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Sustainability of Bacterial Concrete

1. Introduction

Concrete is an essential and widely used building material to construct buildings and many structures such as bridges and dams. However, it contributes around 9.5% of global carbon emissions and causes environmental pollution. Moreover, concrete is susceptible to external factors and cracks may form easily (Patel, 2016). These issues may impact the comfort and health of living inhabitants. The factors mentioned indicate the need to reduce concrete production and carbon dioxide (CO_2) emissions and find a way to solve the material's unsustainability. A solution to these problems could be in the form of bacteria.

An eco-material called, bacterial concrete, has the potential to be a sustainable solution to the issues made by traditional concrete. The material consists of concrete and dormant bacteria that is able to self-heal cracks and reduce CO_2 emissions. This paper aims to evaluate the feasibility and sustainability of utilising bacteria in concrete to solve the problems brought about by traditional concrete.

2. Concrete

2.1 History of Concrete

Concrete is an integral building material in modern society. Most of us spend our lives around places made of concrete: buildings, sidewalks, roads, and various structures are all constructed with the amazing material. In fact, concrete has been around for a long time – the ancient Romans used a concrete-like material made of lime and water, to construct well known structures like the Colosseum (Schifman, 2017). In modern times, concrete is made by mixing water, cement and a combination of aggregates such as clay, calcium, and silica. A slurry viscous concrete liquid is formed and will be poured, moulded, and hardened to form a multitude of structures (Patel, 2016).

2.2 Properties of Concrete

Concrete is a versatile material that can form a plethora of structures. The material boasts a wide range of properties. It has high compressive strengths of 10-40MPa that allows the material to withstand heavy loads without being crushed (Hizami Abdullah et al., 2018). Concrete also has great durability and is resistant to high temperatures. Steel reinforcements are commonly used to provide additional support and durability, and strengthen concrete structures (Smith, 2019). Although concrete displays many impressive properties, the material has its shortcomings.

2.3 Limitations of Concrete

Concrete's low tensile strength causes the material to be brittle and crack easily when it is bend by external forces (Stanaszek-Tomal, 2019). Thus, steel reinforcements are used to reduce the incidence of cracking. The formation of cracks would allow water to seep in and reach the steel reinforcements resulting in corrosion and rusting. If left untreated, the structure will be very vulnerable to external traumas and could collapse (Stanaszek-Tomal, 2019). As a result, concrete does not have a long lifespan when it is not maintained properly. To fix these issues, regular concrete or sealing agents are used to seal up minute cracks. For aging structures, they are demolished to build new ones (Patel, 2016). However, these solutions come with more problems.

Concrete is not environmentally sustainable as it produces landfills and is poorly recycled. Demolished structures would be disposed and create landfills. If the amount of concrete waste increases, more land is needed to be converted into disposal sites, and this would damage and displace eco-systems and habitats (Maheshi, 2015). The presence of unknown particles in concrete waste, such as chlorides, may react with concrete and alter the material's composition and result in a decrease in strength and durability (Vázquez, 2016). The concrete does not retain its original strength and would be dangerous to be used as a building material after it is recycled.

Concrete is also known to generate huge amounts of CO_2 and is a burden on the environment. Patel (2016) reported that concrete production makes up around 9.5% of global carbon emissions. The main reason is due to the production of cement, which is a key component in the formation of concrete. In 2014, the world produced 4.3 billion metric tons of cement, and this figure is projected to increase exponentially as the world becomes increasingly urbanized (Patel, 2016). Cement acts as a glue in concrete. To make cement, limestone and clay are crushed and large amounts of fuel is needed to combust and heat the mixture to a high temperature of 1500 °C. Limestone decomposes to form calcium oxide that will be used in the cement product (Chelsea Harvey, 2018). As a result, the entire process releases massive amounts of CO_2 into the atmosphere and contributes to global warming. Figure 1 shows the energy and CO_2 produced by several building materials used in the production of traditional concrete (Stanaszek-Tomal, 2019).

Building Materials	Energy (MJ/kg)	kg CO_2/kg
aggregate	0.083	0.0048
concrete (1:1.5:3 e.g., floor panels in situ, construction)	1.11	0.159
cement mortar (1:3)	1.33	0.208
steel (general—average recycled content)	20.10	1.37
bricks (all)	3.0	0.24

Figure 1: Energy and CO_2 emitted from each component of concrete (Stanaszek-Tomal, 2019).

With many vulnerabilities in traditional concrete, high CO_2 emissions from the production of concrete and landfills created by demolished structures, it is clear that concrete brings harm to the environment. Thus, it is imperative that a sustainable solution is needed for one of the world's commonly used material.

3. Bacterial Concrete

The idea of utilising bacteria in concrete may seem novel, but the concept was developed in the early 1990s by an architecture professor named Carolyn Dry. Dry originally mixed glass capsules into concrete that would break and release a glue to seal up cracks in the concrete. However, the glue was too viscous to seep out and fill the cracks, and the glass capsules were not able to survive the concrete mixer. Despite this research's shortcomings, it served as an inspiration for researchers to find ways to introduce healing agents into concrete (Patel, 2016). One of these ways is using bacteria.

3.1 What is Bacterial Concrete?

Bacterial concrete is a biological material that utilizes concrete and endospores of bacteria. Bacteria are cultured in media, extracted and form endospores when they do not receive nutrients. The endospores are transferred to capsules that contain minerals and other food sources (Stanaszek-Tomal, 2019). These capsules are mixed with concrete. When cracks are formed in the concrete, these bacteria are activated when they encounter moisture, and produce calcium carbonate ($CaCO_3$) that will fill and seal the cracks (Patel, 2016). Filling up the small cracks quickly in concrete would deter larger cracks from forming. In addition, the sealing of cracks would reduce the rate of oxidation of the steel reinforcements and increase the lifespan of the structure (Stanaszek-Tomal, 2019).

3.2 Microbes in Bacterial Concrete

The bacteria used in the concrete are chemoorganotrophs – organisms that oxidise organic compounds to get energy. These microbes come from several species such as: *Bacillus Subtilis*, *Bacillus pseudofirmus*, and *Bacillus sphaericus*. These bacteria are alkaliphiles that can survive the alkaline concrete environment and are able to produce $CaCO_3$. They have metabolic processes such as urea hydrolysis and photosynthesis, that allow them to produce energy (Stanaszek-Tomal, 2019).

3.3 Mechanism of Bacterial Concrete

Urea hydrolysis is the most studied metabolic process as it is less complex. Urea hydrolytic bacteria such as *Bacillus sphaericus,* produced 20-80% more $CaCO_3$ than other metabolic pathways (Achal et al., 2011). Thus, this section will focus on the hydrolysis of urea.

The mechanism of self-healing bacterial concrete begins when a crack forms in the concrete and rupture certain capsules containing the bacteria endospores. These capsules – containing nutrients such as calcium ions and urea – serve as a food source for the bacteria to carry out urea hydrolysis and the precipitation of $CaCO_3$ (Castro-Alonso et al., 2019). Upon contacting with moisture from the air or water sources, the endospores would be activated, and the bacteria consume the nutrients to produce $CaCO_3$. The mechanism for the formation of $CaCO_3$ can be seen be in the diagram below.

$$CO(NH_2)_2 + H_2 \rightarrow NH_2COOH + NH_3 \quad (1)$$

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

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (3)$$

$$NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH \quad (4)$$

$$HCO_3^- + H^+ + 2NH_4^+ + 2OH \rightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \quad (5)$$

$$Ca^{2+} + Cell \rightarrow Cell^- Ca^{2+} \quad (6)$$

$$Cell^- Ca^{2+} + CO_3^{2-} \rightarrow Cell^- CaCO_3 \quad (7)$$

Figure 2: Production of $CaCO_3$ via urea hydrolysis (Castro-Alonso et al., 2019).

A bacterial enzyme called, urease, catalyses the hydrolysis of urea ($CO(NH_2)$) to form ammonium and carbonate ions shown in reaction 5. These products cause an increase in the surrounding pH. With a favourable alkaline environment and calcium and carbonate ions present in the capsules, the bacteria metabolize the ions to form $CaCO_3$, as seen in reaction 6 -7 (Castro-Alonso et al., 2019).

$CaCO_3$ is an ideal material to patch up cracks as this compound is compatible with starting materials of concrete. There have been multiple studies that showed the addition of bacteria enhanced the properties of concrete. The results of these studies are exciting and will be further explored in the next section.

4. Influence of Bacteria on concrete

Extensive investigations have been conducted on the self-healing bacteria concrete to identify physical and chemical properties that would show the viability of the material in the construction industry. A few examples of results from selected research studies are briefly presented.

4.1 Influence on Strength

Several studies found that the addition of bacteria increased the compressive strength of the concrete. One such example was a study conducted by Mondal & Ghosh (2018). Different cell concentrations of *Bacillus Subtilis* were inoculated into several concrete blocks and left to culture over 28 days. After testing the concrete blocks' compressive strength, the concrete with a cell concentration of 10^5 cells/ ml achieved a compressive strength of 55 MPa that is higher than the typical compressive strength of concrete (Mondal & Ghosh, 2018). In addition, concrete has poor tensile strength, but adding bacteria into the material managed to improve this property. Safiuddin et al. (2018) mixed *Bacillus Sphaericus* with concrete and compared the tensile strength with traditional concrete after 28 days of culturing. It was found that bacterial concrete a tensile strength of 3.45 N/ mm, a significant increase compared to traditional concrete tensile strength of 3.26 N/mm (Safiuddin et al., 2018). These studies showed that the addition of bacteria into concrete, made concrete more durable such that it can withstand heavier loads and possibly, reduce the incidence of cracking.

4.2 Self-Healing Properties

Bacterial concrete has the ability to seal up cracks with the help of $CaCO_3$-producing bacteria. In one study by De Belie et al. (2018), bacteria were able to seal cracks from 10 µm to 200 µm in the presence of water. In another study, researchers modified the bacterial concrete by adding a combination of polymer materials to preserve moisture in the concrete. It was found that large amounts of $CaCO_3$ was produced and cracks up to 700µm were sealed. Also, water penetration was found to have decreased by 70% (Gupta et al., 2018). From the results, bacterial concrete can self-heal cracks and reduce the water permeability of concrete such that it would protect steel reinforcements more effectively.

Furthermore, an experiment conducted by Tziviloglou et al. (2017) showed that bacteria concrete can seal up cracks in a timely manner. The researchers created nine identical concrete prisms and cracked them to form 0.4mm wide cracks. Three of the prisms acted as controls while the rest had bacteria mixed in the concrete. Three of the bacteria samples were soaked in water for 28 days, while the other three bacteria prisms were soaked for 56 days. The results showed that $CaCO_3$ was produced, and some prisms achieved complete crack healing and were impervious to water (Tziviloglou et al., 2017). This experiment demonstrated that bacterial concrete was able to heal cracks within a short period of time.

The data from the above studies have shown that bacterial concrete, when used in specific conditions, could be a realistic solution to solving the problems with traditional concrete stated in earlier sections. Although it is imperative to discuss the viability of self-healing bacterial concrete, the economic and environmental impacts and long-term sustainability of the material must be evaluated as well.

5. Economic Considerations

To determine the economic feasibility of bacterial concrete, its critical to compare the material to traditional concrete. One major problem with bacterial concrete is the cost to prepare it. A study by Bravo Silva et al. (2015) found that the cost of encapsulating the bacteria in calcium capsules and mixing them with concrete amounted to €5760 (USD $6522)/ m^3, while the production of traditional concrete only costs USD $23/ m^3 in the Belgian market. The high cost can be attributed to several factors: aseptic conditions, costly growth mediums and skilled workers are required to ensure the bacteria are properly encapsulated (Bravo Silva et al., 2015). All these factors contribute to bacterial concrete's exorbitant cost. Thus, bacterial concrete would not be economically feasible, and investors would be hesitant to invest in such an expensive material.

Despite bacterial concrete's high preparation costs, there may be situations where the benefits of the material go beyond economic discussions. In certain situations, bacterial concrete could reduce the cost to repair and replace aged or weakened concrete structures. Business Insider reported that it would cost USD$123 billion to repair over 20000 aged and structurally deficient bridges in America (Thompson, 2017). For instance, the Brent space bridge in Cincinnati, Ohio, has decayed concrete that is crumbling and exposing the steel reinforcements to air and water. The corrosion of the supports would compromise the bridge's structural integrity. The cost to fix and maintain the bridge amounts to USD$2.5 billion (Fitzsimmons, 2018). Instead of repairing structures by applying more concrete or sealing agents to seal up cracks, or demolishing and re-building the bridge, bacterial concrete could help to diminish these costs as its self-healing properties would reduce the need to regularly use concrete to seal up defects or cracks in existing structures, thereby extending the lifespan, and saving maintenance costs.

Bacterial concrete also has advantages outside economics by being more environmentally friendly compared to regular concrete. The next section will elaborate on the environmental impacts of the material.

6. Environmental Considerations

Concrete places a huge strain on the environment due to its susceptibility to cracks which would compromise the integrity of structures. The current solution to solve these problems is to tear down and re-build structures, but that would mean requiring large amounts of concrete to form the new concrete structures. The concrete waste from demolished structures generates landfills and results in more land pollution. However, utilizing bacterial concrete could ameliorate these issues with its self-healing feature. Instead of using more concrete to seal up the cracks, bacteria can do that via the production of $CaCO_3$. As such, self-healing concrete would reduce the need to demolish damaged structures, reduce the dependence of using concrete to seal up cracks, and mitigate the production of concrete waste.

The production of cement to form concrete releases CO_2 into the atmosphere, and the build-up of this greenhouse gas is one of the main contributors to global warming. It is hoped that by relying on bacterial concrete's self-healing properties, concrete production would decrease and in turn, decrease CO_2 emissions.

One potential environmental impact of bacterial concrete could be harmful is the production of certain by-products from urea hydrolysis. Ammonia, found in household cleaners, is produced during the hydrolysis of urea, as seen in the reaction mechanism in figure 2. This chemical is highly basic and has been linked to respiratory problems (Castro-Alonso et al., 2019). This gas could be harmful to people and other organisms in places with enclosed spaces such as underground tunnels.

In addition, ammonium (NH_4^+) and hydroxide ions (OH^-) produced in step four of figure 1, could damage eco-systems as these ions may enter soil and nearby water sources and increase the pH. A change in the pH could be toxic to plants and animals and result in growth problems and death (Castro-Alonso et al., 2019; Ivanov et al., 2019). With this knowledge, this would mean that bacterial concrete would not be ideal near water bodies and can only be used in certain situations. It is currently unknown how much by-products are produced from urea hydrolysis. Hence, more research is required to assess the extent of the impacts of these chemical species on the surroundings.

Bacterial concrete has the potential to be a viable solution to the issues brought about by traditional concrete. In the next few years, with more comprehensive testing, it is hope that the properties of bacteria concrete would be better understood, and the material would eventually be applied in the construction industry.

7. Sustainability

The economic and environmental impacts of bacteria concrete provided solutions and issues that may be key to determining its sustainability. Sustainability is often defined as meeting the needs of the people without compromising the ability for future generations to meet theirs. It is a vague term, but the United Nations' sustainable development goals can act as a guide to determine the sustainability of bacterial concrete (United Nations, 2015).

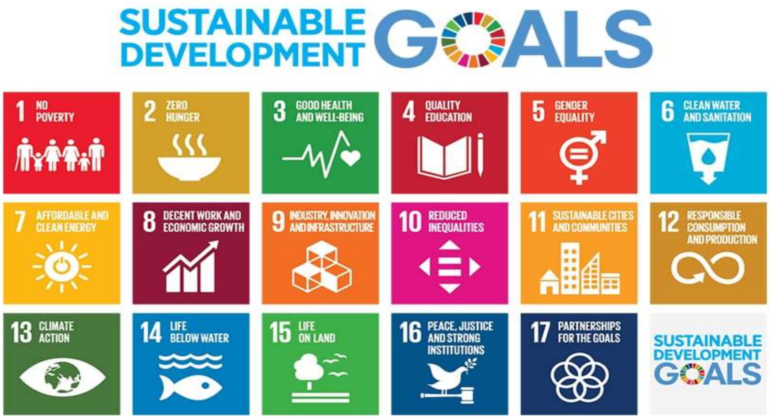

Figure 3: United Nations Sustainable Development Goals (United Nations, 2015).

The United Nations outlined seventeen goals that serve as a blueprint to how the world can progress and achieve a more sustainable future. Bacterial concrete has the potential to satisfy some of these goals and prove itself to be a sustainable material.

The thirteenth goal of UN's Sustainable Development Goals states the need to tackle and reduce climate change and global warming (United Nations, 2015). From earlier sections, the production of cement to make concrete, emits CO_2 into the atmosphere and contributes to global warming. With bacterial concrete's self-healing properties, the need to use concrete to seal up cracks would decrease. Also, the encapsulated bacteria would take up some volume in the concrete, reducing the amount of concrete needed to form bacterial concrete. This would lead to a decrease in concrete production, reduce CO_2 emissions and remove a considerable proportion of carbon in the atmosphere. As such, bacteria concrete would satisfy goal thirteen.

The UN's fifteenth goal, life on land, states the importance of conserving and protecting eco-systems (United Nations, 2015). Bacterial concrete can play a part in protecting habitats. Traditional concrete is known to be a poorly recyclable material as concrete waste does not retain its original strength. As such, aging structures would be torn down and replaced with new structures. The concrete waste would be disposed and create landfills. More sites will have to be designated for waste disposal if landfills continue to increase. These landfills would displace, and damage environments inhabited by a multitude of species of flora and fauna (Maheshi, 2015). Bacterial concrete would aid in reducing the production of concrete and extending the lifespan of existing concrete structures. The production of concrete waste and landfills would decrease, and thus, reduce land pollution. Hence, utilizing bacteria concrete would aid in improving life on land, as stated by goal fifteen.

Finally, bacterial concrete would be able to satisfy goal eleven which aims to provide resilient and sustainable cities (United Nations, 2015). The material can seal up cracks and has shown the potential to increase the strength of concrete, allowing it to handle massive pressures without being crushed. In the future, if cities were made of bacteria concrete, these structures would be more durable and be able to withstand erosion longer than traditional concrete. Future generations would inherit an environment that is structurally safer and more secure than the current period we live in. Thus, utilizing bacteria concrete could provide a more sustainable urbanised environment.

By identifying the sustainable goals that bacterial concrete can achieve, it is evident that the material would be able to provide a sustainable solution to traditional concrete. For bacteria concrete to be possibly used in industrial settings, researchers must continue to study the material.

8. Future research

Bacterial concrete has the potential to be a game-changer in the construction industry, but more work must be done to analyse the material's properties and overcome certain limitations.

8.1 Environmental conditions

Firstly, researchers have, so far, tested the material in the lab where the environment is controlled. The results generated from numerous testing may differ from the outside environment. Bacterial concrete is an eco-material that is sensitive to the environment. Previous sections mentioned that the bacteria endospores need moisture to be activated and initiate the production of $CaCO_3$. If the material is used in a dry environment such as a desert, the bacteria's activity would be very low as there is a lack of moisture, and the self-healing process would not happen. Therefore, the environment determines the viability of bacterial concrete. Researchers should continue to discover ways that they can modify bacterial concrete such it can be applied to a wider variety of environmental conditions.

8.2 Replenishment of Food Source

Secondly, an issue that may be troublesome to solve is the replenishment of food for the bacteria in the concrete. Once the bacteria have consumed all the nutrients in the capsules, they would return to their endospore state (Stanaszek-Tomal, 2019). $CaCO_3$ would not be produced to seal up future cracks. The addition of tubes in the concrete mix could be a viable way to replenish the bacteria (Joseph et al. 2010). When there are no nutrients left, these tubes can channel more nutrients and healing agents into the concrete for the bacteria to metabolize. However, that would mean an additional cost to prepare and mix the tubes with concrete (Joseph et al. 2010). Thus, the material must be altered in a way that these bacteria can be re-supplied with nutrients to ensure they are ready to produce $CaCO_3$ and reduce preparation costs.

8.3 Crack Size

Thirdly, based on the results obtained from various studies, bacterial concrete has, so far, been able to seal small cracks that range from 10 µm to 700 µm (De Belie et al., 2018; Gupta et al., 2018). It is hoped that this material would be able to seal larger cracks. The ability of the bacterial concrete to self-heal cracks can be enhanced with the addition of extra materials such as a shape memory polymer, into the concrete mix. The polymer is activated when there is high internal pre-stressing on the concrete. The polymer is able to shorten or shrink to sufficiently close the gaps in cracks (Jefferson et al. 2010). This method would allow bacteria to produce $CaCO_3$ to seal up the cracks easily. Researchers can still find other ways to incorporate materials to enhance bacterial concrete and control preparation costs.

8.4 Interaction with other Micro-organisms

Another area to focus is the interaction of microorganisms in the air with bacterial concrete. A plethora of micro-organisms such as fungi, are present in the air. Fungal spores can enter the cracks of concrete and grow. The hyphae of multi-cellular fungi can absorb the nutrients from the surroundings and produce metabolites that damage the concrete (Bertron, 2014). This may harm the $CaCO_3$-producing bacteria and inhibit $CaCO_3$ production. Hence, the interaction of micro-organisms with bacteria in concrete could be another area of research for scientists.

9. Conclusion

Concrete is often an overlooked material as it is seemingly ubiquitous; most of us are unaware of how the material is made, and its structural and environmental issues. Researching this topic was an eye-opener as I was not aware of how a dull and boring material like concrete, has negative impacts on our natural environment. It is uneasy to think of the amount of concrete we are using to construct the structures around us, and how rapid urbanization would accelerate global warming

However, I am thankful and grateful that scientists are doing their best to reduce concrete's contribution to global warming. It is extraordinary that they found a way to turn an unsustainable material into a sustainable one. The idea of using bacteria in concrete is innovative and could change the future of the construction industry. The material has shown to be an improvement of traditional concrete: bacterial concrete is more durable than traditional concrete; the material is able to seal up its own cracks and extend the lifespan of concrete structures; it has the potential to reduce CO_2 emissions and pollution; and save long-term maintenance costs. There are, however, several limitations that would need to be addressed to fully assess the viability of this wonderful material. For now, bacterial concrete is a material of the future.

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