Cement vs. concrete: Their differences, and opportunities for sustainability

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After water, concrete is the most consumed material on Earth. Researchers in the MIT Concrete Sustainability Hub study how to reduce its impact. Credit: Life of Pix/Pexels

There's a lot the average person doesn't know about concrete. For example, it's porous; it's the world's most-used material after water; and, perhaps most fundamentally, it's not cement.

Though many use "cement" and "concrete" interchangeably, they actually refer to two different—but related—materials: Concrete is a composite made from several materials, one of which is cement.

Cement production begins with limestone, a sedimentary rock. Once quarried, it is mixed with a silica source, such as industrial byproducts slag or fly ash, and gets fired in a kiln at 2,700 degrees Fahrenheit. What comes out of the kiln is called clinker. Cement plants grind clinker down to an extremely fine powder and mix in a few additives. The final result is cement.

"Cement is then brought to sites where it is mixed with water, where it becomes cement paste," explains Professor Franz-Josef Ulm, faculty director of the MIT Concrete Sustainability Hub (CSHub). "If you add sand to that paste it becomes mortar. And if you add to the mortar large aggregates—stones of a diameter of up to an inch—it becomes concrete."

What makes concrete so strong is the chemical reaction that occurs when cement and water mix—a process known as hydration.

"Hydration occurs when cement and water react," says Ulm. "During hydration, the clinker dissolves into the calcium and recombines with water and silica to form calcium silica hydrates."

Calcium silica hydrates, or CSH, are the key to cement's solidity. As they form, they combine, developing tight bonds that lend strength to the material. These connections have a surprising byproduct—they make cement incredibly porous.

Within the spaces between the bonds of CSH, tiny pores develop—on the scale of 3 nanometers, or around 8 millionths of an inch. These are known as gel pores. On top of this, any water that hasn't reacted to form CSH during the hydration process remains in the cement, creating another set of larger pores, called capillary pores.

According to research conducted by CSHub, the French National Center for Scientific Research, and Aix-Marseille University, cement paste is so porous that 96 percent of its pores are connected.

Despite this porosity, cement possesses excellent strength and binding properties. Of course, by decreasing this porosity, one can create a denser and even stronger final product.

Starting in the 1980s, engineers designed a material—high-performance concrete (HPC)—that did just that.

"High-performance concrete developed in the 1980s when people realized that the capillary pores can be reduced in part by reducing the water-to-cement ratio," says Ulm. "With the addition of certain ingredients as well, this created more CSH and reduced the water that remained after hydration. Essentially, it reduced the larger pores filled with water and increased the strength of the material."

Of course, notes Ulm, reducing the water-to-cement ratio for HPC also requires more cement. And depending on how that cement is produced, this can increase the material's environmental impact. This is in part because when calcium carbonate is fired in a kiln to produce conventional cement, a chemical reaction occurs that produces carbon dioxide (CO_2).

Another source of cement's CO_2 emissions come from heating cement kilns. This heating must be done using fossil fuels because of the extremely high temperatures required in the kiln (2,700 F). The electrification of kilns is being studied, but it is currently not technically or economically feasible.

Since concrete is the most popular material in the world and cement is the primary binder used in concrete, these two sources of CO_2 are the main reason that cement contributes around 8 percent of global emissions.

CSHub's Executive Director Jeremy Gregory, however, sees concrete's scale as an opportunity to mitigate climate change.

"Concrete is the most-used building material in the world. And because we use so much of it, any reductions we make in its footprint will have a big impact on global emissions."

Many of the technologies needed to reduce concrete's footprint exist today, he notes.

"When it comes to reducing the emissions of cement, we can increase the efficiency of cement kilns by increasing our use of waste materials as energy sources rather than fossil fuels," explains Gregory.

"We can also use blended cements that have less clinker, such as Portland limestone cement, which mixes unheated limestone in the final grinding step of cement production. The last thing we can do is capture and store or utilize the carbon emitted during cement production."

Carbon capture, utilization, and storage has significant potential to reduce cement and concrete's environmental impact while creating large market opportunities. According to the Center for Climate and Energy Solutions, carbon utilization in concrete will have a $400 billion global market by 2030. Several companies, like Solidia Cement and Carbon

Cure, are getting ahead of the curve by designing cement and concrete that utilize and consequentially sequester CO_2 during the production process.

"What's clear, though," says Gregory, "is that low-carbon concrete mixtures will have to use many of these strategies. This means we need to rethink how we design our concrete mixtures."

Currently, the exact specifications of concrete mixtures are prescribed ahead of time. While this reduces the risk for developers, it also hinders innovative mixes that lower emissions.

As a solution, Gregory advocates specifying a mix's performance rather than its ingredients.

"Many prescriptive requirements limit the ability to improve concrete's environmental impact—such as limits on the water-to-cement ratio and the use of waste materials in the mixture," he explains. "Shifting to performance-based specifications is a key technique for encouraging more innovation and meeting cost and environmental impact targets."

According to Gregory, this requires a culture shift. To transition to performance-based specifications, numerous stakeholders, such as architects, engineers, and specifiers, will have to collaborate to design the optimal mix for their project rather than rely on a predesigned mix.

To encourage other drivers of low-carbon concrete, says Gregory, "we [also] need to address barriers of risk and cost. We can mitigate risk by asking producers to report the environmental footprints of their products and by enabling performance-based specifications. To address cost, we need to support the development and deployment of carbon capture and low-carbon technologies."

While innovations can reduce concrete's initial emissions, concrete can also reduce emissions in other ways.

One way is through its use. The application of concrete in buildings and infrastructure can enable lower greenhouse gas emissions over time. Concrete buildings, for instance, can have high energy efficiency, while the surface and structural properties of concrete pavements allow cars to consume less fuel.

Concrete can also reduce some of its initial impact through exposure to the air.

"Something unique about concrete is that it actually absorbs carbon over its life during a natural chemical process called carbonation," says Gregory.

Carbonation occurs gradually in concrete as CO_2 in the air reacts with cement to form water and calcium carbonate. A 2016 paper in Nature Geoscience found that since 1930, carbonation in concrete has offset 43 percent of the emissions from the chemical transformation of calcium carbonate to clinker during cement production.

Carbonation, though, has a drawback. It can lead to the corrosion of the steel rebar often set within concrete. Going forward, engineers may seek to maximize the carbon uptake of the carbonation process while also minimizing the durability issues it can pose.

Carbonation, as well as technologies like carbon capture, utilization, and storage and improved mixes, will all contribute to lower-carbon concrete. But making this possible will require the cooperation of academia, industry, and the government, says Gregory.

He sees this as an opportunity.

"Change doesn't have to happen based on just technology," he notes. "It can also happen by how we work together toward common objectives."

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