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Mimicking Bone Healing Process to Self Repair Concrete Structure

Novel Approach Using Porous Network Concrete

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Abstract

To repair concrete cracks in difficult or dangerous conditions such as underground structures or hazardous liquid containers, self healing mechanism is a promising alternative method. This research aims to imitate the bone self healing process by putting porous concrete internally in the concrete structure to create a porous network similar to 'spongious bone'. When crack is formed and detected by sensors, healing agent can be infused into the porous network so as to fill up voids and seal a crack or cracks in the concrete body. This idea was tested using cylindrical samples. A porous concrete core was placed in the center of the concrete cylinder. Uniaxial direct tensile load was applied to create cracks close to the notch of the sample. A healing action was performed by injecting healing agent manually. The results show that a macro-crack is sealed and strength of concrete is regained. Therefore, the concept is considered as to be feasible for self repair mechanism in concrete.

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Keywords: self healing concrete; porous network concrete.

1. Introduction

The fact that components of concrete, cement, sand, gravel, admixtures and additives, vary in properties, size and function make concrete a heterogeneous, complex, and brittle material. Cracking leads to a decrease of the strength and stiffness. Moreover, the presence of cracks will increase aggressive chemical ingress into concrete structures. Consequently, concrete cracks may become larger and

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reinforcement of concrete structures may be exposed to the environment that increases the risk of degradation of the materials. This will lead to declining durability and service life of concrete infrastructures. A new paradigm in materials design opens the possibilities to substantially increase the service life of concrete structures by adopting self-healing mechanism.

Along with the principle of 'damage prevention', conventional engineering has been concentrated to design and produce more robust materials. This type of materials has properties of strength and stiffness optimized to be able to avert damage formation. As natural consequences of its application, however, all material fails due to degradation or damage. Therefore, structures built based on this principle will need damage monitoring and once damage occurs, costly repair may be carried out (Tittleboom 2011).

On the other hand, through the evolution of millions of years, nature has developed appealing complex material which has self healing capacity (Bhushan 2009). These biological materials show how damage can be managed using network system of millions of neurons for sensing (sensory neuron) and actuation (motor neuron) and regulated by elegant system of signal processing. For instance, broken bones may self-regenerate and wounded skin tissues are able to heal autonomously.

Inspired by these biological materials the 'damage management concept', has been introduced by Van der Zwaag (Zwaag 2007). According to this concept materials can be re-designed in such a way that damage can be 'healed' by an autonomous process. In the case of concrete, this means that the voids made by cracks must be blocked up by new matter in order to seal the cracks, so that aggressive substances may not longer enter, and eventually mechanical properties are restored.

At Microlab TU Delft, one of the proposed ideas is to mimic nature by making novel porous network system in concrete in the form of the spongy part of the bones. This system uses prefabricated thin porous concrete cores which are placed internally in the concrete structure. In the later stage (epoxy-based)healing agents can be transferred through the interconnected pores to reach the damage zone, including micro and macro cracks, and glue the cracks surface together. The goal of the project is to create a self healing material or rather a self healing component in a concrete structure which can tackle many concrete structures problems such as; preventing leakage by forming dense barrier, blocking substance transfer through cracks by crack sealing.

2. Concept Development

2.1. Self Healing Mechanisms in Nature and Synthetic Systems

The route of healing action of synthetic systems can be compared with the biological route as shown in figure 1. Biological systems respond to injury in three steps (Blaiszik 2010), 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 transfered into damage location, then, followed by matrix remodelling which is conducted by chemical repair.

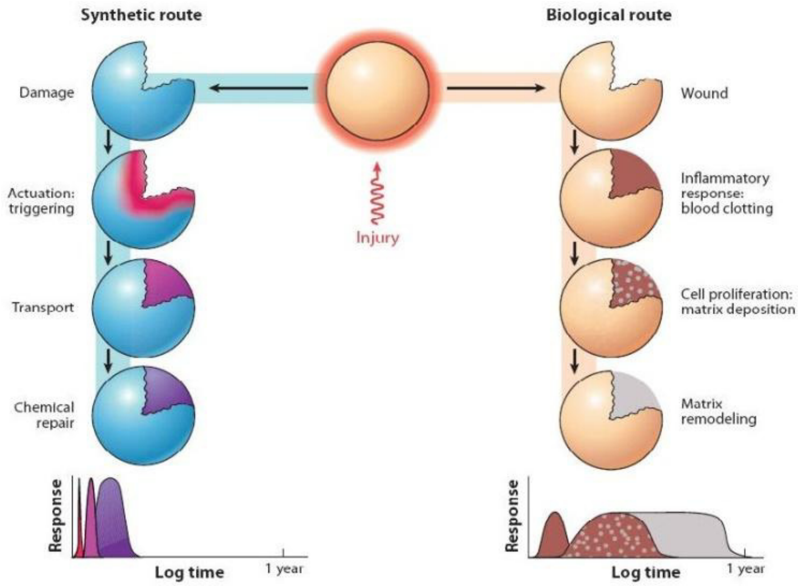

Figure 1. A comparison of self healing mechanism between synthetic and biological system (after Blaizik, 2010).

Figure 2 shows several healing mechanisms in synthetic systems that have been tried successfully namely capsule based, vascular, and intrinsic healing techniques (Blaiszik 2010). These techniques have been used for different materials ranging from polymer to ceramic, including concrete.

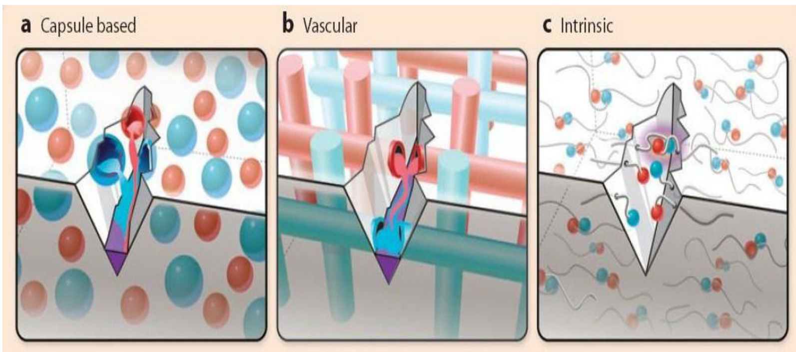

Figure 2. Three basic types of self healing techniques (after Blaizik, 2010).

2.2. *Study of Bone Morhology and its Healing Mechanism*

For this research the inspiration comes fromthe nature of bone and of the complexity of its healing mechanism. Ideas are developed to imitate the process by proposing autonomous repairing mechanisms for concrete.

Structurally, bone can be described as complex hierarchical composite material which consists of cells, fibers, fundamental substances, and different tissues in which collagen is the main structural protein. Morphologically bone can be classified into cortical (or compact) bone and cancellous (or trabecular / spongious) bone as depicted in figure 2.

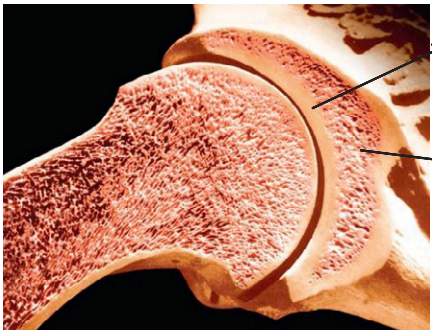

Figure 3. Longitudinal section of the humerus (upper arm), showing outer compact and inner cancellous (spongy) bone (Balbas 2010).

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).

2.3. Mimicking Bone Healing in Concrete Structures

The new self healing technique for concrete material was proposed by imitating bone morphology, that make use of prefabricated cylinder porous concrete core, which are placed internally in the concrete beam as shown in figure 4. The porous network constitutes alternate means for (1) channeling temporary or permanent materials to form a dense layer and (2) distributing healing agent to cracks in the main body.

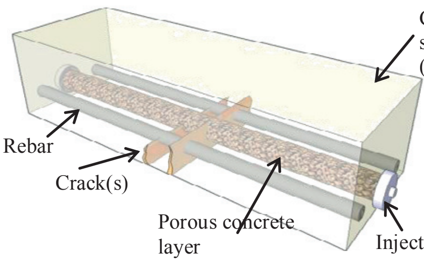

Figure 4. A conceptual design and application of porous network concrete

In general the proposed self healing mechanism concept will be carried out in an autonomous manner. This effort can be tackled by adopting intelligent materials concepts which have three basic requirements of capabilities; sensing, actuating, and adaptive controlling to the environment (Leung 2001).

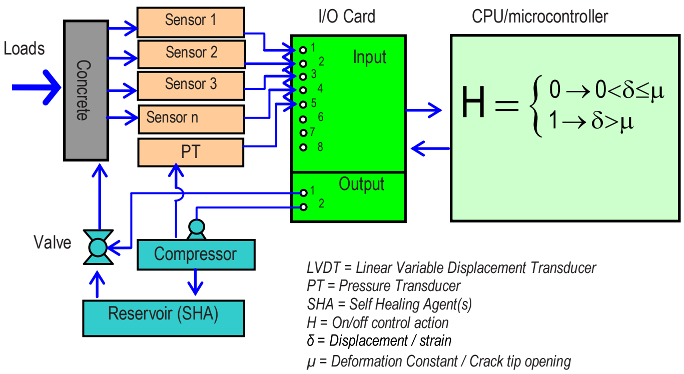

Figure 5. A design of on-off control scheme for self healing mechanisms in porous network concrete

Figure 5 shows the control scheme in this proposed self healing concrete. Damages in the concrete, e.g. cracks located in difficult area for human observation, are detected using sensors. Then data will be collected and calculated by a computer which is then triggers a signal to the actuator. This actuator will switch on a pump that injects healing agent into a reservoir through the porous network concrete layer and makes it dense and also seals cracks. This injection process will be stopped automatically using an algorithm which compares the measured parameters with ultimate or designed values.

3. General Approach and Experimental Test

To test the proposed concept in the preliminary phase of the research, the authors designed cylindrical concrete samples. In order to mimic bone structure a porous concrete core was made and placed in the center interior of solid concrete. Uniaxial direct tensile load was applied to create cracks close to the notch in the middle of the sample. Healing action was performed by injecting healing agent manually through the topside injection channel using a syringe. The setup is depicted in figure 6.

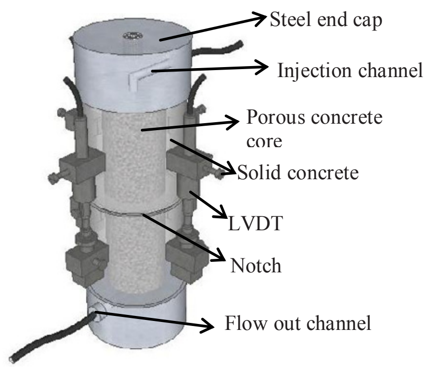

Figure 6. Conceptual design of material and method of proposed healing action

3.1 Material design

To create porous network concrete a porous concrete cylinder was used as a core. Based on the works of many researchers (Yang 2002, Mahboub 2009),porous concrete initial mix design was formulated using 2-4 mm single graded aggregate. Weight composition was 1513 kg/m^3 gravel, 355 kg/m^3 ordinary Portland cement CEM I 42.5, 22 kg/m^3 Pulverized Fly Ash (PFA) and 1.4 l/m^3 super-plasticizer with 0.28 water/cement ratio.

Porous concrete cylinders of Ø35 mm with 130 mm height were casted in PVC mould and compacted by pressing and top vibrating. After casting all samples were covered with plastic. In 24 hour samples were demoulded and cured in curing chamber(±20^{o}C, 95% RH). After seven days the samples were taken out of the curing chamber and allowed to achieve saturated surface dry (SSD) condition for 24 hours.

Figure 7. Porous concrete cynlider that would be used as porous core in PNC samples.

Achieving SSD, one sample was covered with PVA water soluble plastic and one sample was not covered. A cold water soluble plastic, SOLUBLON PVAL-film grade KA 40 micron supplied by HARKE Chemical GmbH was used in this experiment.

Afterwards the porous cylinder was put in the center of anØ56 mm PVC mould as shown in figure 8.Medium strength self compacting concrete designed based on the work of Mohammed (Mohammed 2004), was used as outer solid concrete and casted around the porous cylinder core. The samples are treated with similar curing procedure as explained above for next 7 days.

Figure 8. Casting preparation where porous concrete cylinder was placed in the center of the mould and normal strength self compacting concrete was poured around.

Figure 9 shows porous network concrete, a new hierarchical material that has been developed in which pore connection can be used as media for transportation of healing agents. Boundary between porous core and solid concrete was more obvious in the samples in which the porous core was covered with PVA film resulting in more regular circle core while an irregular boundary can be seen in samples without PVA film cover as shown in figure 10.

Figure 9. Bone-like concrete; a new hierarchical material is made in which sponge-like coreis surrounded by solid concrete.

Figure 10. a. left; more regular circle of porous core due to PVA film cover, and b. right: irregular boundary due to penetration of cement paste into uncovered porous core.

3.2 Creation of crack

At an age of 7 days, porous network concrete samples were taken out from the curing chamber and dried in an oven at 35°C for 24 hours. Then, tensile stress was applied to create a crack in the notch region in the middle of the sample height (see figure 10). The test has been done in deformation control at the rate of 0.1 μm per second until a displacement of about 200 μm was reached. Plastic sheets were placed in the top and bottom side centre of the samples to avoid glue contact between the porous core and steel end clamps, so tension was isolated to the solid concrete.

3.3 Crack healing by manual injection

At a crack opening of 200 μm the tensile load was removed. Then the samples were taken out of the instrument and healing agent was injected using syringe through the top side end cap as can be seen in the figure 12.

Figure 11. Deformation controlled tensile test.

Epoxy was chosen as healing agents explicitly to seal the crack (Schlangen 2009, Issa 2007). The healing agent consists of epoxy resin Conpox Harpiks BY 158 (liquid) and hardener Haerder HY 2996 (liquid) with weight ratio of 0.3. Fluorescent dye (powder) is used with 1% weight proportion to epoxy to help visualize pore and cracks under Ultra Violet (UV) light.

Figure 12. SHA was manually injected into porous layer at the top side.

After the injection process the samples were kept in the oven at ±35^{o}C for 24 hour. This process is carried out to ensure epoxy polymerization has taken place completely. After complete polymerization, one of the samples was tested in a second cycle under tensile loading.

3.4 Visualitation of crack healing

One sample was cut longitudinally (vertical) to see how epoxy fills pore spaces and cracks. Under UV light the longitudinal section of the samples was portrayed. Another method of visualization applied in this research is putting a sample in the X-ray µCT Scanner. 3D image reconstruction has been done using ImageJ to process image stacks, DeVIDE to reconstruct 3D image, and MeshLab to visualize the image produced.

4. Results and Discussions

Some tendencies have been recognized, although there is certainly some variability in the results obtained from the experiments due to the heterogeneous nature of the system investigated. The average load-displacement response of the cylinder tested is presented in figure 13.

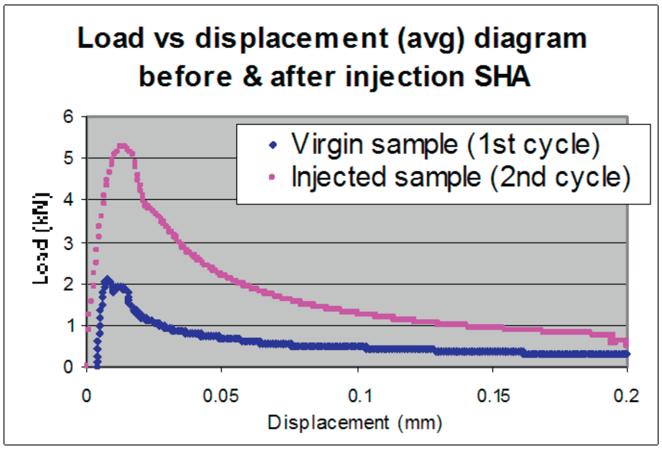

Figure 13. Deformation controlled tensile test.

It may be seen that for virgin samples there is a peak value of tensile load around 2.2 kN. It is noticed that the peak tensile load value occurs when the crack mouth opening displacement (CMOD) reach 15 µm, followed by non-linear softening behaviour until CMOD reached 200 µm when the test was stopped. Figure 14 visually confirms crack formation in the notch area of the cylinder.

Figure 14. Crack formation of concrete cylinder in the notch.

The efficacy of the manually assisted healing action of porous network concrete may be examined by comparing the mechanical response of the healed cylinder to the initial response of the virgin cylinder. The second loading cycle results in a similar load-CMOD response, but with higher peak value approximately 5.2 kN at 25 μm crack width. It may be noted that also a higher material stiffness in the linear elastic phase has been obtained which is illustrated by the diagram of the injected sample.

This apparent 'enhancement' of response in term of higher value of initial stiffness and peak tensile load occurs due to the following reasons: The low viscosity epoxy is believed flow and fills up all void spaces in the porous concrete core including crack in the fracture process zone (FPZ), hence, creating a polymer-cementious composite action which enhances the mechanical properties in the cylinder.

Visual confirmation of healed response is provided by a new crack surface formation which occurred in the cylinder. Figure 15 shows the original and final crack patterns on the side face of the cylinder and new fracture surface that shifted some millimeter away from the notched area where the previous crack was formed. It is clear from Figure 14 that in spite of the concentration of the stress built up by the notch that created the original macro-crack during the first loading cycle, the final crack occurred at a different location for the self-healing specimens. The crack at this new location was not observed to occur in the first cycle, and therefore, this is clear evidence of the effectiveness of the bonding capabilities of the epoxy when used within a concrete.

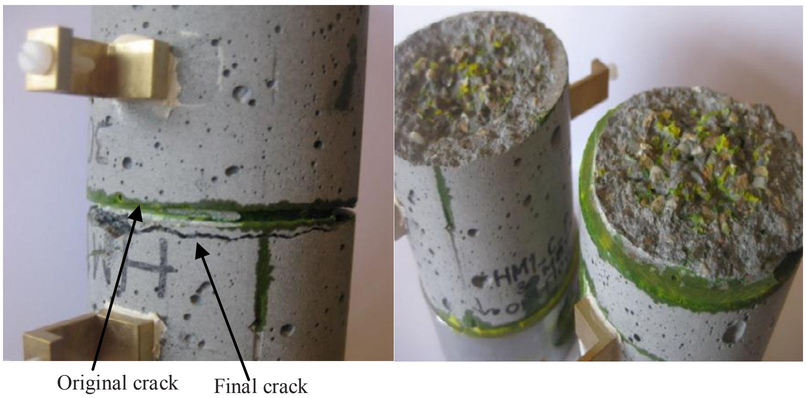

Figure 15. Deformation controlled tensile test.

Further qualitative evidence of the efficacy of the autonomic healing process is given by visual confirmation of the longitudinal section of the sample which was portrayed under UV light as depicted by Figure 16.The figure shows the different material phases in the hierarchical porous network concrete material.

Bright green epoxy polymer can be seen filling up all space including crack in the fracture process zone of the sample. It may be noticed that the boundary line between solid phase and porous concrete is visible and filled with epoxy. It can be concluded that PVA film was dissolved during or after casting the self compacting concrete. This phenomenon ensured that the porous concrete could be kept porous in the interior of the concrete structure.

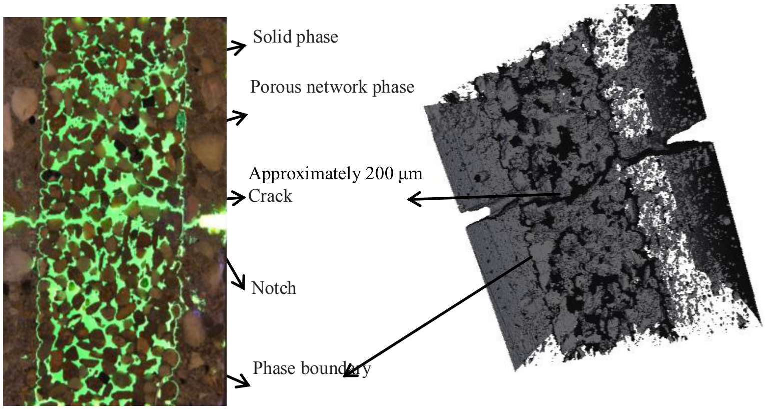

Figure 16. (a) Longitudinal cross section showing the crack which has been filled by epoxy. (b) 3D reconstruction of the vascular concrete after crack propagation.

5. Concluding Remarks

In this paper a new approach of self healing that makes use of a porous network concrete is described. This rather innovative idea mimics bone shape material and its healing process when injury happens. Prefabricated porous concrete cylinders were place internally in the centre of concrete cylinder structures, which is somewhat similar to bone in terms of morphology. Manual healing intervention at the right time and location can be done effectively. A method is proposed to turn the manual healing onto a completely automated self healing system. In addition, the authors consider that self healing agent (SHA) e.g. chemical-based, bacteria containing liquid, or cement slurry can be chosen depending on the application criteria in the practical situation.

Comparison both mechanical responses between virgin and healed samples shows clear evidence that healing has taken place using the proposed porous network concrete. The effectiveness of the novel approach is also confirmed by visual evidence provided.

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References

Tittelboom KV, De Belie N, Loo DV, and Jacobs P (2011). Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. Cement and Concrete Composite, Vol. 33, pp.497-505.

Bhushan B (2009). Biomimetics: lessons from nature-an averview. Philosphical Transaction of the Royal Society A: Mathematical, Physical, and Engineering Science, Vol. 367, pp. 1445-1486, April 28, 2009.

Zwaag SV (2007). An Introduction to Material Design Principle: Damage Prevention versus Damage Management. In self Healing Materials: An alternative Approach to 20 Centuries of Materials Science, Vol. 100. The Netherland: Springer.

Blaiszik BJ, Kramer SLB, Olugebefola SC, Moore JS, Sottos NR, and White SR (2010). Self-Healing Polymers and Composites.Annual Review of Materials Research, Vol. 40, pp.179-211.

Balbas EM (2010). Optical Techniques for the Study of Living Tissue. Doctoral Thesis Delft: TechnischeUniverstiteit Delft.

Kalfas IH (2001). Principle of Bone Healing. Neurosurgical Focus, Vol.10 , 04/01/2001.

Leung CKY (2001). Fiber optic sensors in concrete: the future. NDT and E International, Vol. 34, pp.85-94.

Yang J and Jiang G (2002).Experimental study on properties concrete materials.Cement and Concrete Research, Vol. 33, pp.381-386.

Mahboub KC, Canler J, Rathbone R Robl T, and Davis B (2009). Pervious Concrete: Compaction and Aggregate Gradation. ACI Materials Journal, Vol. 106, pp.523-528, November 1, 2009.

Mohammed S (2004). Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans. Cement and Concrete Research, Vol. 34, pp. 1199-1208.

Schlangen E and Joseph C (2009).Self healing Processes in Concrete. In Self-healing Materials: Fundamentals, Design Strategies, and Applications.

Issa CA and Debs P (2007).Experimental study of epoxy repairing of cracks in concrete.Construction and Building Materials, Vol.21, pp.157-163.