>
<td>Kunamineni Vijay, (2017)</td>
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Hollow fibre has a high potential to enable concrete to self-repair. This is because hollow fibre is filled with specific chemicals that act as a healing agent and is distributed throughout the cement matrix. The healing agent will then be released into the cracks. This type of self-healing process is capable of enhancing the strength and durability of the concrete [3].

The self-healing approaches are promising techniques for the remediation of micro-cracks in concrete. All the approaches focus on improving the durability of the concrete and the self-healing process of concrete when cracks occur. Self-healing concrete can also prevent sulphate and chloride from entering the concrete. Indirectly, this can prevent the reinforcement in concrete from being corroded [4].

On the other hand, self-healing concrete system can be done with selective heating around the cracks. When a crack is generated, the self-diagnosis composite reduces the conductive part and increases its resistance around the crack. The repair agent released from the melted surface of the pipe fills up the cracks and subsequently hardens [5].

Meanwhile, bacteria-based self-healing concrete also exists in the literature. The self-healing agent should be able to minimise more micro-cracks in concrete. Bacteria and calcium can function as healing agents which target concrete cracks. Both bacteria and calcium are normally added along with the concrete mixing process. The strength of bacterial concrete has been shown to be higher than normal concrete [2].

3. SELF-HEALING CONCRETE

Self-healing concrete is defined as concrete which possesses the ability to repair small cracks autonomously. The idea of self-healing concrete was inspired by organisms such as trees or animals where the damaged skin of these organisms can be repaired autonomously. The remediation of cracks is important for the service durability and structural safety in concrete structures [6]. Recently, researchers in biotechnology and civil engineering sciences have been focusing on developing self-healing concrete technology.

In the 1980s, only a few articles related to self-healing concrete could be found and serious studies were not established until the 1990s [6]. Self-healing concrete technology that consists of several processes was proposed for the design of self-healing concrete. The processes include the natural process, the chemical process and the biological
process. Among these processes, the biological process became the latest method in designing self-healing concrete. Fig. 1 below shows all the corresponding sub-taxonomies for three key comprehensive taxonomies in self-healing concrete which are described in subsequent sections [6].

Fig. 1: A novel taxonomy for research in self-healing concretes [6]

Several reviews have been done on self-healing concrete made of natural or man-made materials [6]. A comprehensive explanation on the chemical and biological methods was included in the reviews. One of the biological methods for designing self-healing concrete made use of calcium carbonate precipitation. A comprehensive review on physical, chemical and biological processes has not yet been conducted even though several review papers on self-healing concrete have been published [7]. A comprehensive review on self-healing concrete is based on three key taxonomies which include natural self-healing, chemical self-healing and biological self-healing [6].

3.1 Natural Self-Healing Process

Four natural processes can partially repair concrete cracks. As shown in Fig. 2A, the formation of calcium carbonate or calcium hydroxide is one of the natural ways to prevent cracks from forming. Cracks can also be blocked by the impurities present in water as shown in Fig. 2B. Furthermore, cracks can be blocked by the hydration of unreacted cement particles or cementitious material as shown in Fig. 2C. Cracks can be blocked by the expansion of hydrated cementitious matrix in crack flanks such as the swelling of calcium silicate hydrate gel as shown in Fig. 2D. In many cases, more than one of these processes or mechanisms in Fig. 2A to 2D can
happen simultaneously. In fact, most of these mechanisms can only partially fill the entrance of some cracks and cannot completely fill the cracks. This will be useful to prevent the development of cracks or deep penetration of harmful chemicals such as acids into the cracks [6].

Among the proposed self-healing mechanisms in the natural process, the formation of calcium carbonate and calcium hydroxide in Fig. 2A is one of the most effective methods which can be used to heal concrete naturally. This view is supported by the fact that some white residues can be found on the outer surface of the concrete cracks. This white residue known as calcium carbonate has been widely reported by other studies such as Wu et al. (2012). The fundamental mechanisms for the formation of calcium carbonate and calcium hydroxide are represented in Equation (1) to (3). In step one, carbon dioxide is dissolved in water.

\[
H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ HC03 \leftrightarrow 2H^+ + CO_3^{2-} \tag{1}
\]

Free calcium ions are released as a result of cement hydration and dissipation through concrete as well as along the cracking surfaces. The calcium ions then react with \(CO_3^{2-}\) and HC03. As a result, calcium carbonate crystals are formed. Reaction (2) and (3) can only happen at a pH above 8 or between 7.5 and 8. The crystals grow on the surface of the cracks and finally fill the gap.

\[
Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO3 \tag{2}
\]

\[
Ca2 + HCO3 \leftrightarrow CaCO3 + H^+ \tag{3}
\]

Neville (2002) claimed that further hydration of anhydrite cementitious components is mainly due to the natural self-healing properties in concrete. However, only very young concrete applies in this case and the formation of calcium carbonate most likely causes self-healing at later ages. Natural self-healing can be useful for cracks with widths between 0.1–0.2mm (Yang, 2007).
3.2 Chemical Self-Healing Process

The chemical healing process mainly refers to artificial healing by injecting chemical compounds into the cracks. Self-healing concrete is designed by mixing chemical liquid reagents such as glue with fresh concrete in small containers. This paper explains two common chemical methods that make use of glue addition to concrete for healing purposes namely, hollow pipettes and vessel networks containing glue and encapsulated glue [9].

4. PROPERTIES OF FRESH AND HARDENED CONCRETE

A study has been made [1] to investigate the presence of effective microorganism blended cement concrete (EMBCC) as a self-healing agent on the properties of fresh and hardened blended cement concrete (BCC). One way to reduce micro-cracks and make concrete more durable is to incorporate effective microorganisms into concrete. A slump test was conducted to measure the workability of the fresh concrete. Fig. 3 below shows the relationship between the average slump and the types of mixes. The BCC mixture had a higher degree of workability and satisfied the targeted slump. Meanwhile, the EMBCC mix had a higher slump than the BCC mixture but the EMBCC slump exceeded the range between 60mm to 180mm. It can be concluded that the EM containing fly ash affected the workability of EMBCC by improving the workability of the concrete mix.
In order to test the properties of hardened concrete, the compressive strength test as well as the, flexural strength test was carried out. The compressive strength test was carried out on blended cement concrete in water (BCCW), blended cement concrete in air (BCCA), effective microorganism blended cement concrete in water (EMBCCW) and effective microorganism blended cement concrete in air (EMBCCA). The results showed that the workability of the effective microorganism blended cement concrete was higher than the blended cement concrete. However, the compressive and flexural strength of the effective microorganism blended cement concrete was lower than the blended cement concrete. This shows that the use of effective microorganism in concrete mixes do affect the properties of blended cement concrete.

Fig. 4: Modified compressive strength versus concrete age [1].
5. DURABILITY OF SELF-HEALING CONCRETE

Besides, studies on self-healing concrete and the development of self-healing coating for concrete surfaces are worth considering. The durability of concrete structures largely depends on the permeability of the concrete cover. A tight and self-repairing coating would really be a big step forward as it neutralises the scatter in the quality of the cover concrete to a large extent [10].

Furthermore, when concrete is exposed to imposed deformations such as thermal or hygral stress, the concrete may crack. Cracks may penetrate through the whole thickness of a concrete body. These cracks may jeopardise the liquid tightness of the concrete or its function as a radiation shield. Designing self-healing concrete with the potential to seal and heal these cracks require a self-healing capacity. In order to keep the production of concrete cost-effective, the self-healing agent should be affordable. The higher the cement content, the larger the inherent self-healing capacity of concrete [11]. From that point of view, high strength concrete with high cement content is considered favourable. However, from the sustainability point of view, mixtures should contain as little cement as possible. A low cement content is may be beneficial for the environment as it lowers CO2 emission but it reduces the concrete’s inherent capacity to conduct self-healing. In case low cement mixtures are required for sustainability reasons, any self-healing capacity should be realised via appropriate mixture modification.

6. DEFORMATION AND CRACKING OF SELF-HEALING CONCRETE

The basic application concept for the crack healing phenomenon in concrete using granules is developed from the autonomic healing concept in polymer composites as seen in the fig. below. Fig. 5 shows how cracking is used as a trigger for releasing healing agents into the crack surface [8].
Fig. 5: Autonomic healing concept in polymer composites [8].

Self-healing granules are manufactured in advance and will be cured in plastic boxes or bags for a period of time. After that, the granules are added to concrete mixtures just before casting to reduce the possibility of being broken under the impact of aggregates as seen in Fig. 6a. When the crack occurs in concrete and penetrates the embedded granules which are distributed uniformly in the matrix, the inner materials will be dissipated into the crack surface under the effect of water flow as shown in Fig. 6b.

Besides that, the cracks will gradually be healed and the water leakage is stopped by the formation of new products that result from reaction between self-healing materials and flowing water or other hydration products as shown in Fig. 6c. It is thought that the crack-healing capability of concrete is contributed by the combined effects of hydration/pozzolanic reactions; calcite precipitation; and the effect of swelling/expansion of the cementitious matrix.

Fig. 6: Self-healing concept in concrete using granules [8].
Based on the concept stated above, several trials of concrete incorporating various types of granules and self-healing ingredients were cast and investigated for crack-healing capability. According to Viet Hung (2013), the process can be divided into five steps and the details of each step are presented as the following:

- Step 1: Fabrication of self-healing granules
- Step 2: Casting concrete incorporating granules
- Step 3: Curing concrete specimens
- Step 4: Conducting water pass test through a penetrated crack
- Step 5: Analysing/evaluating the obtained results and giving feedback for the next trial

The durability of concrete can be increased by incorporating bio-based self-healing techniques. When cracks are formed, bacterial spores and healing agents such as calcium lactate are released from the clay particles by ingress of water [12]. The results showed that the crack healing capacity increased for wide cracks measuring 0.46 mm compared to control specimens with cracks measuring 0.18 mm after 100 days of submersion in water. This indicates that self-healing agents have the ability of increasing the durability in concrete structures under wet conditions [13].

The creation of cracks can be divided into two types namely standardised cracks and realistic cracks. In freshly formed concrete, micro-cracks caused by segregation or debris can be observed with the naked eye [14]. These types of cracks may be called standard cracks. On the other hand, realistic cracks may be formed by wrapping fibre reinforced polymer (FRP) on concrete cylinders. Tensile tests are then carried out to create cracks in the concrete specimens [15]. The impact of vegetative cells on the hydration of cement in the concrete matrix and compressive strength was investigated. Besides that, the influence of urea producing bacterial cells showed a precipitation of CaCo3 which helped in the self-healing process. Compressive strength which was similar or higher than neat mortar was observed and analysed.
Fig. 7: Images of the crack-healing process in control specimens a) before healing, b) after 100 days of healing, c) biochemical agent-based specimen before healing, d) after 100 days of healing [9].

6.1 Future Challenges

Self-healing processes such as the natural process and the chemical process are well known in the design of self-healing concrete. The biological process is a relatively young but promising technology which has not been fully understood. Until now, many bacteria can be isolated from nature that is useful for designing self-healing concrete. Bacteria are very easy to culture. The isolation of bacteria is not very complex and many methods describing the addition of bacteria to concrete are available. However, bacteria are not resistant against harsh conditions such as high pH, low level of water and high temperature. Furthermore, few articles exist on the use of fungi for self-healing concrete design. The mechanism of fungi for filling cracks or the optimum growing condition of fungi has not been completely understood. Thus, it should be further examined in future studies.

7. CONCLUSION

This paper reviewed a wide range of methods for designing self-healing concrete. A taxonomy was proposed to cover possible methods for the design, namely natural, chemical and biological methods. Chemical methods are conventional methods that have been used as the sole method to design self-healing concrete. In the literature, a brief discussion was done on all three types of self-healing mechanisms. Studies showed that self-healing by encapsulation has the potential to deliver higher quality self-healing. Several key challenges of the capsule-based self-healing system were also identified. There was also limited data on the repeatability of the self-healing process under multiple loading.

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