Credit: ACE-MRL, University of Michigan

Roppongi Tower, Toyko, Japan, constructed with ECC materials.

Bound for new frontiers

Cement researchers are bringing new strength, flexibility, self-healing capabilities and a smaller CO_2 footprint to industry.

by Wendy Hankle

Less than five years ago, construction began on two high-rise buildings in the Tokyo area. The buildings, one at 41 stories the other at 27, were an ambitious project – but not because of their size, location or function. The buildings used a material called "bendable concrete," an engineered cementitious composite. This ECC looks like regular concrete, but is 500 times more resistant to cracking and 40 percent lighter in weight.

Credit: ACE-MRL, University of Michigan

Self-healing concrete works because it can bend. When it's strained, many microcracks form instead of one large crack that causes it to fail. Here, a specimen is bending as a force of 5 percent tensile strain is being applied. Regular concrete would fail at 0.01 percent tensile strain.

"As a result of using the bendable concrete, the buildings are able to deform and deflect energy," explains Victor Li, a University of Michigan professor of civil and mechanical engineering. "Buildings using bendable concrete are considered some of the safer buildings in Japan."

Bendable concrete was developed by Li and his students in a UM laboratory. It takes the bite out of concrete's brittle properties, infusing the material with more ductility, enabling it to actually stretch like steel and have a strain point. But bendable concrete isn't the end of the story for Li – it's the beginning of a new frontier.

"As I see it, we need better concrete for more durable structures with less maintenance requirements," Li says. "We need concrete material that creates infrastructures that have less environmental impact, that are more sustainable, and, finally, a concrete that allows us to do things more effectively than we are doing now."

It's a tall order. And Li's group at UM is in good company tackling it.

Florence Sanchez is a researcher and assistant professor of civil and environmental engineering at Vanderbilt University. She's exploring the promise of nanomaterials in concretes and cements. It's a burgeoning area of research, encompassing the potential of specific materials such as nanosilica and nanotitanium oxide – not to mention the promise of nanotubes functioning within the concrete mixture as something of a "nanorebar."

"The tensile strength is very high, stronger than steel, but as light as aluminum," says Sanchez, chair of ACerS Cements Division, of reinforcing concrete with nanotubes. "It's a pretty interesting idea because we would be able to have a material that could be extremely strong yet we can reduce the weight."

And, heaven knows, the current system of reinforcing concrete with steel rebar could use some updating. When concrete cracks, it paves the way for water and deicing salts to reach the steel rebar, which then corrodes, swells and increases the cracks in the material. It's a self-sustaining cycle: cracks lead to corrosion, which leads to more cracks and corrosion. But, even taking the cycle of deterioration into account, industry can be slow to adopt new technologies and materials.

"Concrete's one of the most widely used materials in the world," says Zach Grassley, assistant professor at Texas A&M University. Grassley's research interests encompass development and analysis of cementitious materials. "The difficult thing in the concrete industry is if you want to be able to sell something, sustainability is not easy. Those technologies that give you up front cost reductions are the ones that people get excited about."

Grassley points to some of the concrete technologies that did just that – self-consolidating concrete, for instance, which had great upfront costs for the contractor that were offset by the savings in labor. Use of SCC – a highly flowable, nonsegregating concrete that spreads into place using its own weight – has grown tremendously since it was introduced in the 1980s.

Grassley, chair-elect of the Cements Division, sees a role for government agencies, too, in providing encouragement to support wider use of more sustainable materials.

"That type of an impetus could come from government agencies like DOTs," Grassley says. "The contractors aren't going to do it voluntarily, so if the way things are specified, changes, such that long-term performance has some value, then things will change."

Beyond nanorebar

But researchers aren't standing around with their hands in their pockets waiting on industry to carry the ball. Work is going on now to develop materials that will shape the future. Sanchez says she's excited about the potential of "nanoengineering" cementitious materials, working with additives such as nanosilica and nanotitanium oxide to obtain materials with greater durability, strength, or even self-cleaning properties.

Alhough the potential of nanomaterials in admixes is great, fully understanding the implications and properties provides another set of challenges. Sanchez points to the difficulty in getting a handle on the dispersion of the nanoreinforcements in cement mixture, and ensuring a good bond between the two.

"That's been the biggest slowdown in this area," Sanchez says. "That's where the research is going on right now."

Nanotubes and nanomaterials also carry other baggage that might inhibit adoption.

"The primary limitation is not in the raw materials themselves. The cost is fabrication," Grassley explains. "Carbon is everywhere. It's a cheap material."

Grassley likens it to the development of computer processors. Silica is also an extremely abundant raw material, but again, the cost was in fabrication. Once computers hit the mainstream, things started rolling. "I think the same thing will probably happen with carbon nanotubes and nanofibers," Grassley says.

But the possibilities for cements and concretes don't stop with nanomaterials. Harnessing the piezoelectric properties of concrete is one new focus of exploration for UM's Li. Li's secured funding from the National Institute of Standards and Technology combining a current area of his research – self-healing concrete – with a new capability: telling you where it hurts.

Self-healing concrete is an ECC that has the capacity to control the width of its cracks, allowing for the formation of many tiny cracks when overloaded instead of a few large ones. These smaller cracks expose tiny amounts of unhydrated cement, which, when water and carbon dioxide are added, form something of a "scar."

Future work has Li taking things one step further. Using the material's piezoelectric capacities – instead of costly sensors – self-sensing concrete would correlate electrical property changes with damage and recovery, then report the data in the form of electrical currents to a computer. Once the data is reported, it can be put in graphic form.

"Basically using electrical measurements in 3-D form, one can actually look for damage inside the material," Li explains. "We will be able to see the internal damage and the material's recovery, just like an X-ray or CAT scan provides that same perspective in the human body."

Maria Juenger, an associate professor at University of Texas, is looking into ways to reduce the carbon footprint of cement and concrete production by using a system called calcium sulfoaluminate cement. The secret to the diminished CO_2 contribution is found in two aspects of the material: Less limestone is needed to make the phases, producing less CO_2 in the kiln, and lower heating temperatures are used requiring less energy to grind it.

"Calcium sulfoluminate cement has been around for a while, but people haven't been using it that much, mostly because building codes in the United States are so restrictive," she says.

When contrasted with the longevity of Portland cement, this material has a lot of unknowns. Research is starting at the beginning: She is building a case for the implementation of the new system to make sure it's durable. Juenger estimates that implementation is a few years away.

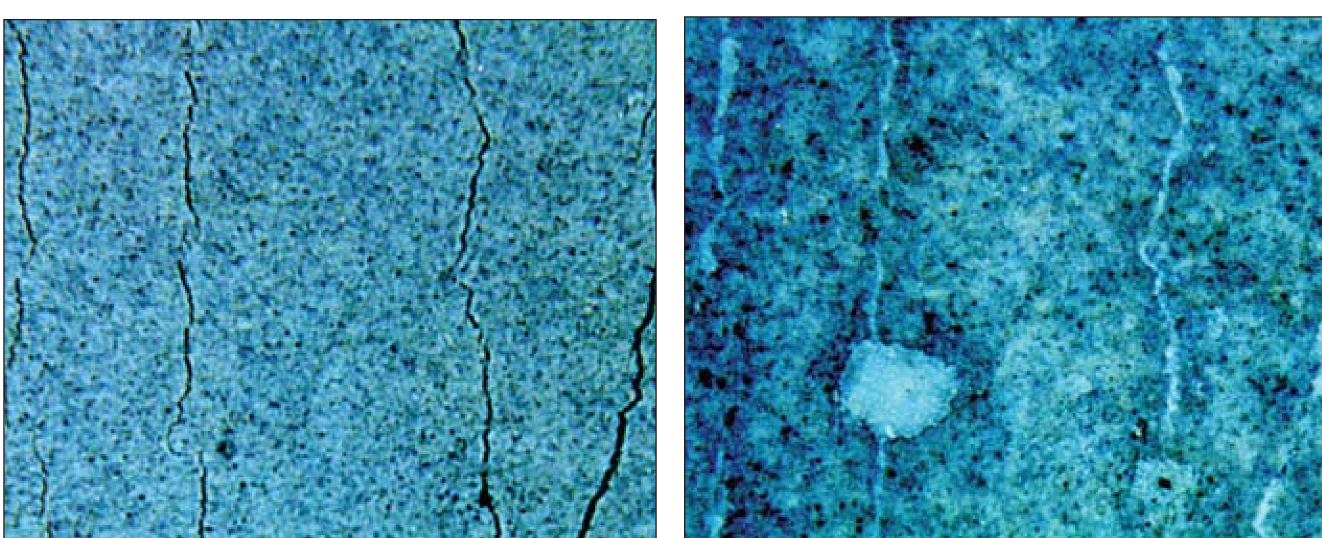
"We make it in the lab and that's fun, but there's a limit when you're making 5 grams and trying to figure out if that's going to be an industrially feasible material," Juenger adds. Research persists in part because of the support given by concrete companies. Many have signed agreements to reduce their CO_2 production and energy use, Juenger says, and this provides an opportunity for delving more deeply into the potential of calcium sulfoluminate cement.

Exploring potential

Sussing out the properties of experimental cement and concrete mixtures is an integral part of detailing their capabilities – and making them attractive possibilities for real-life applications.

Joe Biernacki is a professor at Tennessee Tech University. He leads a cements research group that looks at kinetics as a variety of types of reactions. Biernacki, Cements Division secretary, says he is interested in applying his background in chemical kinetics and transport phenomenon to the field of cementitious materials.

"The work we do we link to the environment," Biernacki says. "If we can make concrete last twice as long, just a factor of two would be remarkable. It would certainly make concrete more environmentally friendly."



Credit: ACE-MRL, University of Michigan

These close-up photographs illustrate how the concrete cracks (left) before and (right) after healing.


Credit: ACE-MRL, University of Michigan

The white lines on this slab of bendable concrete show where the material has healed itself with no human intervention. Only water and carbon dioxide are necessary.

Biernacki's interest is in research using nondestructive in-situ techniques to study the multiscale mechanical response of Portland cement and composites utilizing synchrotron X-ray and neutron diffraction. Calcium hydroxide is a big area of potential, Biernacki says.

"By directly observing the strain in calcium hydroxide, we can study all manner of things like creep and drying," he explains.

Jim Kirkpatrick is the dean of the College of Natural Science of Michigan State University. He's also the trustee for ACerS' Cements Division. Like Biernacki, Kirkpatrick is interested in understanding the atomic-scale structures of cements and how phenomena at those scales have an effect on chemical and mechanical properties. Kirkpatrick sees potential in understanding nanoparticles through NMR spectroscopy, taking the traditional models using silicon and substituting calcium.

"The most common tool to look at atomic-scale construction is silicon 29 NMR, but the atomic-scale structure around calcium is quite different," Kirkpatrick says. "Calcium 43 NMR is very difficult, but it turns out with the modern high-field NMR spectrometers, it is possible."

Kirkpatrick's interests also lie in models of cement that involve clusters on the scale of 5–50 nanometers, specifically in figuring out how hardened cement paste can be so strong with that type of nanostructure. "To me that's just a fascinating question, and a lot of people are working on it.

"It's become clear over the past 10–15 years that the hydrated cement paste is very complicated nanostructured material," Kirkpatrick continues. "Understanding its chemical and mechanical properties is going to require understanding the molecular and nanoscale structure and chemistry."

Biernacki and his colleague, Don Visco, associate professor of chemical engineering at Tennessee Tech, are attacking the challenge from a different angle. The two have developed a technique for encoding the structure of molecules that have a particular performance behavior in a given application. The encoded data is run through a computer model that correlates the properties or performance in the application and predicts new molecular structures to enhance the desired aspects of performance.

"This has the potential to, for instance, design a mixture to alter the rheological properties of concrete," Biernacki says. "We also might be able to design entirely new molecules."

Standing on the cutting edge of research in the field of cements and concrete requires a bit of delayed gratification.

"Silica NMR work that people did back in the '80s and '90s is now standard stuff in the industry," Kirkpatrick says. "To me, that's the way this works. I don't take on problems of immediate interest to industry, but we try to develop techniques and understanding and principles that can be used in ways that we never ever predicted."

UM's Li share's Kirkpatrick's strategic view and optimism. "Future civil infrastructure," he says, "will be safer, more durable and environmentally friendly, and significantly intelligent, as a result of on-going research in cement technology at the micron and nanoscales today." ■