Necessity-the-Mother-of-Invention: Bioconcrete

(Rachel Armstrong)

Concrete infrastructure forms the foundations of daily modern life.
[Image courtesy Freepik, royalty free images]

The Necessity: reducing greenhouse gas emissions to slow global warming

The Context

Second only to water, concrete is the substance that we use most on a daily basis. It is ideal for building foundations and structural support as it can withstand heavy loads and high pressures, lasting for decades without significant maintenance or repairs. Along with steel, concrete is, because of its strength, durability, versatility, and affordability, the material of choice for our most challenging feats of modern engineering—from buildings, to industry, road bridges and coastal defences. Concrete is made by mixing cement, water, and aggregates like sand, gravel, or crushed stone. It is also extremely versatile and can be moulded into different shapes and sizes to suit a wide range of design needs. Additionally, concrete mixtures can be modified to improve their workability, sustainability, and other properties for any given task. The cement acts as a binder, binding the aggregates together to create a solid mass.

To make cement, limestone and other materials such as clay or shale are extracted from quarries or mines and then crushed and ground into a fine powder, which is heated to very high temperatures in a kiln where it is transformed into clinker. The clinker is typically heated to a temperature of around 1450°C (2640°F) in a rotary kiln, where a chemical reaction called calcination takes place. The clinker is then ground into a fine powder and mixed with gypsum, which helps to regulate the setting time of the cement. When water is added to the cement, it undergoes a chemical reaction called hydration, where the water reacts with the cement to form calcium silicate hydrate (C-S-H) gel. This gel fills the space between the aggregates, binding them together and creating a solid matrix. As the reaction continues over time, the C-S-H gel continues to form, resulting in a stronger and more durable material (http://www.madehow.com/Volume-1/Concrete.html).

The aggregates used in concrete, such as sand, gravel, or crushed stone, are sourced from natural sources like rivers, pits, or quarries. Those with a higher compressive strength and a better bond with the cement matrix also contribute to the overall strength of the concrete. Adding plasticizers can also modify the properties of concrete such as its strength, setting time, and workability. For example, superplasticizers can be used to increase the fluidity of the concrete mix without adding extra water, resulting in a denser and stronger concrete structure. Overall, the strength of concrete is a result of a complex interplay of chemical reactions between its components, and optimizing the composition of the concrete mix is key to achieving the desired strength, workability, and durability.

The production of clinker releases carbon dioxide as a by-product, which is a significant contributor to greenhouse gas emissions. In addition, burning fossil fuels to heat the kiln to such high temperatures, and transportation of raw materials and finished concrete products, also create significant CO2 emissions. Today, concrete production accounts for 8% of global carbon emissions, which is more than aviation (2.5%). New types of concrete are necessary to make more environmentally friendly foundations for our industries, cities and infrastructure by being either extremely long lasting, or by using microorganisms to make sustainable biocement.

The Challenge

Although concrete is remarkably durable, typically lasting up to a hundred years, it can be degraded by a range of environmental factors such as chemicals in the environment, water, physical stresses, resulting in cracks which compromise the integrity and strength of the structure, which requires repair or replacement. One common cause of concrete failure is due to the presence of water, which can cause corrosion of reinforcement steel within the concrete that is introduced to increase its strength and durability in situations where it will be subjected to significant tensile or bending stresses. This corrosion process can generate expansive rust products that can cause cracks and weakening of the concrete. When concrete fails due to corrosion of steel reinforcement, the chemical reaction that occurs is the oxidation of iron in the steel, which results in the formation of iron oxide (rust) and the loss of strength of the steel.

Concrete can also fail due to chemical attacks from aggressive substances such as acids, sulphates, and alkalis, which react with the cement paste and aggregates, leading to the formation of new compounds that can cause the concrete to crack and degrade. For example, when concrete is exposed to acid, the acid reacts with the calcium in the cement paste to form calcium salts, which can cause the concrete to become brittle and weak.

Finally, concrete can fail due to physical forces such as stress or impact. In these cases, the chemical composition of the concrete may not change significantly, but the physical integrity of the structure is compromised, resulting in cracks and fractures.

As replacing large concrete structures generates huge amounts of carbon emissions, as well as costs, it is better to treat degraded concrete early when the cracks first appear and are very small, so they can be quickly sealed to prevent further cumulative damage.

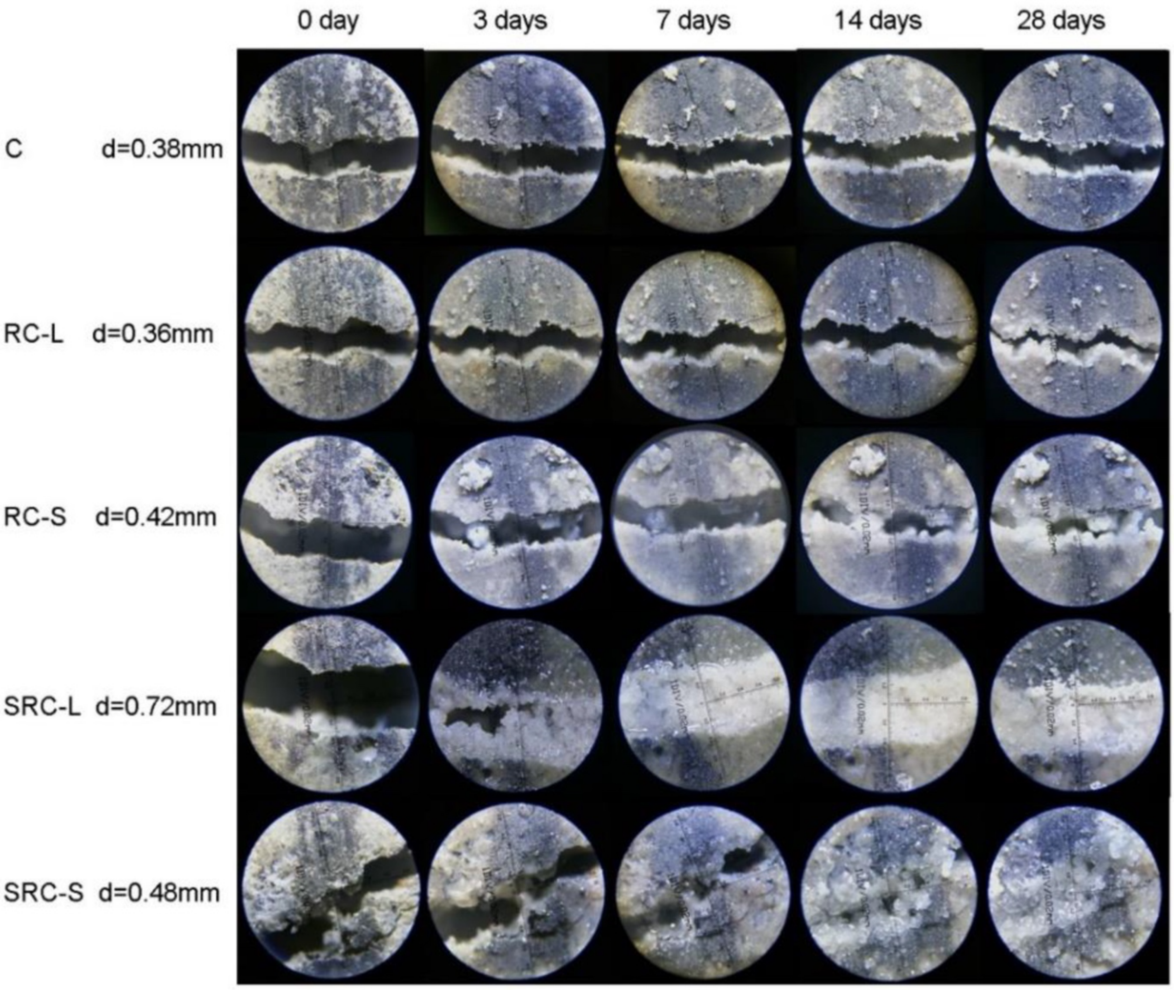
Cracks in concrete. [Image courtesy Freepik, royalty free images]

The Invention

A breakthrough in concrete production was developed by H.M. Jonkers at the Technical University of Delft, in the Netherlands by creating a self-healing concrete product called "bioconcrete". Spore-forming bacilli, such as *Sporosarcina pasteurii, Bacillus cohnii, B. halodurans,* and *B. pseudofirmus* that can tolerate the high alkalinity of concrete are added to the concrete mixture before it is poured. As cracks form in the concrete over time, water and oxygen penetrate the surface of the concrete and reactivate the 'sleeping' bacteria, which secrete enzymes that precipitate calcium carbonate (calcite) to fill in cracks as a byproduct of their metabolic processes. These crystals then plug the hairline cracks to strengthen the concrete in a kind of self-healing process. Over time, this bacterial process produces enough limestone to expand and fill in the cracks created by the water, thereby rebuilding the concrete structure from the inside out, and completely sealing it from further damage.

The Consequences

Bioconcrete is best used where structures are prone to weathering, and those that are difficult for repair workers to access. Because it eliminates the need for future expensive and complex repairs, bioconcrete has the potential to be a more sustainable and environmentally friendly alternative to traditional concrete repair methods, which often involve the use of chemical sealers or costly repair work. Importantly, bioconcrete also helps reduce the carbon footprint of concrete by reducing the need for repairs and replacements over time.



Experimental demonstration of microbially-mediated concrete healing. Five different concrete specimens (top to bottom) were placed in a water box at 20 °C for 21 days and observed at the indicated times (left to right). The specimens were C: untreated Portland concrete (control); RC-L and RC-S: two kinds of untreated rubber concrete, each with a different rubber particle size; and SRC-L and SRC-S, the same kinds of rubber concrete that had previously been inoculated with *Sporosarcina pasteurii* spores. As can be seen, there were no signs of crack repair in the untreated control cement, only modest crack repair in the rubber cements, due to the hydration of unhydrated cement particles, but complete crack repair in the rubber cement samples containing *Sporosarcina pasteurii* spores, due to active bacterial mineralization.
Image source: Xu et al., 2019. https://doi.org/10.3390/ma12142313.

The Significance

Bioconcrete is most significant when applied to civil engineering projects such as bridges, tunnels, and roads, as they need significant ongoing maintenance. It is estimated that bioconcrete could save billions of euros on annual maintenance fees. Further refinements of the recipe could even reduce the cost of bioconcrete by as much as 50 percent, making the substance only slightly more expensive that ordinary concrete mixes.

References

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