THE APPLICATIONS OF BACTERIAL SELF-HEALING CONCRETE AS A WATER IMPERMEABLE BUILDING MATERIAL

Alexis Korenoski alk226@pitt.edu, Dylan McGettigan dpm56@pitt.edu, Natalie Steibel nas246@pitt.edu

Abstract*—Concrete is the most widely-used building material in the world, with a potential lifespan of 50-100 years. However, water seeping into cracks in the concrete lowers its pH and causes metal supports to oxidize. Over time, this oxidation compromises the structure's strength. To mitigate damage caused by these cracks, structures are currently built larger than necessary. This leads to an increase in the amount of material required and, therefore, higher construction costs. Concrete by nature is difficult to recycle, and researchers have determined that recycled concrete retains only a fraction of the parent concrete's compressive strength. Additionally, the production of cement, a component of concrete, releases high amounts of carbon dioxide into the atmosphere. These factors suggest a need to reduce the production of concrete and increase its lifespan.*

This need can be met by implementing bacterial self-healing concrete in structures where water exposure is an issue. This special type of concrete utilizes dormant bacteria to repair cracks that would normally require human intervention. Bacterial self-healing concrete is currently being researched by Dutch scientists Erik Schlangen and Henk Jonkers. They have created the world's first structure, a lifeguard stand, comprised entirely of the material. This structure provides data from the concrete's performance in real-world conditions. Using data from this structure and other material trials, this paper will show how self-healing concrete has potential to revolutionize the construction industry by increasing the life of concrete structures, reducing repair costs in some applications, and lessening concrete's negative impact on the environment.

Key Words—bacteria, calcium carbonate, concrete, environment, self-healing, sustainability

INTRODUCTION: CONCRETE AS THE BUILDING MATERIAL OF THE WORLD

Concrete has been used as a building material for thousands of years since the invention of the concept by the early Romans. Modern day concrete composed of Portland cement was discovered in the early 17th century. This material is a mix of various minerals and compounds, such as fly ash, clay, calcium, and silica. These materials are mixed together with water, then poured and left to harden. The readily available ingredients and molding process have enabled people to utilize concrete in structures of all shapes and sizes, from backyard patios to the foundations of skyscrapers.

Concrete by itself is not suitable for the construction of large structures that are under stress from multiple directions. Alone, it has an extremely high compressive strength, but relatively low tensile strength. To remedy this, most modern concrete is reinforced with steel mesh or bars (rebar). Reinforced concrete has emerged as the most-widely used building material in the world. According to Patel, a writer from the journal 'Chemical & Engineering News', "The world produced 4.3 billion metric tons of cement in 2014" [1]. This cement is the main component of concrete. Nearly all man-made structures make use of this versatile material. It is used in the foundations of buildings, piers of bridges, and as a component of sidewalks and highways. Furthermore, concrete can be made with admixtures such as epoxy that make it resistant to harsh environments. Concrete is used in sewers and oceans where it endures a relentless harsh chemical attack from sulfates and hydroxides. Despite all that concrete can endure, the most common reason for its deterioration is water ingress. Water causes oxidation of the iron in steel reinforcement, damaging its strength and subsequently the strength of the entire concrete structure. In addition, when water freezes and thaws it can split large cracks in the structure. Both processes have caused severe deterioration of the concrete that comprises such a significant amount of the world around us.

A Concrete Crisis

Concrete is used in many places, and evidence of concrete decay can be observed anywhere the material is found. Concrete is highly susceptible to cracking due to its porous nature, and developments in its composition have increased its strength but done little to fix the tendency to form cracks. These unavoidable fissures allow water to rust the steel in the concrete, forming stains on the surface. The visible rusty orange stains are so called 'concrete cancer' and there is no cure. Once water seeps into the structure, exposed steel begins oxidizing at a faster rate. The concrete must be manually repaired quickly, because if it is left untreated, the chemical oxidation can deteriorate the reinforcements to the point of failure.

Because concrete is costly to repair, in some cases it is more cost-effective to demolish the structure and build a new one. Concrete is difficult to recycle. It requires grinding the old material and using it as aggregate in new concrete. As Akbarnezhad points out in his work on the properties of recycled concrete, the new concrete experiences "A proportional increase in Los Angeles abrasion loss with mortar content due to breaking of mortar into powder during the test" [2]. The Los Angeles abrasion test measures the ability of a material to resist being crushed and degraded. A sample of concrete is placed in a rotating drum with steel spheres for a designated amount of time. Then, the resulting crushed concrete is passed through sieves to determine how much of the concrete disintegrated to different ranges of particle sizes. Akbarnezhad tested recycled concrete compounds of various compositions, to conclude that the recycled concrete does not retain the strength properties of the parent. This difficulty of recycling leads to the build-up of concrete in landfills around the world.

Nevertheless, people still produce billions of tons of concrete every year. The production of cement is not the most sustainable process either. According to Patel, "Cement production creates roughly 9.5% of global carbon emissions" [1]. In recent years the global carbon levels in the atmosphere have reached record highs, with nearly ten percent of the emissions due to cement production. Reducing the production of cement would decrease the amount of carbon dioxide released.

It is unlikely we will be able to prevent concrete from cracking because it is used in such harsh environments. According to Nele De Belie, a researcher of the durability of cement materials and structural engineer, "The appearance of small cracks (<300 μm in width) in concrete is almost unavoidable, not necessarily causing a risk of collapse for the structure, but surely impairing its functionality, accelerating its degradation, and diminishing its service life and sustainability" [3]. These factors and the inevitability of cracks described by De Belie suggest a need to reduce repairs by solving the problem of cracks. This reduction of damage would lead to less demolition and less concrete production, and therefore a more sustainable solution for one of the world's most common building materials.

The Current Solution

To remedy the issues described above, engineers have developed multiple strategies to prevent concrete from cracking. The first method is traditional manual repairs. This involves filling the cracks, patching them, or breaking away damaged concrete and setting new material. According to Filipe Bravo Silva, a concrete researcher at Ghent University, "Until now, applying some compounds either to fill the cracks, such as epoxy resins, or to prevent the formation of these cracks, such as plastic polymers applied on the surface of the concrete, are the common ways to improve and/or extend the life of concrete structures. However, for both processes, human interventions are required leading to an added cost in labor work. The cost for crack injection in tunnel elements can be estimated to be of the order of €130 ($147) per m^3 of concrete" [4]. Bravo Silva describes how it is a costly process to patch a crack. Patching is not a permanent fix, as the rebar has already begun to oxidize once the water has seeped into the concrete.

Another practice used to prevent water ingress is to 'over-dimension' structures. This involves building with thicker concrete to prevent cracking that extends deep enough to damage the steel reinforcement. Microbiologist Henk Jonkers and civil engineer Erik Schlangen are two Dutch scientists working on the development of bacterial self-healing concrete. They note that over-dimensioning is a negative result of using traditional concrete. They describe the process as follows: "To prevent cracks in structures, many companies build the concrete thicker, but this causes over-dimensioning of structures, and this is costlier to pay for more building material" [5]. By over-dimensioning structures today, we are increasing the need for cement production and simultaneously the volume of concrete demolished. Neither manual repairs nor over-dimensioning offer permanent and cost-effective solutions to the problems caused by water ingress.

BACTERIAL SELF-HEALING CONCRETE

One material that is resistant to the inevitable cracks is bacterial self-healing concrete. This technology utilizes dormant bacteria sealed in capsules in the concrete matrix. As described by Jonkers and Schlangen, "Self-healing concrete can repair itself by closing micro-cracks and thus protect itself from ingress of deleterious gasses and liquids that can affect its durability" [5]. The water ingress activates the bacteria to produce calcium carbonate (also known as calcite or limestone) which fills the crack. By filling the crack quickly, this concrete prevents larger cracks from forming and stops further oxidation of the steel supports.

History

The idea of self-healing concrete was first developed in the early 1990s. The concept branched from the idea that concrete without admixtures or biological healing agents is capable of healing itself. This process occurs very slowly and not to the extent needed to recover water-tightness. Researchers began testing ways to speed up the process. Carolyn Dry, an architecture professor at the University of Illinois at Urbana-Champaign, was the first to seriously consider the idea. She proposed including glass capsules in the concrete that contained methyl methacrylate glue that would be released when the capsules were broken. However, the glue was too viscous to flow fast enough to fill cracks and the glass capsules would not survive the concrete mixing process [1]. Others have tried healing mediums in concrete such as polymers, gels, clays, waxes, and films to varying degrees of success. In the mid-2000s, Jonkers and Schlangen began to research encapsulated bacteria as a biological healing agent. All these proposed methods had the same idea, as described by Patel: "The trick to making self-repairing concrete is to heal microscopic fissures before they become large cracks" [1]. After success in the lab, Jonkers and Schlangen have constructed the world's first building of their bacterial self-healing concrete that operates by the mechanism Patel describes. This building provides them with important data on how the material performs in real-world conditions.

How it Works

The mechanism of bacterial healing begins when water seeps into a crack formed in the concrete. Many cracks start off as microscopic fissures, and this is all the bacteria need to activate. A few types of bacteria are suitable for applications in self-healing concrete, including *Bacillus pseudofirmus*, *Bacillus cohnii*, and *Bacillus sphaericus*. The bacteria are embedded into the concrete matrix inside 'spores', or spherical capsules filled with calcium lactate which serves as a food source for the bacteria when they are activated. The bacteria can survive in the concrete matrix for over 200 years, and they can be reactivated multiple times if the healed area were to crack again [5]. When the concrete cracks, it ruptures the capsules, allowing water to activate the bacteria. This water catalyzes the decomposition of urea and formation of calcium carbonate according to the following reactions:

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \qquad (1)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \qquad (2)$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^- \qquad (3)$$

$$2OH^- + H_2CO_3 \rightarrow CO_3^{2-} + 2H_2O \qquad (4)$$

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \qquad (5)$$

$$CO_3^{2-} + Ca^{2+w} \rightarrow CaCO_3 \qquad (6)$$

FIGURE 1 [4]
Chemical equations for the microbial hydrolysis of urea (1-5) and formation of calcium carbonate (6)

Figure 1 shows the six reactions from the hydrolysis of urea to the precipitation of calcium carbonate. The process can be summarized by the following excerpt from Jonkers and Wang, in their paper on the applications of *Bacillus sphaericus* in self-healing concrete. "Bacterial urase can catalyze urea hydrolysis. Urea is decomposed into ammonium and carbonate ions resulting in an increase from neutral pH to a value of about 9. In the presence of calcium ions in the surroundings, calcium carbonate can be formed" [6]. This calcium carbonate accumulates to seal the crack. The other compounds produced in the process include ammonium ions, gaseous ammonia, carbonic acid, and water.

The precipitation of calcium carbonate occurs according to the following figure from page 199 of Jonkers' work *Self-Healing Concrete: A Biological Approach.*

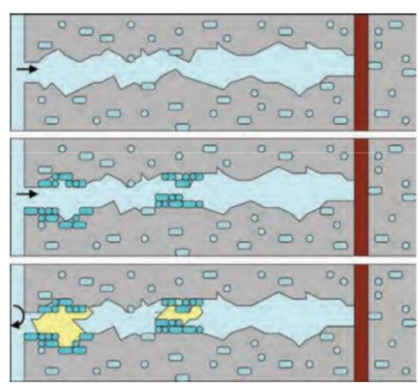

FIGURE 2 [7]
Diagram of bacterial self-healing concrete producing calcium carbonate to prevent water ingress

Jonkers describes this visual as follows: "Scenario of crack-healing by concrete-immobilized bacteria. Bacteria on fresh crack surfaces become activated due to water ingression, start to multiply and precipitate minerals such as calcite ($CaCO_3$), which eventually seal the crack and protect the steel reinforcement from further external chemical attack" [7].

Figure 2 clearly shows how the bacteria multiply to produce calcium carbonate, which eventually allows the structure to recover water-tightness. Note the arrows on the left of the figure indicating the ingress of water. By the time the calcium carbonate has precipitated (yellow) the water can no longer enter the structure to oxidize the steel reinforcement (brown).

This calcium carbonate is an ideal material for repair because it consists of compounds found naturally inside the concrete matrix. According to De Belie, "Limestone formed inside the matrix of concrete can result in densification of the matrix through filling of pores and can contribute to self-healing of cracks, decreasing its (water) permeability and leading to a regain of lost strength" [3]. These properties have been tested and proven in the lab, as well as in the first real-world application in the form of a lifeguard stand

The Lifeguard Stand

Jonkers and Schlangen were the first to take bacterial self-healing concrete out of the lab and into the elements. They built a lifeguard stand in the Netherlands using the material. They have observed the formation of cracks in the structure, and according to Patel, "These cracks filled up with limestone as expected, keeping the structure watertight" [1]. This full-scale experiment proves the effectiveness of self-healing concrete as a water-impermeable building material when implemented in environments where water exposure is likely. The lifeguard stand has remained watertight since its construction in 2011, and it can heal cracks up to 0.8mm wide in just three weeks [1].

The following figure, from Patel's article, shows images of Jonkers' concrete before and after self-healing. Patel describes the image as follows: "In self-healing bioconcrete, dormant bacterial spores contained in clay pellets (black and grey circles, top) germinate when cracks expose them to moisture. The microbes feed on calcium lactate to form limestone, sealing the cracks (bottom)" [1].

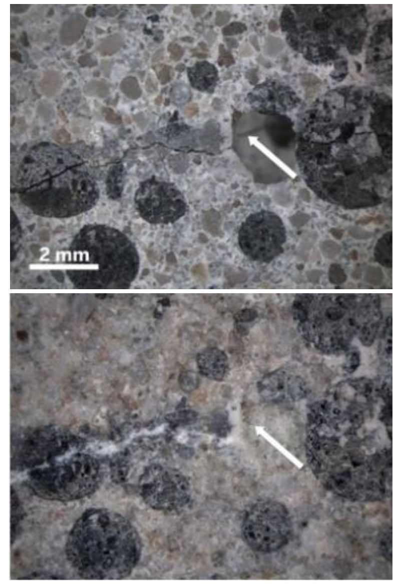

FIGURE 3 [1]
Cracked concrete before and after self-healing

Figure 3 clearly shows the build-up of calcium carbonate in the large hole and crack in the concrete slab. By regaining water-tightness, the lifeguard stand has been able to withstand the elements in the Netherlands without human intervention for repairs. The steel rebar that reinforces the structure has remained stable and the strength properties of the structure have not changed.

SELF-HEALING CONCRETE IN THE LAB

Self-healing concrete has been studied extensively in laboratory environments. These tests have revealed physical and chemical qualities about the material that are useful in judging its suitability for applications in the construction industry. The following information is clear from the tests conducted.

A serious concern when considering bacterial self-healing concrete is whether the bacteria added into the concrete will negatively affect the strength of the material. To test this, Jonkers measured various amounts of the bacteria *Sporosarcina pasteurii* and inserted them into identical blocks of concrete, with a control block for comparison. According to Jonkers, "The results of the concrete compatibility test show that the addition of bacteria to a final concentration of 10^9 cm^{-3} does not affect strength characteristics" [7]. Therefore, when this precise concentration of bacteria is added to concrete, it can be safely assumed that the integrity of the structure is not significantly altered.

This point is further demonstrated by Muhd Afiq Hizami Abdullah, a civil engineering researcher who works at the University of Malaysia Perlis. Abdullah studied the compressive strength of samples of bacterial self-healing concrete and found that "The previous researches indicate the ability of bacterial self-healing concrete to achieve compressive strength of more than 60MPa" [8]. This demonstrates that the material has the capacity to exceed traditional concrete in terms of compressive strength. While it has the capacity, Abdullah notes that most of the tests on the self-healing concrete found that it had a compressive strength within 10 to 40MPa, which is normal for traditional concrete [8]. In other words, there is no consequential loss of compressive strength with the addition of bacterial capsules in self-healing concrete.

Another noteworthy aspect of the material is its reliability in filling cracks of various sizes. According to Nele De Belie, "…Still no consensus is found regarding the maximum healable crack sizes: mostly values of 10-100 µm are mentioned, sometimes up to 200 µm, and only in the presence of water" [3]. De Belie has concluded that there is no evidence that very large cracks can be healed by the concrete, nor can cracks that occur in an environment where the concrete is not exposed to water. These two limitations are important to consider when choosing to use self-healing concrete in a structure. If the structure is to be built in a desert where water is not abundant, self-healing biological concrete might not be worth the additional costs.

De Belie also points out that the process by which the cracks are healed could be expedited by the inclusion of catalysts to speed up the rate of reaction. Similarly, the maximum size of cracks that the material can heal can be increased by adding fibers of steel, polymer, or natural materials to the concrete mix, increasing the cost of the material, but simultaneously increasing its reliability [3]. More testing is necessary to determine the payoffs of the addition of these materials.

One of the most prominent experiments that shows the promise of self-healing concrete was conducted by Henk Jonkers and Erik Schlangen. To test the ability of self-healing concrete to heal cracks in a timely manner, Jonkers and Schlangen created nine identical prisms of concrete, then they cracked the samples so they each contained a crack that was around 0.4mm wide. Three of these samples were designated as controls, they did not contain any bacteria. The other six prisms contained bacteria embedded in the matrix inside capsules of calcium lactate. They soaked the samples in water. Three of the bacterial concrete samples soaked for 28 days, the other for 56 days. All six bacterial prisms showed evidence that calcium carbonate was produced, and two of the prisms recovered full water-tightness [5]. This experiment confirmed that bacterial self-healing concrete can heal cracks in a timely manner. One of the most powerful aspects of the experiment was that it demonstrated how bacterial self-healing concrete utilizes water, a weakness of regular concrete, to catalyze the healing of itself.

These data reinforce the idea that self-healing concrete is a realistic solution to the problems described in the sections above, when applied in specific situations. However, it is important to discuss not only the functionality of self-healing concrete, but also its economic impact, environmental concerns, and long-term sustainability compared to traditional concrete.

THE IMPACT OF SELF-HEALING CONCRETE

Economic Considerations

As detailed above, the current method of dealing with concrete's natural tendency to form cracks involves the economically unsustainable methods of individual crack treatment and over-dimensioning. The inherently high costs of these solutions and their temporary nature suggest the need for a solution that is more economically feasible in the long run. Bacterial self-healing concrete could be one such solution.

It is true that bacterial self-healing concrete has a significantly higher cost of production than traditional reinforced concrete. This is one of the major reasons why the material is not currently being mass produced. According to Bravo Silva, "The bio-based additive for concrete, consisting of encapsulated spores to mix in the concrete before the casting process, results in prices of €5760 ($6522) per m^3" [4]. Considering concrete itself is rather inexpensive to produce, any product applied to concrete that adds an additional cost of more than $23 per m^3 is deemed too expensive to consider in the current market. It will take significant research to reduce the upfront costs of self-healing concrete before contractors will be convinced of its superiority to traditional concrete and implement it on a wider scale [4].

Part of the reason that bacterial self-healing concrete has such a high initial cost is because it is difficult to prepare the bacteria and the capsules that contain them. The microbes themselves require completely aseptic conditions, pricey growth mediums, and extensive labor to produce. Additionally, the successful encapsulation of the bacteria is variable and contributes €30 to € 50 ($34 to $57) per kilogram of bacteria produced to the overall cost of the material [4]. The calcium lactate that the bacteria require as a food source is also expensive, but Jonkers and Schlangen are researching a cheaper sugar-based nutrient that could replace it [1]. The bacterial production process and the medium of encapsulation are two areas where future research could lower production cost.

These prohibitively high costs are difficult to justify to investors who are not convinced of self-healing concrete's ability to extend the life of structures and reduce the overall cost of the building. Exacerbating the issue is the fact most contractor's warranties for buildings they construct last only about 10 years and do not cover cracks [4]. The benefits of self-healing concrete may not be readily apparent until many decades in the future, reducing the likelihood that contractors will choose to presently invest in this material. It is important to note that self-healing concrete is still in development and the high initial cost will likely diminish over time. Moreover, when one considers that current methods require nearly $150 of repair costs per m^3 of concrete every time a crack appears, and self-healing concrete could eliminate this chronic fee, the initial costs seem less severe [4].

There are, however, situations where the benefits of self-healing concrete transcend economic discussions. Such instances are detailed by Bravo Silva and include situations where money is less of a concern than the safety of priceless objects. "For example, in an underground museum or library, the quick healing/repairing of cracks is crucial to the maintenance of the right conditions to preserve the highly valuable objects inside" [4]. In situations like the one described by Bravo Silva, self-healing concrete can prove its worth as a long-term solution without the constraints of investors or contractor warranties. The material also offers advantages in fields outside the realm of economics by being a more environmentally-friendly alternative to traditional concrete.

Environmental Considerations

Concrete's lack of longevity additionally places a strain on the environment. The current solution of over-dimensioning, along with the practice of tearing down and rebuilding structures entirely, both utilize the overuse of concrete. This exploitation of the material creates a surplus of waste which becomes essentially useless and expensive.

With its longer lifespan, self-healing concrete has the potential to minimize this pollution by reducing the amount of concrete needed. Over time, the new material requires no added concrete or repairs. Additionally, by avoiding the demolition of buildings due to cracks in the structure, the production of great amounts of waste can be prevented. Concrete is difficult to recycle and cannot be efficiently reused since it does not retain its parent strength. The self-healing concrete addresses structure problems before they occur, as opposed to building structures only to tear them down years later.

While the creation of waste is currently one of the most evident destructive impacts of concrete, the pollution creation begins with the manufacturing of the material itself. As stated previously, the production of cement, a key component of concrete, produces a high percent of the world's carbon emissions. The buildup of carbon dioxide in the atmosphere is one of the main contributors to global warming. By decreasing the amount of concrete manufactured, the use of self-healing bacterial concrete will therefore decrease carbon emissions.

In recent years, bacteria, specifically those that produce calcium carbonate, have been proven to have positive impacts on building materials. According to Boon, a researcher of the applications of microorganisms in concrete, "Compared to conventional materials for concrete maintenance, biogenic $CaCO_3$ has the distinct advantages of environment friendliness and excellent compatibility with the concrete matrix" [9]. Calcium ions are a component of the concrete matrix, so the material is derived from both the concrete and the bacteria. Calcium carbonate is a natural material that is insoluble in water. Furthermore, the material is produced by living organisms and does not disrupt local ecosystems. The exact impact of bacterial self-healing concrete on ecosystems has not been directly investigated due to the limited full-scale production testing. However, concrete researchers De Belie and Boon have concluded that the precipitation of calcium carbonate is regarded as one of the most environmentally friendly materials for use in engineering applications [9]. This conclusion echoes that of the scientific community, among which the consensus seems to be that the calcium carbonate should not have a significant negative impact on the chemical or biological systems that are interrupted when the concrete structure is built.

One environmental impact of self-healing concrete that could be potentially harmful is the production of ammonium ions during the hydrolysis of urea. Scientists Ivanov and Kawasaki have performed research on bacterial biogrouts, which are materials similar to biological self-healing concrete. These biogrounts and self-healing concrete both utilize the same mechanism of hydrolysis of urea to produce calcium carbonate. Ivanov and Kawasaki note that "A disadvantage of this biogrout is the release of a large quantity of toxic ammonia to air, as well as harmful ammonium and hydroxide ions to water" [10]. Gaseous ammonia, a base also found in household cleaners, has been linked to respiratory illnesses. Hydroxide ions have a strong impact on the pH of the water around the concrete. This could be detrimental to local marine ecosystems if it is released in large quantities. Ammonium ions also alter the pH by acting as a weak acid. The buildup of these compounds can be toxic to fish and could potentially disrupt the nitrogen cycle, which is vital to all life in an ecosystem. These are important hazards that need to be considered when determining if self-healing bacterial concrete is suitable in particular applications. Ivanov and Kawasaki discuss an application where biological materials that utilize the hydrolysis of urea might not be suitable. They have observed that "The release of gaseous ammonia is a big concern due to the confined space in tunnels or buildings" [10]. Self-healing concrete has promise as a building material in tunnels because of its ability to maintain integrity without maintenance, but the concerns highlighted by Ivanov and Kawasaki are cause for further investigation. Because ammonia is toxic when it is highly concentrated, more research needs to be done to analyze the quantities of harmful compounds produced by bacterial self-healing concrete and assess their impact in different applications.

The use of self-healing concrete has the potential to be a sustainable solution for the issue of cracking concrete. The current practices produce surplus waste and are therefore destructive to the environment. Self-healing concrete suggests that the solution to the concrete crisis is not a larger quantity, but instead a material with a longer lifespan. In the coming years, with more full-scale testing, the effects of this concrete will be better known. As of today, it continues to show promise as a sustainable solution to the current problems of the concrete industry.

An Analysis of Sustainability

The economic and environmental impacts of self-healing concrete are indispensable data to consider when determining its sustainability. However, it is necessary to first provide a formal definition of sustainability to analyze how it applies to the material. According to Andrew Basiago, professor in the Department of Land Economy at the University of Cambridge, "Broadly speaking, 'sustainability' is embodied in four principles: futurity (a concern for the welfare of future generations), equity (the fair sharing of economic benefits and burdens within and between generations), global environmentalism (a recognition of the global dimension of ecological problems associated with use or depletion of natural capital by one or some at the cost of others) and biodiversity (the maintenance of the integrity of ecological processes and systems)" [11]. This definition is especially useful because each aspect of it can be specifically applied to self-healing concrete.

To the point of futurity, it is clear from previously-stated information that bacterial self-healing concrete promises a much longer lifespan than traditional concrete. Buildings constructed of self-healing concrete will continue to stand long after those built of abiotic reinforced concrete have eroded due to the processes outlined above. Therefore, it can be stated that the use of self-healing concrete shows more concern for future generations than traditional concrete because it promises structures that will last longer and cost less to maintain. The future generations will enjoy a secure and stable built environment that will degrade at a slower rate.

Equity can be addressed through the discussion of economic benefits of self-healing concrete. In some applications, self-healing concrete would diminish the costly need for concrete structures to be repaired and replaced. The American Society of Civil Engineers estimates that repairs of decaying infrastructure cost around $130 billion per year. This economic burden can be crushing for communities where everyone must dole out money to pay for repairs. In Cincinnati, OH, the Brent Spence Bridge, a double decker interstate bridge that runs across the Ohio River into Kentucky, is in desperate need of repairs. Chunks of rotted concrete fall from the bridge almost every day, leaving exposed oxidized supports. This massive bridge has proved to be neither sustainable nor reliable, and it is no longer a solution to the problem of traffic across the Ohio River. Instead of heaping the burden of rebuilding the entire concrete environment on future generations, contractors can spare them the wasteful economic practices of demolition and futile repairs by investing in bacterial self-healing concrete now.

Furthermore, concern for global environmentalism is one of the main reasons that self-healing concrete was developed. As previously mentioned, the production of cement releases the greenhouse gas, carbon dioxide, into the atmosphere, contributing to global warming. Bacterial self-healing concrete reduces this production of cement in two ways. First, by increasing the life of structures, it decreases the need to produce cement to replace those traditionally demolished and rebuilt. In addition, it offers another marginal decrease in the production of cement because the bacterial self-healing concrete matrix is composed of the clay spores containing the bacteria. These spores take up volume, therefore decreasing the amount of cement needed in the matrix. By using self-healing concrete, there would be a significant reduction in the manufacturing of cement, removing a sizeable portion of carbon from the atmosphere. Because global warming is a widespread threat to the environment, the use of bacterial self-healing concrete would have a positive impact on the planet's atmosphere, qualifying the material as sustainable as defined by Basiago.

Finally, not only does the production of concrete release greenhouse gases into the atmosphere, it significantly damages local ecosystems. Traditional concrete is expensive and difficult to recycle, therefore waste concrete from aging structures comprises a large volume of landfills. According to a publication from Linnaeus ECO-TECH, "Site selection of waste management facilities can be a major issue as all infrastructural projects have the capacity to damage the ecology of the site on which they are developed, causing landscape changes, loss of habitats and displacement of fauna" [12]. In other words, the creation of landfills disrupts environments by displacing local fauna and flora. By reducing the amount of concrete in landfills and consequently cutting down on the surface coverage requirements of newly-built landfills, self-healing concrete makes a compelling contribution to local ecology and sustainability.

Using Basiago's definition of sustainability and information detailed in the above sections, it is plain to see that self-healing concrete could be a revolutionary invention in terms of sustainability. The use of traditional concrete is, by nature, an unsustainable process both environmentally and economically. If the construction of buildings with traditional concrete is not waned off, it will eventually become an impossible task. Self-healing concrete could offer a solution to this pressing matter once the material is mass produced.

CONCLUSION: CONCRETE OF THE FUTURE

Self-healing concrete is a material that could revolutionize the construction industry in the near future. The material is superior to traditional abiotic reinforced concrete in several areas. It is readily apparent that traditional concrete lacks long-term sustainability for a number of reasons. Traditional concrete has a short lifespan, deteriorating or needing to be replaced after just a few decades. Self-healing concrete lasts much longer than traditional concrete because it can heal cracks caused by water with no human intervention. It can do this because of the processes outlined in this paper, which involve water-activated bacteria that produce calcium carbonate to fill cracks in the concrete. Moreover, traditional concrete is expensive to produce and impossible to recycle efficiently, therefore indicating it is neither economically sustainable nor environmentally friendly. Because self-healing concrete can renew itself and extend the life of the buildings it comprises, it requires much less concrete to be produced, therefore saving money on building costs in the long run and reducing the amount of waste associated with the demolition of traditional concrete structures.

The material is a relatively new adaptation on a longstanding substance, so it is not without flaw. The high cost of cultivating the bacteria used in development of the material results in upfront expenses that are orders of magnitude higher than traditional concrete. Because contractors cannot justify incorporating a material this expensive in their projects, and their warranties do not cover cracks in concrete, it has not yet gained much headway in the construction industry. However, due to the results of the laboratory experiments detailed above, it has proven its ability to accomplish what researchers intended. According to Jonkers, "The results of the experiments show that immobilized bacteria and certain classes of needed food sources do not negatively affect concrete strength characteristics. It can therefore be concluded that bacterially controlled crack-healing in concrete by mineral precipitation is potentially feasible" [7]. It can be extrapolated that there are few experimental limitations to the self-healing concrete in its current state, but the economic and environmental impact of the material is not yet fully understood. Further research will be required to reduce the cost of producing the bacteria so that the material may have a lower upfront cost and be accepted by contractors. Until then, this innovative material will remain the "concrete of the future."

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