Self-Healing Concrete in Commercial Construction

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Crack formation is common among concrete used for all different types of construction. While cracking is inevitable in concrete, it can create instabilities that can compromise an entire building's structural integrity. New advancements are being made in the biological and engineering fields that are providing a solution to this problem. Certain bacteria and chemicals when mixed provide a reaction that creates limestone material to re-heal cracks in concrete. Using these materials to create this reaction, while incorporating the reactants necessary in concrete mixtures for building, it is possible to eliminate maintenance costs and improve building strength over time. Currently, these materials have not been mass produced for the construction market because they are still in the trial phases in many European experiments. It is my intention to discover which methods and materials have proven most effective and cost efficient. This paper will also provide insight as to why self-healing concrete has not yet seen many practical uses in the U.S. and the applications it may have in the future.

Key Words: Self-Healing, Concrete, Crack Formation, Biological, Structural Integrity

Introduction

Concrete has been one of the main building blocks of construction, dating all the way back to many of the first structures ever built. The material can withstand very large amounts of pressure without breaking giving it a large value to commercial construction contractors who primarily focus on large buildings that need to be able to hold heavy loads. However, there is a flaw in this valuable material being that it can hold up great under compression, but not so steady under tension. Tensile forces cause cracks to form throughout this material which can make the material weak as well as expose rebar and other elements inside it that contribute to its extensive strength. These cracks contribute to immense maintenance costs for companies every single year, especially for buildings located in areas of high seismic activity.

Dr. Henk Jonkers, a microbiologist at Delft University, has researched the possibility of producing a form of bio-concrete that could bring valuable benefits for civil engineering projects. Along with other colleagues from Delft he has run experiments on this new phenomenon that could have unending potential and could save millions of dollars on maintenance costs. Some concrete is already autonomous and can heal its own cracks, but the bacteria that this group proposes to incorporate has a much better rate of re-healing cracks. "The Delft group quantified autonomous self-healing of control samples and compared that to the self-healing capacity of concrete with an inbuilt bacteria-based self-healing agent. While self-healing of 0.2mm wide cracks occurred in 30% of the control samples, complete closure of all cracks was obtained in all bacteria-based samples. Moreover, the crack sealing capacity of the latter group was found to be extended to 0.5mm cracks" (Arnold, 2011).

Although Jonkers was the first to try to find a solution to the problem of concrete cracks, many different scientists have since proposed solutions with different bacteria and chemicals. Selection of bacteria depends on the survival capability of bacteria in an alkaline environment. Majority of the healing bacteria have properties that only allow them to survive in pH values of 10 or higher. This requirement has led to numerous experiments run by countless biologists and engineers. While many of them propose mixing the bacteria and mineral admixtures straight into the concrete, others propose polymer capsules filled with different solutions to be mixed into the concrete. This has created the issue of equal dispersion throughout the concrete as well as the problem of taking up more space inside the mixture and causing less strength in the original material. However, studies have shown that these polymer capsules can be equally distributed quite easily and do not take up enough space to cause any sort of strength repercussions. As different techniques are brought to testing by different scientists a trend has begun for more publications on different types of self-healing concrete as seen in the figure 1 below.

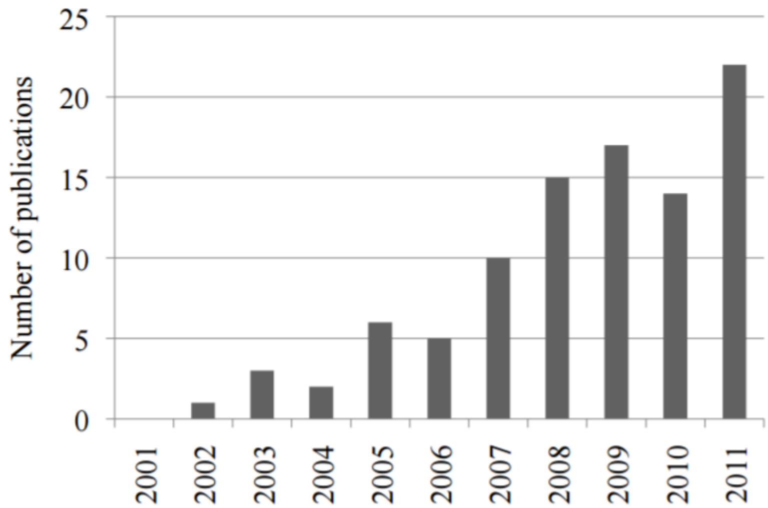

Figure 1: Number of publications on self-healing concrete from 2001 to 2011
Source of Information: Google Scholar Archives

General Background

Self-healing materials are synthetically created substances that have a unique ability to automatically repair damage to themselves without any help from humans or other outside resources. "Self-healing in cementitious materials can be classified broadly into three groups: intrinsic healing, capsule based healing and vascular healing, in accordance with approaches which originate from self-healing of polymers" (Blaiszik, Kramer, 40).

Intrinsic healing occurs when the non-hydrated cement particles receive water and become hydrated allowing them to crystalize. Intrinsic healing is usually controlled through Engineered Cementitious Composites (ECC). The main ingredients in ECCs are similar to those in regular Fiber Reinforced Concrete including; water, fiber, sand, cement and other additives. One of the biggest benefits of ECCs are their ability to take on large loads after cracking begins while still undergoing significant deformation. ECC fibers work with the cementitious matrix to keep fractures minimal in size and equally dispersed. This helps the concrete to keep the cracks small enough to the point where water can get in and hydrolyze the dry cement particles to start creating more material for self-healing.

Capsule based healing occurs when capsules that are embedded in the concrete rupture and a self-healing mechanism is released that either reacts with air, or another reactant that is embedded in the concrete matrix or other capsules. Capsules can either incorporate chemicals or bacteria for self-healing. The benefit of bacteria is that certain bacteria can live for years without anything else inside the capsules while many chemicals lose their healing capabilities over time without a reaction. Figure 2 below shows the many different shapes and combinations that can be used in capsular healing. Capsules that are cylindrical as opposed to spherical have shown to have better rates at healing because they can take up larger areas and be built at higher lengths. However, if the capsules line up the same way as cracking, then they can have less of an effect so it is important to watch for during mixing and more so setting. Capsules can be made of polymers, glass, clay and other materials but polymer capsules have proved to be most efficient and successful throughout mixing and placing concrete. As seen below once the crack occurs the external reactants either water, air, or heat can get in and start the reaction.

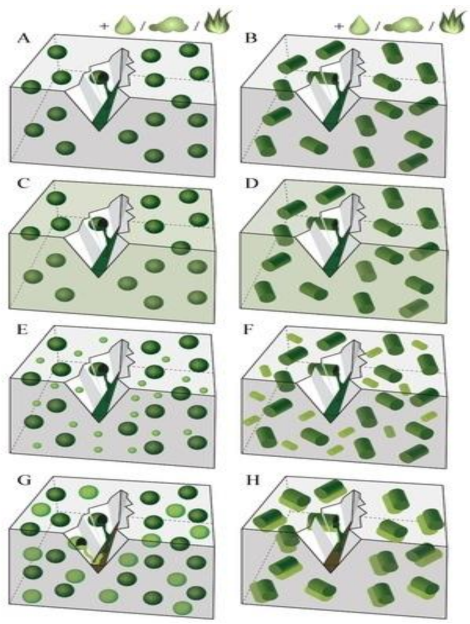

Figure 2: “Capsule based self-healing approaches. Leakage of healing agent from the capsules into the crack due to gravitational and capillary forces. Reaction of spherical/cylindrical encapsulated agent (dark colored inclusions) upon contact with (**A**, **B**) moisture or air or due to heating; (**C**, **D**) the cementitious matrix; (**E**, **F**) a second component present in the matrix (small, light colored inclusions) or (**G**, **H**) a second component provided by additional capsules (big, light colored inclusions)” (Van Tittelboom, De Belie, 2013).

Source of Information: Self-Healing in Cementitious Materials – A Review; Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering, Ghent University (Van Tittelboom, De Belie).

Vascular based healing occurs when a system of tubes filled with the healing agent run through the concrete from the interior of the building to the exterior of the building. There can be one channel or multiple channel vascular healing systems depending on different factors such as; number of healing agents, building shape, concrete strength, etc. The main problem with vascular based healing is that it is not as pervasive because the tubes must be placed in certain locations where cracks are anticipated to occur.

Biological Self-Healing Agents

The microbial hydrolysis of urea, or small scale water reaction with urea can generate calcium carbonate which is also known as limestone. This reaction is sped up due to an unreleased enzyme in the urea and carbonate and ammonium ions are produced as a result. Each mole of urea results in the formation of two moles of ammonium ions and one mole of carbonate ions. Finally, the reaction of the produced carbonate with calcium forms the creation of limestone precipitate amongst the microbial cell walls. Figure 3 below represents the process by which the hydrolysis of urea creates calcium carbonate spreading out from the cell walls.

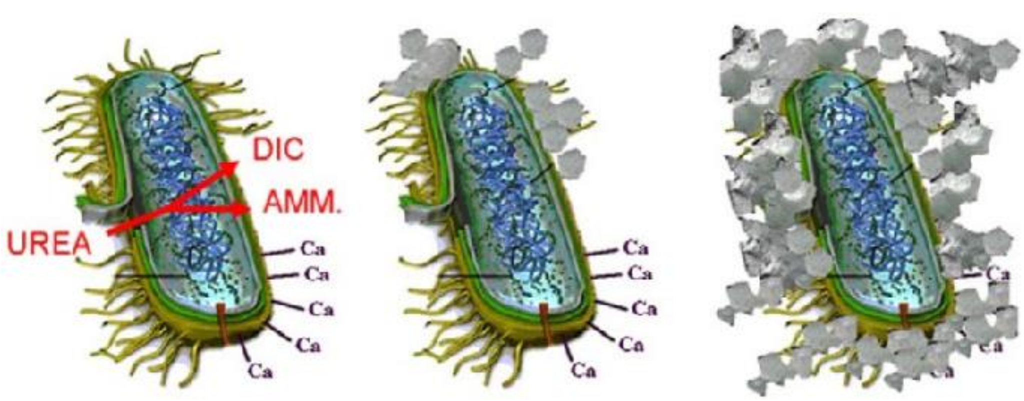

Figure 3: Schematic overview of the ureolytic carbonate precipitation occurring at the microbial cell wall. DIC: Dissolved Inorganic Carbon; AMM: Ammonia 10

Source of Information: Silva (2015). Journal of Commercial Biotechnology p. 33

Although many micro-organisms can rapidly hydrolyze urea and lead to fast production of calcium carbonate, the ones most closely related to bacillus sphaericus have proven most effective and have produced the largest quantities of calcium carbonate. While these micro-organisms are clearly the most effective and have given the best results, they are not necessarily the most cost effective. In fact, they prove to be the most expensive solution when compared to the ureolytic bacterial mixed culture method. In a direct quote from the journal, we see this higher cost being an obstacle that is preventing the spread of mass production of this healing agent. "However, to bring such self-healing agent to the market, some practical aspects should be taken in consideration. The use of pure bacterial cultures with high specific ureolytic activities has considerable importance when related to fundamental research but, generally, these axenic pure cultures, represent a high cost for industrial application" (Silva, 2015).

Green Basilisk

Green Basilisk is a TU Delft spin-off company that was created in cooperation with Jonkers and other Delft members to bring their patented technology to the international market. This company uses biological self-healing agents which consist of bacteria in polymer capsules or mixed into the concrete. The company carries three products; a healing agent for concrete mixtures, a self-healing repair mortar, and a liquid repair spray. Instead of selling these products, Green Basilisk licenses the technology to construction companies to avoid any possible misapplications of the concrete. For information on these different products view the product brochures in the extra notes section of the project folder. A graph below shows the promising strength capacity that bacterial concrete has compared to conventional concrete. As can be seen from the data, the compressive strength of bacteria concrete had a significant strength advantage throughout all days of testing.

S.No.	No. of days	Split tensile strength of conventional concrete cylinders, N/mm^2	Split tensile strength *B. sphaericus* concrete cubes, N/mm^2	% increase in Strength
1.	3	3.78	4.30	13.75
2.	7	4.62	5.28	14.28
3.	28	4.85	5.74	18.35

Figure 4: Comparison of compressive strength of conventional concrete and bacterial concrete

Source of Information: Peruzzi R, Poli T, Toniolo L. The experimental test for the evaluation of protective treatments: a critical survey of the capillary absorption index. J Cult Herit 2003;4(3):251–4.

The company has a large project portfolio following several of the different projects that the self-healing products have been used in. One parking garage in Apeldoorn Netherlands was treated with the liquid repair spray and yielded great results. An area of approximately 12,000 square meters was treated with the liquid spray. Then, the floors were tested to check that self-healing had occurred. "The water penetration rate was determined in accordance with a protocol defined by the registration of the number of continuous drops per minute. A typical outcome was determined by decrease of about 45 drops per minute per crack (0.2 to 0.3 mm wide) before treatment, to a single drop per minute approximately four months after treatment" (Green Basilisk). This shows how effective the product was at re-healing the pre-existing cracks in the concrete structure. The self-healing spray was so effective that the owner of the garage had the rest of the structure treated as well.

Another aspect of interest this company has are its many partner companies all around the world. The company has 7 partners that provide their product for use to companies in the regions surrounding them. The areas these partners serve are; South Korea, Japan, Germany, Singapore, Portugal, China and Belgium. These partners also sell other concrete sealing and healing products but all of them focus on using natural ingredients to help mitigate environmental effects of concrete production. It would seem to be a good idea for someone from North or South America to partner with this company to sell their product over here, but unfortunately the cost of shipping the product and the liability of ensuring that companies used it correctly from such a large distance away presents too much risk. If scientists in America could find a way to create a similar product and start licensing it, this could have immense values in the fields of infrastructure and underwater concrete structures.

The biggest problem currently, seems to be the price of the product which costs about twice as much as regular concrete per cubic meter. The reason it is so much more expensive is because of the calcium lactate nutrient for the bacteria to feed on, but Jonkers hopes to soon find a different sugar based nutrient that can be substituted to reduce the costs significantly. If the Green Basilisk team could find a substitute that could start the reaction upon cracking, as well as not require the assistance of water or air to start the creation of calcium carbonate, the product would be much more marketable. Once this sugar based substitute ingredient is found and is less expensive, prices are expected to drop almost to the cost of regular concrete. When this breakthrough occurs, Green Basilisk will have many more investors knocking on the door to start partnerships.

Xypex

Another popular concrete admixture with self-healing properties that is actually used by contractors in America currently is Xypex. Xypex is a chemical admixture that can be added to concrete and will expand a crystalline structure when water is added in the mixture process. The only problem with this mix is that it uses chemicals instead of natural bacteria, and it forms the crystalline structure when the concrete is mixed to be placed. This leaves potential for unhealed cracking after the concrete is set and the product data states that even when it does heal cracks it can only heal cracks up to 0.4 mm. This mixture is more of a waterproofing admixture than a self-healing one, purely based off its use largely in underwater structures and its crystalline expansive material that is aimed at blocking water leakage through pores. More information for this product can be found on the product data sheet for Xypex in the extra notes section of the project binder.

Although this material is similar to the bacteria based self-healing technology in that it is aimed to help seal the concrete, it is hardly able to compare to the bacteria based technology's ability to heal cracks of size 1 mm as well as their ability to lie dormant in the concrete for up to 200 years before being called upon to react and create limestone healing. Another problem with these integrated admixtures is that they lose much of their healing ability during the concrete mixing phase. For these main reasons as well as structural capabilities, encapsulated bacteria based self-healing is more effective than this material.

Self-Healing Concrete and the Market

While there are many admixtures similar to self-healing concrete being used in the U.S. on the market currently, these products are aimed more at waterproofing and do not have the same capabilities that biological or intrinsic self-healing concrete has. While biological self-healing concrete is spreading into the market over in Europe, it is failing to make a successful beginning to the construction market over here in the U.S. Intrinsic self-healing concrete seems to also be experiencing trouble getting pushed to the U.S. construction market as well.

After conducting a survey on self-healing concrete amongst many contractors, subcontractors, and concrete suppliers, some of the key reasons this product isn't being widely used have come to light. First, the price for the material per cubic yard of concrete is basically double the normal price. Next, the reactions that happen to create a material to fill in the cracks could be releasing harmful products into the air. After interviewing a Project Manager at a large commercial contractor in the Bay Area she was concerned about the environmental effects saying, "Should these bacteria be introduced in greater than natural concentrations into buildings or waterways (tunnels)? Is it safe or are there potential adverse effects? In the age of indoor air quality, eliminating pollutants, and reducing volatile organic compounds and other potentially harmful additives from construction products, has the impact been evaluated?" (Trina Warren, Devcon Construction Inc.). Also, self-healing concrete has not undergone sufficient testing for the product's worth to be ensured. Many of the commercial contractors shared the opinion that the cracking of concrete didn't make as big of an impact on structural integrity in commercial projects but might have a bigger impact in heavy civil structures. "Concrete cracks. It is a known property of the material, and it does not adversely affect the life of a building structure for its intended use. Concrete can last for decades without losing its structural properties if it is kept in the proper environment. It seems to me that self-healing concrete is more suited for infrastructure such as bridges and highways" (Anonymous Survey Respondent). Another aspect of this phenomenon that was questioned by contractors was will this addition of self-healing ingredients to the mixture have an impact on workability or strength of the concrete mix? Furthermore, when the cracks are sealed back up the material inside the cracks might not even retain the same or significant structural capacity.

One of the biggest reasons that this product hasn't made waves in the commercial construction market is that when a building is being built, the contractor and owner are trying to turn it over quickly to a user who then intends to occupy the building in the near future. Usually projects that commercial contractors work on have a certain life-span and concrete can maintain its structural capabilities throughout that time. Self-healing concrete will be most beneficial hitting the market for projects such as bridges, tunnels, and highways where maintenance and repair costs are extremely costly and the structures need to retain structural integrity over a long time period.

Methodology

The methodology for this research project consisted of the following:

- Comparing the different techniques used to create self-healing properties in concrete
- Discovering through a cost/benefit analysis which method is most feasible
- Discovering test and sample projects that use this method in their concrete
- Reaching out to the company Basilisk Concrete in the Netherlands for cost applications and successful projects with self-healing concrete (first company to bring products with microbial bacteria self-healing applications to market)
- Surveying several concrete subcontractors in the U.S. to discover any flaws in design or reason the product hasn't surfaced in the U.S. construction market
- Providing a recommendation to contractors and subcontractors as to whether investing in this product would be beneficial

My methodology was primarily qualitative with some quantitative information from the product's pricing and cost analysis. My most applicable source for data on this subject was the company Green Basilisk Concrete which is a spinoff company created at Delft University from the biologists and engineers that designed the first successful self-healing concrete. Also, the insight I received from concrete subcontractors as to why the U.S. hasn't caught on to this product in the industry was extremely beneficial to my analysis.

Survey Results and Analysis

A survey yielded some results that help to give an idea on what contractors, subcontractors, and concrete lab technicians see as being the largest barriers for self-healing concrete hitting the U.S. building market. However, many of these participants did not feel that they knew enough about self-healing concrete because it is such a new and untested method so they instead gave live feedback on what they thought they could contribute on the topic from their expertise in the industry. When asked what they considered as the main reason for self-healing concrete not being as largely used in the U.S. vs. Other Countries, about half of them chose higher material price and the other half chose minimal proven product testing. One response to an open-ended question about thoughts regarding the logistics of this topic returned the answer, "Self-Healing Concrete seems to have minimal applications due to its problematic areas such as; workability, strength, indoor air quality and lack of proven testing" (Anonymous Survey Respondent). Another question asked, would commercial sale of a self-healing concrete solution be valuable to the industry in your opinion? This question yielded an astounding 95% choosing yes with a few of the responses adding that they would only see it valuable if the price was brought down to be comparable to regular concrete.

Also, it is important to note that after reaching out to about twelve different concrete suppliers, only three of them had sufficient knowledge of self-healing concrete or could find anyone in the company that had extensive knowledge to share on this topic. This shows that there are still much more tests to be run before this product can hit the market for commercial sales in any field of construction in the U.S.

Conclusion

The information provided by literature on self-healing materials, as well as the ideology and opinions of those in the construction field here in the U.S. have provided several conclusions on the direction of self-healing concrete for future applications. First, the use of capsule based healing seems to have much more promise going forward due to its abilities regarding; healing larger cracks, staying protected during mixing, requiring less external requirements to start reacting, and regaining full strength. Whereas the abilities of intrinsic healing and vascular healing have limitations in movement, curing abilities, workability, and structural efficiency. Also, the abilities of chemical and bacterial encapsulated self-healing are extremely similar, but bacterial seems to have better ability at healing larger cracks. Chemical self-healing also does not have as long of a lifespan after being mixed into concrete compared to the almost 200-year lifespan of bacterial healing. Furthermore, after gathering opinions from those in the field, self-healing concrete seems to be still in the testing and trial phases and has not entered onto the market in the U.S. Many believe it is on the verge of a large breakthrough but that this product would best be suited for tunnels, highways, and bridges as opposed to residential or commercial construction.

For these reasons, it would be recommended that going forward self-healing concrete be extensively tested in only polymer capsulated solutions. Also, it is recommended that the testing of these solutions be carried out by interdisciplinary parties including biologists, engineers, construction and concrete quality technicians to provide a solution that is viable in all areas including, strength, environmental impact, cost efficiency, and workability. At this current time my recommendation to concrete suppliers in the U.S. as well as contractors and subcontractors would be to not invest in this product until there have been more tests and projects completed that include self-healing concrete. Going forward it would also be recommended that only heavy civil builders that work on bridges, highways, tunnels, and marine projects with long life-spans consider investing in this project in the near future due to its promising applications in this area as opposed to the commercial and residential construction markets.

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