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STATE-OF-THE-ART OF BACTERIA-BASED SELF-HEALING CONCRETE

Crack appearance in the concrete structure due to the low tensile strength is inevitable and can cause degradation of the structure integrity. Bacteria addition in the concrete structure is one promising way of achieving crack healing. When bacteria concrete is used, the bacteria can be added directly in the mixture or protected in different types of materials, usually lightweight materials. Along with the bacteria, additionally nutrients and calcium source are part of the mixture, as well. As a result, calcium carbonate is precipitated in the vicinity of the crack which will fill the crack and block all the harmful substances to penetrate in the concrete structure.

Over the years, many papers are witnessing the successful work of bacteria based self–healing concrete where the maximum crack width healed can reach almost 1 mm (0.97 mm).

However, it is worth mentioning that the addition of bacteria to the concrete mixture certainly causes some complications in the preparation process and this material should be observed at a completely new level.

Based on available experimental work, a review from the perspective of encapsulation material, incubation conditions, strength, sustainability and some closely related properties are discussed.

Keywords: concrete, bacteria, self-healing, encapsulation

1. INTRODUCTION

Concrete is currently most used material globally due to the fact that is relatively cheap and available. The speed of urbanization is faster than ever and more intensive than ever. According to Justo-Reinoso et all.[6] this era might be remembered as “concrete era” for future generations. Bagga et all [2] are predicting that every month, in the next 40 years, a city big as New York will be build.

Appearances of cracks due to the low tensile strength are considered the biggest drawback of concrete. Smaller crack widths that are 0.2-0.3 mm are not considered harmful and dangerous for the integrity of the concrete structure but are allowing the harmful substances to get in the concrete structure and cause deterioration and steel corrosion, which can further lead to serious structure damage. Thereby, monitoring and control of the concrete structures must be mandatory. On the other hand, costs for maintenance are high. In Great Britain, the costs for maintenance are almost half (44.6%) of the total budget assigned for infrastructure [15]. Therefore, a compromise in between must be provided.

Self-healing concrete is created material as a reaction to the high maintenance costs and it is inspired by the ability of the human body to self-heal after injury.

Addition of bacteria into the concrete structure is just one way of achieving self-healing but is considered a successful way according to the results obtained from different experimental work. It is still considered as a material in development phase and that is why a lot of variation in the laboratory work can be observed.

2. STATE-OF-THE-ART

The concept of self-healing is known concept years back as further hydrations of unhydrated cement that can fill small cracks. Nevertheless, this way of self-healing is just a result of use the standard components of the concrete mixture. Today, the progress in the field of self-healing concrete is remarkable. The novelty in self-healing comes when additional materials are incorporated in the concrete structure in order to get planned crack filling.

Many different materials are tested as potential healing agents.

Van Tittelboom et al. [17] in their review paper presented the evolution of the published paper through the years, pointing up the publication of White et al. in 2001 as an impulse in the research area of self-healing materials.

In the last few decades, the intensity of research in the field of bacteria concrete can be noticed. The beginnings of the self-healing bacteria concrete are linked to the initial research of professor Jonkers [5]. They investigated self-healing concrete with metabolic mineral production by directly adding the bacteria Bacillus cohnii and calcium lactate to the concrete mix.

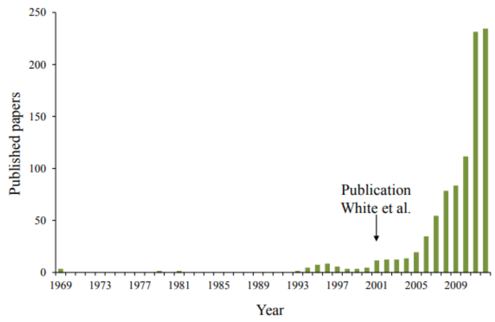

Figure 1. Scientific achievements in the area of self-healing materials through the years [17]

Particles with a size of 1-5 μm appeared on the surface of the crack on the control samples at the age of 7 and 28 days. In contrast to the control samples, in the samples that contained bacteria and calcium lactate, the size of the mineral particles that appeared were 20-80 μm, but only in the 7 days old samples. At the age of 28 days, this influence was unnoticeable. This is a consequence of the fact that survival rate of the bacteria when added unprotected in the concrete mixture is poor. As a solution to the short lifespan of the bacteria, protection is required by encapsulating the self-healing agent in protective material. In the Table 1 are presented some of the materials that are usually used as a protection material for bacteria.

Wiktor et al. [22] tested encapsulation process with the use of expanded clay. Oxygen consumption test and crack closure test after 100 days showed viability of bacteria and complete closure of 0.46 mm crack width, when samples healed full immersed in water.

Tziviloglou et al. [16] tested different healing regimes for samples healing (fully immersion in water and wet/dry cycles). Wet/dry cycles are simulating more realistic exploitation conditions for the construction. The results after 28 and 56 days fully immersion showed that regained water tightness (RWT) was 31 and 82% for Control samples, and for Bacteria samples 69% and 91% RWT after 28 and 56 days, respectively. Control samples exposed on wet/dry cycles showed very poor results to the crack closure, but bacterial samples showed 98% crack closure after 56 days of curing.

Tan et al. [9] tested different duration of wet/dry cycle (3 days wet/4 days dry). Longer exposure on air without water negatively affected the process of self–healing.

Table 1. Different type of encapsulation material, calcium source and growth media

Encapsulation material	Reference	Type of bacteria and growth media
Microencapsulation	Paine et al. [9]	Bacillus pseudofirmus Calcium acetate, yeast extract, glucose
	Wang et al. [19]	Bacillus sphaericus, Calcium nitrate, yeast extract, urea
Aerated concrete granules (ACG)	Tan et al. [14]	Bacillus cohnii, Calcium nitrate, yeast extract
Expanded perlite	Alazharie et al. [1]	Bacillus pseudofirmus Calcium acetate, yeast extract
	Paine et al. [8]	Bacillus pseudofirmus Calcium acetate, yeast extract
Expanded clay	Wiktor et al. [22]	Bacillus alkalinitrilicus, Calcium lactate, yeast extract
	Tziviloglou et al. [16]	Bacillus cohnii, Calcium lactate, yeast extract
	Risdanareni et al. [13]	Bacillus sphaericus, Calcium nitrate, Yeast extract

Generated material in the cracks is usually calcium carbonate. Bacteria can precipitate calcium carbonate through few pathways, but usually the following is required:

(1) sufficient concentration of dissolved inorganic carbon in the pore water in the vicinity of crack to enable formation of CO_3^{2-} ions,
(2) local pH change
(3) attraction of Ca^{2+} ions to the negatively charge bacteria surface, where bacteria may act as a nucleation point, and
(4) sufficient quantity of Ca^{2+} ions to precipitate calcium carbonate, Tan et al [14].
Microbially induced calcium precipitation (MICP) can be achieved through three pathways [1]:

- enzymatic hydrolysis of urea
- dissimilation of nitrates and
- aerobic metabolic conversion of calcium salts.

Urea hydrolysis is an effective way of calcite precipitation with ureolytic bacteria. Wang et al. [21] emphasised that due to the high $CaCO_3$ precipitation, hydrolysis of urea is most commonly used.

The minimum number of spores required for the self-healing process to occur was considered for the first time in the paper of Alazhari et al. [1]. Expanded perlite as 20% replacement of aggregate with 8 x 10^9 spores/g calcium acetate can provide self-healing of cracks.

Wang et al [18] used diatomaceous earth (DE) as protective carrier for bacteria. DE was considered as a successful carrier for bacteria due to the high absorption capacity. Cracks with width 0.15-0.17 mm were partially of fully closed depending on the immersion media.

Activation of the bacteria at the same moment of crack formation is important parameter for the self-healing process to occur. In order to prevented earlier activation of bacteria, separately encapsulation of bacteria and nutrients was considered by Paine et al. [10] Expanded perlite as encapsulation material was coated with dual layer of sodium silicate and Portland fly ash cement to prevent leakage of the encapsulated material.

Ceramsite as bacteria carrier was investigated by Chen et al. [4]. Separately were encapsulated bacteria and nutrients (yeast extract and sucrose). Four different mixtures were prepared, all of them with ceramsite: C1- without any addition, C2 – just glucose added, C3- Bacillus Mucilaginous and Brewers Yeast and C4 bacteria and nutrients. Test results of water permeability showed initial water permeability coefficient 7.9~8.3 x 10^{-5} m/s.

After 21 days of healing, water permeability coefficient dropped to $5.3x10^{-6}$ ~ 9.5×10^{-6} m/s for C1, C2 and C3, and for C4 the value reached 0.8×10^{-7} m/s.

Graphite nanoplateletes (GNP) compared to Light weight aggregate (LWA) were investigated by Khaliq et al [7]. Specimens were pre-cracked on 3, 7, 14 and 28 days and also observed during the 28 days healing period (3, 7 ,14 and 28 days). Results showed that specimens pre-cracked at early age of 3 and 7 days showed maximum healing efficiency when bacteria was incorporated in GNP, but at later age pre-cracked specimens with LWA incorporated bacteria showed better results. This can be explained with the fact that the process of continuous hydration make denser structure that can destroy the GNP.

Natural fiber as bacteria protection with three different type of bacteria Bacillus subtilis, Bacillus cohnii and Bacillus sphaericus were tested by Rauf et al [12] Jute, flax and coir fiber were used and among them, flax fiber showed results as the best host environment for bacteria considering the healing ability. Flax and jute fiber in combination with Bacillus sphearicus showed 95.1% and 98.4% regained compressive strength. Average surface healing on fiber concrete was 75-85% and 60-65% at 7 and 28 days pre-cracked specimens, respectively.

Wang et al. [20] used silica gel and polyurethane (PU) for bacteria immobilization. Despite the fact that the amount of precipitation material in the case of silica gel immobilization bacteria was higher compared to the polyurethane immobilized bacteria, the regained strength of samples with polyurethane showed higher values but the main reason might be the PU itself. As for the self-healing efficiency testes through water permeability test, PU immobilized bacteria showed lower values of water permeability coefficient.

Wang et al. [19] considered microencapsulation as a way of protection of bacteria. They observed maximum crack width healed in bacteria specimens of 0.97mm.

Self-healing concrete is elevating the regular concrete level in terms of sustainability by eliminating the repairing phase. However, the contribution can be even greater when using some waste materials.

Recycled concrete aggregates is good substitute material for the natural aggregate usually used in the concrete mixture. Despite the fact that natural aggregate has better characteristics, as a natural material, the resources are limited. As a carrier for bacteria and when used in reasonable amount, recycled concrete aggregate from old demolished concrete structures was considered good substitute material, showing bacteria concrete crack closure of 0.6 mm, after 28 days of healing [21].

Xu et al. [23] used rubber particle (waste rubber) as bacteria carrier. Using waste materials as a carrier for bacteria is beneficial for the environment and supports nowadays struggle of gaining sustainable materials. Two different mixtures were prepared with different size of particles, 1-3 mm (SRC-L) and 0.2-0.4mm (SRC-S). Interesting results were observed from this paper that crack width of 0.86 mm was completely healed and crack width of 0.38 mm was only 11% healed (SRC-L). This is indication that bacteria is not uniformly distributed in the concrete mixture. Also healing of specimens containing larger rubber particles SRC-L) were showing better crack closure results compared with specimens containing smaller rubber particles (SRC –S). 50% of the cracks with initial width of 0.22 – 0.86 mm were 100% healed (in SRC-L specimens) compared to only few cracks with initial width 0.22-0.54mm healed 100% (in SRC-S). This may be because bacteria have more space to grow.

Chahal et al [3] considered replacement of cement with fly ash. Cement replacement with 10, 20 and 30 % fly ash was combined with three different bacteria concentrations 10^3, 10^5, 10^7 cells/ml. After 28 days, bacteria fly ash concrete showed increase of compressive strength of 22%.

Bacteria is not only contributing to the self-healing process, but is playing an important role in the strength properties as well. Ramachandran et al [11] were among the first who investigated the influence of bacteria on the concrete strength by adding live and autoclaved bacteria. When using Bacillus pasteurii bacteria with concentration of 7.8×10^3 cells/m^3, 18% compressive strength improvement was noticed. Except live bacteria, autoclaved bacteria also showed improvement in the concrete strength properties, playing a roll of fibers.

Bacteria based self-healing concrete can consider many more aspects that are affecting the process (nutrients and calcium source effect, different temperature exposure, optimization of the process, a life cycle assessment perspective and many more). That is why this material is so long stuck in the development phase. Laboratory work are best way for testing new materials but also expensive and last long. Data modeling can be consider as a step forward in this area.

3. CONCLUSION

Bacteria-based self-healing concrete is a promising solution for maintenance of the concrete structures. Results of the experimental work, so far, are showing that micro-cracks can repair themselves and penetration of harmful substances can be prevented if proper materials are added in the concrete mixture. Bacteria-based self-healing concrete is getting huge attention due to the successful results of healing cracks up to 0.97mm. It is important to mention that with the addition of bacteria, the concrete mixture becomes more complex to work with. Directly added bacteria in the mixture cannot survive for a long period, so encapsulation of bacteria can be considered as a solution. Different encapsulation material can be part of the mixture but they are usually lightweight materials that affect the strength properties. Therefore, the quantity of these materials should be limited. Furthermore, using waste materials can contribute to the concept of sustainability of self-healing materials.

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