Cement production involves low energy, but its carbon footprint is high. The key to reduction is in the clinker.

A concrete path to sustainability

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That tourists can still admire the Colosseum and Pantheon built by Roman engineers 2000 years ago is due in large part to the material holding these impressive structures together: cement.

In generic terms, cement is a binder that locks together other materials. The highest-quality Roman cement was a mix of burnt lime (calcium oxide) and volcanic ash. The material's present-day incarnation typically implies "Portland" cement, made by heating limestone (calcium carbonate) and clay in large kilns. Combined with sand and gravel, it makes concrete, the material produced in modern day more than any other. As with anything made on a colossal scale, its environmental impact is fast becoming a concern.

The cement industry is by no means an energy hog. Producing cement in the United States consumes 0.33% of the country's energy, less than the 1.8% used to make steel, according to the Department of Energy. But the carbon dioxide emissions from cement production are not in proportion with the energy used to make cement. Making every ton of cement emits roughly 0.8 ton of CO_2, and cement production accounts for 8% of global carbon emissions.

The pressing concern is that the current use of cement to make concrete is ballooning. Urbanization is rapidly increasing worldwide, especially in developing countries like China, which produces over 57% of the world's roughly 4 billion tons of cement. As sidewalks, buildings, and bridges sprout at an accelerating pace, the world could produce up to 4.8 billion tons by 2050, according to the International Energy Agency.

Producing cement sustainably is necessary if societies are to continue growing. Governments, industry, and researchers are already aware of this need, and are working—in many cases together—toward this goal. "Around half of all materials we make is concrete," said Karen Scrivener, a materials science and engineering professor at the Swiss Federal Institute of Technology in Lausanne. "Because there's so much used, emissions improvements can have a very big impact."

Despite its massive use and long history, cement is one of the most complex materials known. Scientists still do not fully understand its structure and the chemical reactions that happen when it is mixed with water.

The Portland cement-making process requires burning limestone and clay at 1450°C. This drives out CO_2 from the limestone to give lime and results in golf ball-sized pellets, called clinker, that are ground to give the familiar gray powder. Converting limestone to lime results in 60–65% of the carbon emissions from cement manufacture; the rest comes from burning fuel to fire the kilns and the electricity used to grind clinker.

For decades, the industry has been chipping away at cement's energy use by making kilns more efficient and using alternative energy sources such as domestic waste and discarded tires. "The energy used per ton of cement made has been cut by a factor of two since the 1970s," Scrivener said.

Creating a major dent in carbon emissions, though, requires tackling the major emission culprit: clinker. And the most straightforward way to do that is to partially replace it with other materials.

Some common clinker substitutes are fly ash, a residue from coal-burning power plants; blast furnace slag, a by-product of iron and steel production; and, harking back to ancient Rome, volcanic ash. Most major cement companies sell cement in which these waste materials make up 20–30% of the volume. "But you still have emissions related to the rest of the 70% to contend with," said Philip Purnell, a professor of materials and structures at the University of Leeds, UK. "This is not a game changer."

Replacing too much clinker, however, alters cement's properties. The binder's single-most important property is the strength it imparts to concrete, Scrivener said. Once the concrete slurry is poured into a desired mold, it has to be cured to gain strength and harden. Given the speed with which structures are built at present, "we need concrete strength properties in three to seven days," Scrivener said. "In that time range, with a conventional alternative like slag, you may be able to substitute 30–40% by volume and get similar properties at seven to fourteen days."

Because the world demands gigatons of cheap cement, substitute materials also need to be readily available at low cost, as are the clay and limestone that make clinker. But slag and good quality fly ash (with low sulfur and carbon content), can be hard to find and expensive, especially in developing countries that lack the heavy industries that produce those waste materials.

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Producers and builders are increasingly using ternary blends that combine clinker, fly ash, and slag. They are also widening their outlook to natural, locally available materials such as burnt rice husk, limestone, recycled pavement, broken glass, and clay.

Researchers are working on promising new cement recipes. One is a combination of clinker, limestone, and calcined clay that Scrivener has developed together with Fernando Martirena of the Central University of Las Villas in Cuba and Shashank Bishnoi, a civil engineering professor at the Indian Institute of Technology Delhi. The system allows over half the clinker in cement by weight to be substituted by a combination of clay fired at relatively modest 700°C and limestone, which does not have to be converted to lime by removing CO_2.

Initial strength tests of the new cement show promise, but the researchers need to perform long-term studies to demonstrate durability. Nonetheless, Scrivener said, the material could be used in the field within two years in countries such as Cuba, where no other clinker substitutes are available and cement demand is projected to double or triple in the next five years.

Indeed, the Cuban cement industry has launched a trial of 300 tons of a cement blend that replaces 52% of clinker with the limestone-calcined clay material. Cement companies such as India's Aditya Birla and France's Lafarge are enthusiastic about the blend, Bishnoi said, and are supporting its viability tests. Representatives from countries such as Brazil, Thailand, and Russia have also shown interest in the material.

By 2050, 83% of the population in developing countries could be city dwellers. Booming urban construction in China (seen here) and elsewhere requires gigatons of cement for concrete, the main building material used by modern society. *Credit:* Ignus Gerber.

Untried formulations include now-defunct London-based startup Novacem's cement that uses magnesium silicate instead of limestone. The idea is to convert magnesium silicate into magnesium oxide in a low-temperature, low-carbon process. Meanwhile Calera, a startup in Los Gatos, California, claims to have a carbon-negative solution that involves exposing calcium-containing seawater to a CO_2-rich power plant flue gas to precipitate calcium carbonate.

These new approaches might not be practical for many years. The Calera process involves huge processing costs, Scrivener said. And while there are many magnesium silicate deposits around the world for Novacem's technology, they are not uniformly distributed. Nonetheless, said Purnell, "magnesium silicate chemistry has the most promise in the long term."

Any new chemistry needs to meet the industry's strong standards. Unless cement chemistry is right, for instance, steel embedded in the concrete can rust quickly. "Many proposed cements do not necessarily have the right chemistry to stop the corrosion of steel," Purnell said. "No manufacturer is going to replace Portland cement with a completely new material unless they can be absolutely sure they're retaining performance, and there have been no long-term tests that give confidence in the new materials' behavior."

In addition to focusing research on cement clinker, Purnell said the construction industry should look at other traditional tricks that could be immediately implemented to improve concrete. One solution is to use crushed aggregate instead of coarse substances such as gravel. This opens up the use of construction debris as an aggregate source and results in more aggregate material, significantly cutting the amount of cement needed.

Another low-tech solution, said Bishnoi, is to use cements tailored to applications. "Right now, there is one product, one solution fix to any application, whether it's a wall or a twenty-story building, but you could use lower-clinker cement for lower height applications."

The problem is, even simple changes require time in a giant industry set in its ways. Nonetheless, cement companies are already starting to pay attention to cement's environmental impact. The Cement Sustainability Institute, a voluntary program led by cement company CEOs, published a roadmap in 2009 outlining existing and potential technologies to reduce the cement industry's carbon emissions by 2050. In March, Indian CSI members published a roadmap specific to the subcontinent, and other big cement markets, such as Brazil and China, are expected to follow suit.

In India, the cement sustainability push in government and industry is due to limited resources and the need to make cement cheaper, Bishnoi said. National regulations on fly ash content are being moved from 35% by weight to 40% since fly ash is easily available from the coal power plants that generate more than half of the country's power. "There is a lot of external pressure on developing countries to reduce emissions," Bishnoi said. "But I really don't think the pressure is needed. Within India, people might not care about global temperature increase or environmental effects, but they realize that resources are limited, and we have to use them efficiently." □

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