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Helping Concrete Heal Itself

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Giving concrete the power to repair itself could save maintenance costs, increase safety, and help the environment.

Concrete is one of civilization's most durable building materials. The ancient Romans used concrete 2,000 years ago to make structures that still stand today. People now use the material's modern version—aggregates such as sand or gravel held together by a cement and water paste—more than all other construction materials combined. The world produced 4.3 billion metric tons of cement in 2014, and this production will keep increasing as more sidewalks, buildings, and bridges get built in an increasingly urban world.

For all its strength and durability, though, concrete has problems. Stress from carrying loads gradually creates microscopic fissures in the material that allow in water, salts, and ice. These fissures can then turn into gaping cracks, exposing the steel bars often used to reinforce concrete to corrosive elements. Our seemingly resilient infrastructure would crumble without routine, and costly, patching.

To help reduce those maintenance costs and make buildings and bridges safer, researchers are now giving concrete the power to heal itself. By extending the lifetime of structures, self-healing concrete could also reduce the use of concrete for rebuilding and cut concrete's impact on the environment. Cement production creates roughly 9.5% of global carbon emissions, according to a recent European Commission report. And concrete use is set to skyrocket, due to a building boom in countries like China, which used more cement from 2011 to 2013 than the U.S. used in the entire 20th century, as detailed in the *Washington Post*.

Concrete Chemistry

Cement is the glue that holds concrete together. Making cement involves heating limestone (calcium carbonate) and clays to about 1,480 °C. This drives out carbon dioxide from the limestone to produce lime (calcium oxide), resulting in marble-sized pellets containing various calcium minerals that are ground into gray cement powder. Cement's carbon emissions arise when limestone is converted to lime and from burning the fuel needed to heat the giant kilns in which the material is made.

Concrete is the world's most-used construction material. Creating concrete that self-heals cracks could make bridges, buildings, and overpasses last longer before needing expensive repairs. Credit: Shutterstock.

To make concrete, cement is then mixed with water and aggregates like sand or gravel to produce a slurry. After the mixture is poured into place, the cement reacts with water and releases highly alkaline hydroxyl ions, which help form calcium silicate hydrates that bind the aggregates together. The concrete hardens over time, resulting in a material that is strong when compressed. To give it tensile strength, however, construction crews often reinforce it with steel rebars embedded in the concrete. Other materials, often sold as patented admixtures, can be mixed in to give the concrete certain properties, like improved flow and different curing speeds.

Ordinary concrete does have the ability to heal itself, albeit very slowly. "Concrete always has some unreacted cement particles", says Nele De Belie, a structural engineer at Ghent University, in Belgium. "When cracks occur, water and carbon dioxide from air seep in, and this makes more limestone and calcium silicate hydrates. So concrete can heal extremely slowly without adding anything." By adding new materials to concrete, researchers hope to speed up that process.

The trick to making self-repairing concrete is to heal microscopic fissures before they become large cracks,

Published: December 14, 2015

DOI: 10.1021/acscentsci.5b00376
ACS Cent. Sci. 2015, 1, 470−472

explains Victor C. Li, a civil and environmental engineering professor at the University of Michigan, Ann Arbor. In some ways concrete is like biological material, he says: "If we get a paper cut, we expect the skin to self-heal. That wouldn't work if we ran our hand under a butcher knife."

The idea of self-healing concrete originated with Carolyn Dry, an architecture professor at the University of Illinois, Urbana—Champaign, in the early 1990s. Dry tried to embed concrete with glass capsules that would break when a crack formed and release methyl methacrylate glues. But the glues were too viscous to flow out and fill the cracks. Plus, glass capsules would have a hard time surviving a cement mixer.

But since those early efforts, scientists and engineers have found new, more effective ways to embed healing agents in concrete. Now, some of the first commercial products are in sight.

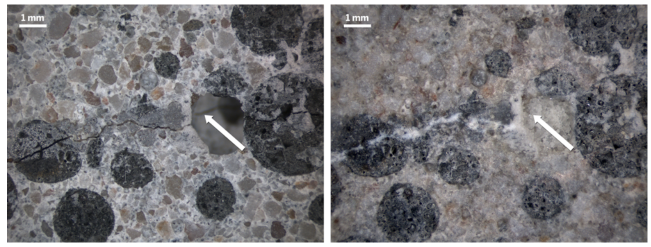
The biggest challenge with encapsulated healing agents is maintaining the concrete's strength and density. "You can't put too much healing agent in because that would compromise mechanical properties, and concrete has got to do its job", says Kevin A. Paine, a professor of civil engineering at the University of Bath, in England.

Also, finding a good healing agent and encapsulating material is tricky. The capsule needs to be inert to the chemicals and additives in concrete and to the healing material it carries. Plus, capsules need to be flexible during cement mixing so they don't break, but then become brittle as the concrete hardens so that they can rupture when needed. "People have come up with good ideas on what goes into the capsule, but making the capsule itself has been a stumbling block", Paine says. Researchers have tried making capsules from clays, gels, waxes, and polymers. These capsules have carried a wide variety of healing agents such as minerals, polymers, resins, and even bacteria.

Living Concrete

Yes, bacteria. Dutch and Belgian scientists have led the groundbreaking work on concrete that harnesses living organisms to heal itself. This promising method, which is closest to commercialization, is the brainchild of microbiologist Hendrik M. Jonkers and civil engineer Erik Schlangen of the Delft University of Technology, in The Netherlands.

Jonkers and Schlangen mix clay pellets containing calcium lactate and spores of limestone-producing bacteria into concrete. They use alkali-tolerant bacteria species such as *Bacillus pseudofirmus* that can survive the high pH of concrete. These bacterial spores can lie dormant for decades. When the pellets crack with the concrete, moisture in the air triggers the spores to germinate. The bacteria then feed on calcium lactate in the presence of moisture and oxygen to form limestone, sealing the cracks. This healing happens in just 3 weeks, and the bacteria can seal gaps up to 0.8 mm wide.



In a self-healing bioconcrete, dormant bacterial spores contained in clay pellets (black and gray circles, left) germinate when cracks expose them to moisture. The microbes feed on calcium lactate to form limestone, sealing the cracks (right). Credit: Delft University of Technology.

The team has tested the material by building a lifeguard station at a lake in The Netherlands with it and then deliberately forming cracks. These cracks filled up with limestone as expected, keeping the structure watertight. The team is now trying to develop a sugar-based nutrient to replace the costly calcium lactate. But Jonkers is reportedly putting the technology on the market by 2016 in three different forms: a concrete, a mortar for patching cracked concrete, and a liquid that can be sprayed onto existing structures.

In another example of microbe-healed concrete, De Belie's team at Ghent packages bacterial spores in a melamine formaldehyde shell and has been able to make concrete that can heal small cracks up to 1 mm wide in 4 weeks. They've recently identified a limestone-producing bacterial strain that does not require oxygen, but instead uses nitrates, which would be added to the concrete, so the microbes could potentially do their healing work deep within concrete structures where there is little access to air, De Belie says.

The researchers are also trying to encapsulate bacteria within a hydrogel. The idea is for the hydrogels to hydrate and nourish the bacteria, allowing them to live longer after germination. Through the European Union funded HEALCON self-healing concrete project, which De Belie leads and which includes TU Delft as a partner, she is scaling up production of the encapsulated bacteria and is planning large-scale tests that will begin next year.

Beyond Bacteria

Bacterial concrete has promise, but De Belie says polymers might have an advantage over bacteria: They would seal cracks much faster. Plus, having an elastic material filling cracks is beneficial for bridges, which have to bend slightly under their dynamic loads. The researchers are experimenting with different healing polymers such as polyurethane and

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methyl methacrylate, but the liquid monomers that form these polymers have a limited shelf life and often react with their capsule material.

Hydrogels, meanwhile, could help speed up concrete's natural healing ability. They can absorb up to 500 times their own weight in water, so by adding them to the cement mix, "the hydrogels retain water and provide it to the unreacted cement around them, so you stimulate the healing process", De Belie says. What's more, hydrogels can be thrown right into the cement mix without encapsulation.

At the University of Bath, Paine, along with chemists and engineers at the Universities of Cardiff and Cambridge, are working on a multicomponent concrete healing system. The project, named Materials for Life and funded by the U.K. government and British construction and civil engineering company Costain, aims to create concrete that can repeatedly repair itself.

The concrete would heal cracks at various stages of formation using three different methods. In addition to bacterial healing, encapsulated chemical agents could patch small cracks up to 0.2 mm wide. The Cambridge group makes microcapsules of polyurethane or calcium alginate and fills them with minerals such as sodium silicate, colloidal silica, calcium oxide, or magnesium oxide that react with water and form cementitious materials to seal cracks.

The second technique uses shape-memory polymers made by Cardiff engineers. Shape-memory polymers can be triggered by heat or electricity to assume a preprogrammed shape. The idea is that when a large, 1 mm wide crack forms, a current passed through the concrete would activate the shape-memory polymers to shrink and pull the concrete together for the healing agents to do their job.

The third component is a network of thin, hollow vessels throughout the concrete to replenish the healing materials once they run out. In October 2015, the researchers launched a six-month pilot trial of the three technologies, separately and in various combinations, at a Costain construction site in South Wales. The aim is to combine all three into one product after getting results from the trial.

Meanwhile, Li at the University of Michigan wants to develop a self-healing concrete that keeps cracks small and speeds up the material's natural healing ability. Microscopic poly(vinyl alcohol) fibers in the concrete spread the force from a heavy load, leading to many small cracks instead of one big crack. Proprietary accelerants added to the concrete speed up the natural reaction of water and carbon dioxide with the unused cement in the concrete. Li is in the midst of commercializing the technology.

But it could still be a few years before sidewalks and buildings are made of any type of self-repairing concrete. The biggest hurdle to using the technology right now is exactly what makes concrete the number one construction material in the world. "It's just such a cheap product", De Belie says. "Anything you add to it adds expense."

Plus, adds Li, "the construction industry is extremely cost sensitive and generally tends to be more careful in terms of adopting materials."

Nevertheless, the researchers are optimistic and believe that a market for self-healing concrete exists. Paine says the first applications will likely be in structures that are hard to access and prohibitively expensive to repair, such as bridges, underground pipes, and underwater tunnels and foundations. "It would be nice to walk away from a concrete structure and never worry about repairing it."

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