SELF HEALING OF CONCRETE: A REVIEW

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Abstract: *Concrete is one of the most important building materials worldwide. One problem with its properties is the low ductility. This brittle behaviour allows easy initiation of natural cracks in the structure, where the cracks introduce water into the concrete matrix which will promote corrosion of the rebar system. To prevent such deterioration, regular inspection of cracks in concrete structures and their repair are usually carried out by means of some kind of human intervention. On the other hand, for example, a small cut on our body can be healed by a simple treatment even though it takes a couple of days. To solve this problem and reduce maintenance and repair, the cracks should be closed. When these cracks are closed by the parent material itself, this phenomenon is called self-healing. In order to initiate self-healing in concrete, preconditions have to be fulfilled, i.e. sufficient unhydrated cement in the matrix, a small and stable crack width, and sufficient water for hydration. Concrete can now be engineered to have a small and stable crack width, combined with an sufficient amount of unhydrated cement. These factors will only support self-healing if water is available. To ensure this water is available inside the crack after cracking of the matrix, water should be encapsulated with a sealing material and embedded inside the matrix. There have been many recent developments in the production of more durable concrete, namely that of self-healing concrete. In this paper different types of self healing methods for concrete are discussed, including self healing with the help of bacteria, popularly known as microbial concrete. From the study, it is concluded that Crack healing of early age cracks does occur and complete recovery of strength is possible when certain conditions are fulfilled.*

Key words: Concrete, self healing, durability, crack healing.

Introduction: Concrete structures often suffer from cracking that leads to much earlier deterioration than designed service life. To prevent such deterioration, regular inspection of cracks in concrete structures and their repair are usually carried out by means of some kind of human intervention. On the other hand, for example, a small cut on our body can be healed by a simple treatment even though it takes a couple of days. In nature, animals and trees usually can heal small bodily damage by themselves.

Once cracking occurs in reinforced concrete members, not only is the stiffness reduced but steel bars corrosion also occurs due to the permeation of rain and aggressive substances, reducing structural safety and serviceability. In order to avoid the dangerous situations caused by such deterioration, application of proper maintenance systems is required. For concrete structures to avoid most such damage, the initial performance of concrete needs to be set at a high level and comprehensive maintenance systems need to be applied. This presents the drawback of higher construction cost. In the meantime, sustainability is now one of the top issues in the field of building and civil engineering from the viewpoint of global ecology. For this reason, extending the service life of structures has become a key objective. In some cases, however, it is difficult for engineers to access damaged sites for repair work because of their location and/or environmental conditions. Some examples are underground structural members, radioactive waste disposal facilities, and walls of tanks storing highly toxic waste.

The availability of self-healing and self-repairing systems would make structures more reliable. For example, if control and repair of early-stage cracks in concrete structures were possible, permeation of driving factors for deterioration could be prevented, thus extending the service life of the structures.

Concept development: The route of healing action of synthetic systems can be compared with the biological route as presented in Blaizik (2010). Biological systems respond to injury in three steps, namely inflammatory response (immediate), cell proliferation (secondary), and matrix remodelling (long-term). In more simplistic manner and mostly at accelerated rate, these processes are similarly mimicked by synthetic (biomimetic) system. Damage in material triggers the second response by which self healing agents (SHA) will be transferred into damage location, then, followed by matrix remodelling which is conducted by chemical repair. Several healing mechanisms in synthetic systems that have been tried successfully namely capsule based, vascular, and intrinsic healing techniques (Blaizik 2010). These techniques have been used for different materials ranging from polymer to ceramic, including concrete. For this research the inspiration comes from the nature of bone and of the complexity of its healing mechanism. For the sake of simplicity the complex healing mechanism of fractured bone is described as follows: When bones have fractured as part of surgical procedures or through injury it will demonstrate similar healing response and process. Immediate bleeding and blood clotting at the fracture site provides the initial framework for the next step and inflammation takes place. Then bone production replaces clotted blood with fibrous tissue and cartilage (soft callus) which later on will be replaced by hard callus. The next step is bone remodelling by which tissues become compact and take form returning to its original shape (Kalfas 2001).

Literature Review:

In recent years, intelligent materials have been extensively developed in various research fields using a new material design approach based on the concept of installing smart functions such as sensing, processing and actuating in the material itself (Science and Technology Agency 1989).

Shahinpoor (1997) reported that intelligent materials are currently defined as materials capable of automatically and inherently sensing or detecting changes in their environmental conditions and responding to those changes with some kind of actuation or action. Once the sensing function catches a change, the influence on the required performance of the structure is assessed. If the influence is not negligible, the change is repaired or improved automatically.

Achal V Mukherjee(2010) successfuly employed a bacterium Sporosarchina pastuerii and another bacteria isolated from cement, Bacillus sp. CT-5, to significantly improve the compressive strength of building materials. He observed that the microbial process increased the compressive strength by 40%. It was also concluded that microbial process lead to around four-fold reduction in corrosion rate of reinforced specimens.

Definition of terms – self-healing and self-repairing

Self-healing, or autogenous healing, of concrete and reinforced concrete is a phenomenon that has been studied by various researchers. Reviews on healing of cracks can be found for example in Lauer & Slate (1956), Jacobsen et al. (1998) and de Rooij & Schlangen (2011). Many experimental results and practical experiences have demonstrated that cracks in concrete have the ability to heal themselves, reducing water flow through cracks over time. According to a review of the literature by Lauer & Slate (1956), the action of self-healing was first discovered by the French Academy of Science in 1836, which concluded that self-healing is the conversion of calcium hydroxide exuded from the hydrated cement and converted to calcium carbonate on exposure to the atmosphere. Many subsequent researchers, however, assumed that self-healing is an action of continued hydration and other actions. Summarizing previous studies, possible mechanisms of self-healing are cited as follows (Ramm and Biscoping 1998):

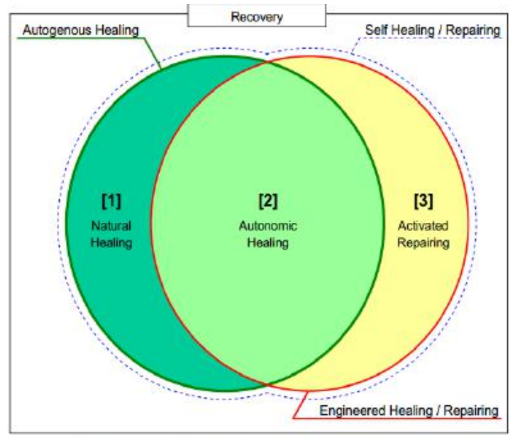
(1) further reaction of the unhydrated cement;

(2) expansion of the concrete in the crack flanks;

(3) crystallization of calcium carbonate;

(4) closing of the cracks by solid matter in the water;

(5) closing of the cracks by spalling-off of loose concrete particles resulting from the cracking.



(a) Definition of self-healing/repairing concrete (JCI 2009, Igarashi et al. 2009).

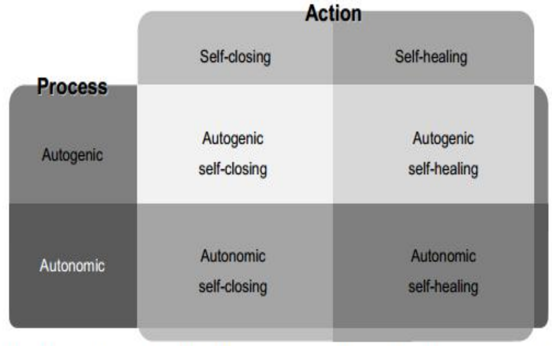
Among these five mechanisms, however, Edvardsen (1999) clarified that crystallization of calcium carbonate within the crack is the main mechanism for self-healing of matured concrete. While various techniques for engineered healing or repairing of cracks in concrete have been proposed so far, the targeted crack widths and adopted techniques greatly differ depending on the objective. For example, strength should be recovered for structural safety performance, but for durability performance, just filling cracks to prevent the permeation of water and aggressive substances is sufficient.

Moreover, the key points are the materials and mechanisms used for filling up the crack. JCI Technical Committee on Autogenous Healing in Cementitious Materials (JCI 2009) proposed the following definition of self-healing/repairing concrete:

1. Natural healing;
2. Autonomic healing; and
3. Activated repairing. Furthermore,
4. Autogenous healing covers natural healing and autonomic healing (i.e. 1+2), and
5. Engineered healing/repairing covers autonomic healing and activated repairing (i.e. 2+3).

Finally Self-Healing/Repairing covers all the actions of closing and/or repairing cracks (Fig. 1 (a)).On the other hand, in RILEM Technical Committee 221-SHC: Self-healing phenomena in cement-based materials, self-healing terms are defined based on the result of the action: “self-closing” or “self-healing”; and on the process of the action: ”autogenic” or “autonomic” (de Rooij & Schlangen 2011) Thus they are subdivided into the following four groups: (1) Autogenic self-closing: own generic material closes cracks; (2) Autogenic self-healing: own generic material restores properties; (3) Autonomic self-closing: engineered additions close cracks; and (4) Autonomic self-healing: engineered additions restore properties (Fig. 1 (b)).

Roughly speaking, previous studies on the subject can be divided into two groups: the first group focuses on the potential retaining capability in concrete (or cementitious composites) to fill cracks and some engineered technologies are installed to stimulate that capability; the second group opts to supplement a function to repair cracks, and some devices are embedded in advance for that purpose. In this report, the former approach is called "engineered self-healing" and the latter is called "self-repairing." The latter can be further subdivided into two sub-groups: one is passive mode self-repairing in which functional elements such as hollow pipes are embedded in the designed position of the structural member similarly to reinforcing steel bars; the other is active mode self-repairing in which cracking is monitored by a sensor and cracks are repaired by actuation devices only when they become wider than a critical width.



(b) Definition of self-healing concrete based on the action and the process by RILEM-TC221 (de Rooij & Schlangen 2011).

(c) Definition of self-healing/repairing concrete by the authors.

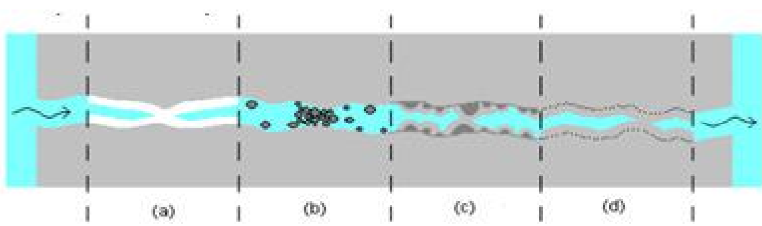
Microbial concrete in crack remediation

Use of microbial concrete has exhibited high potential for remediation of cracks in various structural formations such as concrete and granite (Gollapudi et al., 1995; Stocks-Fisher et al., 1999). Microbiologically enhanced crack remediation has been reported by Bang and Ramakrishnan (2001) where Bacillus pasteurii was used to induce calcium carbonate precipitation. Ramachandran et al (2001) proposed microbiologically enhanced crack remediation (MECR) in concrete. Specimens were filled with bacteria, nutrients and sand. Significant increase in compressive strength and stiffness values as compared to those without cells was demonstrated. The presence of calcite was limited to the surface areas of crack because bacterial cells grow more actively in the presence of oxygen. Extremely high pH of concrete germinated the need for providing protection to microbes from adverse environmental conditions. Polyurethanes wereused as vehicle for immobilization of calcifying enzymes and whole cells because of its mechanically strong and biochemically inert nature (Klein & Kluge 1981; Wang & Ruchenstein, 1993). Bang et al (2001) investigated the encapsulation of bacterial cells in polyurethanes and reported positive potential of microbiologically enhanced crack remediation by polyurethane immobilized bacterial cells.

They also studied the effect of immobilized bacterial cells on strength of concrete cubes by varying the concentration of immobilized cells per crack. Highest compressive strength was obtained with cubes remediated with 5 X 10^9 immobilized cells crack-1for 7 days while after that, increase in strength was found to be marginal.

Autogenous self-healing

In most of the traditional concrete mixtures 20-30% of the cement is left unhydrated. The amount of unreacted cement is higher the coarser the cement and the lower the water/cement ratio of the mixture. If cracking of the concrete occurs, unreacted cement grains may become exposed to moisture penetrating the crack. In that case the hydration process may start again and hydration products may fill up and heal the crack. This inherent self-healing mechanism is known since long and known as autogenous healing. This autogenous healing of cracks in fractured concrete has been noticed by the French Academy of Science in 1836 already in water retaining structures, culverts and pipes. According to Hearn the self-healing phenomenon was studied by Hyde at the end of the nineteenth century already. A more systematic analysis of healing phenomena was executed by Glanville and dates back to 1926. Already at that time a distinction was made between self-sealing and self-healing. Self-sealing was studied systematically by Hearn. Out of seven possible mechanisms four were investigated in more detail, viz. (Figure 2): a) dissolution, deposition and crystallization, b) physical clogging, c) continuing hydration and d) swelling of the cement matrix. From an evaluation of literature data and experiments on 26-years old concrete Hearnconcluded that dissolution and deposition is the main mechanism of self-sealing in mature concretes. Continuing hydration was the second important mechanism, beit more important for young concrete than in mature concrete. Hearn emphasized that concrete with the potential of self-sealing has a significantly higher “immune system” to the environment than non self-sealing concretes. This improvement of the immune system over time was considered of particular importance in view the structure’s service life.



Self healing/sealing mechanisms: a) dissolution, deposition and crystallization, b) physical clogging, c) continuing hydration and d) swelling of the cement matrix.

In all the afore-mentioned studies self-healing is considered an inherent feature of cement-based materials. This feature makes concrete a material with a lot of ‘forgiveness’. Mankind has taken advantage of this peculiar property of concrete, even though the concrete was never designed deliberately to be a self-healing material. Neither the self-healing process itself, nor the required preconditions for making this process to happen are completely understood today. As a consequence the self-healing capacity of cement-based systems is considered a positive feature of concrete indeed, but too unreliable yet to take into account explicitly in the design of concrete structures. Only a few exceptions are known where designers explicitly count on the occurrence of self-healing of cracks, for example in the design of watertight cellars or reservoirs made of reinforced concrete. To ensure that these structures will behave liquid tight the crack width should not exceed a certain crack width. The acceptable crack width depends on the pressure differential over the concrete wall or slab, the crack width and the stability of the crack. Almost no criteria for the type of concrete itself are given. This in fact demonstrates that the self-healing capacity of ordinary concretes is considered a byproduct of the material rather than a feature that could be manipulated by a sophisticated design of the mixture. Preconditions for the occurrence of self-healing in ordinary concretes are, apart from the presence of unhydrated cement and moisture, a limited crack width. The smaller the cracks are, the higher the probability that the cracks will heal. A cement-based product that is designed for a small crack width is ECC (Engineered Cementitious Composites) developed by Li et al. The main purpose for designing ECC was to make a ductile material that is able to make large excursions in the post-cracking phase.

Autonomous self-healing

Whereas autogenous self-healing can be considered an inherent feature of cement-based systems, autonomous self-healing is defined as a purposely designed self-healing mechanism. In a recent PhD thesis Van Tittelboom gave an extensive literature survey of autonomous self-healing. An often mentioned way to realise autonomous self-healing is by dispersing capsules containing either a cementitious or synthetic healing agent. This encapsulation concept has been proposed by White et al in 2001 for self-healing polymers and, as mentioned in the Introduction already, by Dry in the early nineties of the past century for self-healing concrete. On cracking the capsules may rupture, while releasing the healing agent intothe crack. This is the most common concept, but not often used in concrete yet. In case a cementitious healing agent is used the presence of water is a prerequisite for the selfhealing process to happen. The water may penetrate into a crack from external sources. Alternatively water-saturated porous lightweight aggregate particles can be added to the concrete mixture. These particles may release water when a crack occurs andmoisture gradients stimulate the flow of water. Van Tittelboom also investigated the use of small glass tubes filled with a self-healing agent. If a crack passes the brittle glass tube the probabilityit breaks is almost 100%. The internal diameter of the tubes varied from 1.71 to 3.00 mm. A problem with tubes with this diameter is their vulnerability during the concrete mixing process. Less vulnerableare healing agent containing wood fibres or glass fibers with a diameter between 30 to 100 μm as used for self-healing polymer composites. The fact that concrete is a heterogeneous materialby definition, makes that adding capsules to the mixture does not significantly change the nature of the material. As long as the capsules are not broken, their role is not much different from that of aggregates, beit that their strength and stiffness is different. The effect of adding capsules on the still uncracked concrete depends on the mechanical properties of the capsules, their size and shape and their amount. The number of capsules needed to ensure a sufficiently high probability of a crack passing a capsule depends on the size and shape of the capsules. In this respect capsules with a large aspect ratio, with cylindrical tubes as the extreme, are more effective than spherical capsules. The most appropriate agent for healing cracks in a cementitious matrix is still a matter of debate. A polymeric agent is good for filling cracks. However, as a non-cementitious material it may become detached from the crack surface. With elapse of time the polymer may be susceptible to aging which may jeopardise the long-term effectiveness of the healing process. Kishi et al investigated selfhealing of cracks by cementitious recrystallisation of an expansive agent. A cementitious healing agent requires water in order to become effective. In absence of water healing will not occur. How serious this is depends on the required function of the structure and the loading scenario's the structure has to cope with.

Improvement of compressive strength in Microbial concrete:

The applicability of microbial concrete to affect the compressive strength of mortar and concrete was done by several studies (Bang et al., 2001; Ramachandran et al., 2001; Ghosh et al., 2005; De Muynck et al., 2008a,b; Jonkers et al., 2010; Achal et al., 2011b) where different microorganisms have been applied in the concrete mixture. Ramchandran et al (2001) observed the increase in compressive strength of cement mortar cubes at 7 and 28 days by using various concentrations of Bacillus pasteurii. They found that increase of strength resulted from the presence of adequate amount of organic substances in the matrix due to microbial biomass. Ghosh et al (2005) studied the positive potential of Shewanella on compressive strength of mortar specimens and found that the greatest improvement was at cell concentration of 105 cells/ ml for 3, 7, 14 and 28 days interval. They reported an increase of 17% and 25% after 7 and 28 days. But no noticeable increase was recorded in case of specimens treated with Escherichia coli (low urease producing). This concluded that choice of microorganism plays the prime role in improvement of strength characteristics. Jonkers & Schlangen (2007) studied the addition of bacterial spores (108/cm^3) of Bacillus pseudofirmus and Bacillus cohniito concrete specimens and reported an increase of 10% in the compressive strength. Achal et al (2009a) treated mortar cubes with Sporosarcina pasteuriiand observed 17% improvement in compressive strength. Upon addition of Bacillussp. CT-5 to cement mortar specimens, 36% increase in compressive strength was reported (Achal et al., 2011b). Significant increase in compressive strength was observed at the age of 28 days as compared to earlier days. Microbial calcite might have precipitated on the surface of cells and eventually within the pores leading to their plugging which further lead to stoppage of flow of oxygen and nutrients to the cells. The cells either die or turn into endospores and act as organic fiber which enhances the compressive strength of mortar cubes (Ramachandran et al., 2001).

Effect of bacteria in Reduction of permeability:

Permeability can be investigated by carbonation tests as it is increasingly apparent that decrease in gas permeability due to surface treatments results in an increased resistance towards carbonation and chloride ingress. Carbonation is related to the nature and connectivity of the pores, with larger pores giving rise to higher carbonation depths. De Muynck et al (2008b) studied the effectof biodeposition of calcite on permeability characteristics of mortar by B. sphaericus. The presence of biomass contributed to a large extent in the overall decrease of the gas permeability. Significant differences in carbonation depth between treated and untreated specimens were noticeable after 2 weeks of accelerated carbonation in treated mortar specimens. Bacterial treated specimens were found to have better resistance towards chloride penetration as compared to untreated mortar specimens. The increased resistance towards the migration of chlorides of cubes treated with biodeposition was similar to that of the acryliccoating and the water repellent silanes and silicones and larger than in the case of the silanes/siloxanes mixture, which were all reported to be effective in decreasing the rate of reinforcement corrosion (Basheer et al., 1997; Ibrahim et al., 1997).

Achal et al (2011a) reported the decreased water permeability of bioremediated cement mortar cubes treated by Sporosarcina pasteurii. The lower permeability of the bioremediated cubes compared with that of the control cubes was probably due to a denser interfacial zone formed because of calcite precipitation between the aggregate and the concrete matrix. The penetration of water at the sides was found to be higher than that at the top. This is due to better compaction and closing of pores at the top. This demonstrated the profound effect of microbial calcite on the permeability of concrete. The same group studied the effect of Bacillus pasteurii on water impermeability in concrete cubes and found the reduction in penetration of water which was more significant on the top side as compared to sides because of better compaction and closing of pores at the top surface (Achal et al., 2010b). Sixtimes reduction in absorption of water was reported upon treatment of mortar cubes with Bacillussp CT-5 as compared to untreated specimens (Achal et al., 2011b).

Conclusion

Microbial concrete technology has proved to be better than many conventional technologies because of its eco- friendly nature, self healing abilities and increase in durability of various building materials. Work of various researchers has improved our understanding on the possibilities and limitations of biotechnological applications on building materials.

Enhancement of compressive strength, reduction in permeability, water absorption, reinforced corrosion have been seen in various cementitious and stone materials. Cementation by this method is very easy and convenient for usage. This will soon provide the basis for high quality structures that will be cost effective and environmentally safe but, more work is required to improve the feasibility of this technology from both an economical and practical viewpoints.

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