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Inside This Issue:

Bendable Concrete Provides Insight into Sustainable Material Development Process

Materials that work together and interact with each other are the essence of a sustainable system.

A hush falls over the crowd as one of the greatest golfers of all time stoops to place his ball on the tee. The summer sun is high in the mid-afternoon sky as he straightens and squints down the perfectly manicured, lush, green fairway. Gripping his club with the practiced hands of a surgeon holding a scalpel, he assumes a stance, relaxed but purposeful, with his feet in line with the ball's intended path of travel. With an almost imperceptible intake of breath, he begins his backswing, his shoulders and hips rotating as he brings the club back, back, back. Then his swing begins. His body, coiled like a tightly-wound spring, explodes at just the right moment to generate 130 mph club-head speed, which (with a satisfying CRACK) sends the ball over 300 yards straight down the fairway. With the ball still rolling after it lands, he stoops to pick up his tee. Handing the club and tee to his caddy, he acknowledges the roar of the gallery with a glance and a wave.

Tiger Woods' golf swing is beautiful, and you don't have to be a golf enthusiast to appreciate it. It's smooth and elegant but also powerful and intense. The speed of his club head as it comes into contact with the ball is among the highest of all pro golfers. But anyone who has chased the venerable dimpled sphere around a golf course knows that club-head speed is only a small part of the game. Without the proper grip, stance, hip and shoulder rotation, timing, and even emotional state, club-head speed could determine how deep in the woods someone will someday find your ball. An effective golf swing is a precise combination of actions that work together to send a ball a desired distance in a predictable direction.

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>
> Dr. Victor C. Li., Director, U-M Advanced Civil Engineering Materials Research Laboratory

Engineered Cementitious Composites (ECC), under development at the University of Michigan's (U-M) Advanced Civil Engineering Materials Research Laboratory (ACE MRL) since 1992 (the same year Tiger competed in his first PGA Tour event), are similar to a great golf swing. And you don't have to be an engineer to appreciate them. ECC, or bendable concrete, is made up of a precise combination of materials that work together to achieve a desired strength and predictable flexibility. ECC was invented by Dr. Victor C. Li, director of ACE MRL, who applied principles of microstructure tailoring to precisely control the interaction between the different materials that make up ECC. Microstructure tailoring describes the process of predicting the properties and characteristics of combinations of materials based on known properties of the individual materials before combining them. "ECC is a carefully engineered system," Li explains. "Every component is specifically designed to work with the others to achieve desired performance characteristics." The key performance characteristics exhibited by ECC include extreme flexibility, high fatigue resistance, very low fluid permeability, and compressive strength similar to that of high strength concrete.

Bends Without Breaking

ECC flexes without fracturing, due to the interaction between fibers, sand, and cement working in a matrix that binds everything together within the material. "In addition to reinforcing the concrete with fibers that act as ligaments to bond it more tightly," Li explains, "we design the cement matrix with special ingredients to make it more compatible with the fibers and to increase flexibility."

Where ordinary concrete and fiber-reinforced concrete (FRC) are designed to resist cracking, ECC is designed to crack only in a carefully controlled manner. The cracks that appear in ordinary concrete and FRC are Griffith-type cracks; they increase in width as they grow longer. The cracks that are designed into ECC are steady state (or flat) cracks; the width of these cracks remains constant regardless of the length. "Through microstructure tailoring, we're able to design ECC with a combination of materials such that the capacity of the fibers that bridge the cracks is greater than the capacity of the matrix to resist cracking," Li explains. U-M holds several patents on ECC technologies.

Used Around the World

The unique ability of ECC to bend while maintaining physical properties similar to other types of concrete has led to its use in a variety of new vertical and horizontal construction applications in Japan, Korea, Switzerland, Australia and the United States. For example, the Mihara Bridge in Hokkaido, Japan, open to traffic in May 2005, uses a composite deck made of steel and ECC. This bridge is 40 percent lighter than a bridge that uses a conventional design, and the expected service life of the deck is 100 years.

First Application in the U.S.

MDOT initiated the first use of ECC in a U.S. transportation infrastructure project in 2005. The Grove Street Bridge over I-94 in Ypsilanti was originally built using steel girders supported at concrete piers. The girders supported cast-in-place concrete decks. A mechanical expansion joint was used between these simple decks to allow for deck deformations imposed by deflection, concrete shrinkage, and temperature variations. Over time, deterioration of joint performance allowed water and deicing chemicals to leak through the joint and over the substructure, and ultimately resulted in severe damage to the bridge deck and substructure (see Figure 1-A).

Reconstruction of the bridge, completed in December 2005, incorporated an ECC link slab instead of a traditional mechanical joint between deck slabs (see Figure 2-B). "This demonstration project fit well with the department's strategic research plan," Calvin Roberts, Administrator of MDOT's Office of Research and National Best Practices (ORNBP) explains. "Improving bridge joints and increasing the life of bridge decks are two key objectives in the plan." Technical details of the project were summarized in Issue 100 of the *MDOT C&T Research Record* (August 2005).

Link slabs have been in use since the 1930s, and their advantage over mechanical joints was verified and documented through research conducted by Alampalli and Yannotti (1998). Unlike a conventional joint, which requires a great deal of maintenance and is susceptible to debris buildup and water infiltration, a link slab is virtually maintenance-free and provides a debris- and water-tight seal. Research to determine the durability of link slabs, conducted by Caner and Zia (1998), showed that they are subjected to bending loads under traffic conditions and as a result, tensile cracks develop at the tops of the slabs. These tensile cracks expand to allow water infiltration to the reinforcing steel, which leads to corrosion and further deterioration. Caner and Zia also concluded that additional tensile stress may be imposed on link slabs due to shrinkage, creep, and temperature loading.

Dr. Sudhakar Kulkarni, University Research Administrator for MDOT's ORNBP, explains the department's long-term interest in ECC. "The link slab demonstration project is a great example of a strategic application of ECC that enhances the performance of traditional high performance concrete. The combination of these two materials holds great potential for making bridges perform better and last longer."

ECC Capabilities for Link Slabs Documented

Prior to the Grove Street Bridge project, an experimental study funded by MDOT and conducted by Kim, Fischer, and Li (2003) showed that ECC was capable of withstanding the forces exerted on a link slab. Of particular note in this study was the comparison of crack widths between link slabs made with ordinary concrete and those made with ECC. After 100,000 loading cycles in the lab, crack widths in the concrete link slab were approximately 640 micrometers (μm) wide. A μm is one millionth of a meter. Under the same loading conditions, crack widths in the ECC link slab were less than 50 μm wide, which is about ¼ the width of a human hair.

Unexpected Cracking

Three days after placement of ECC on the Grove Street Bridge, early age cracking was found in the link slab. After one year of normal traffic and environmental loading, crack widths were 0.006 in.

1-A – Before Reconstruction 1-B – After Reconstruction

Figure 1. Slab and Support on Grove Street Bridge in Ypsilanti, Michigan, Before and After Reconstruction.

to 0.01 in., still smaller than the AASHTO standard of 0.013 in. after one year, but larger than they should have been. "Fewer cracks developed than expected but the cracks are wider than anticipated," said Roger Till, MDOT structural research engineer. "We have initiated a follow-up project to resolve the cracking issue."

This follow up project, which is an extension of the demonstration project and is expected to be completed in January 2008, will identify potential causes of the cracking. Nearly all are believed to have been caused by the interaction between the ECC link slab, the structural components of the bridge, and the environment. The project sets forth a plan to replicate the cracking so engineers understand it better and can take steps to prevent it from happening in future applications.

Exciting Possibilities for Sustainable Applications

Dr. Michael Lepech, research fellow at the University of Michigan's Center for Sustainable Systems, and a co-author of the ECC link slab project, is keenly interested in this process of experimentation that requires a holistic approach to development. "It comes down to sustainability," Lepech explains. "A sustainable system is one that takes all components into consideration and creates cooperation and synergy among them."

ECC is an exciting material for those interested in sustainability. The very process of designing ECC, for example, lends itself to experimentation with recycled, reclaimed, and waste materials. "Our growing understanding of the interaction between fibers, sand, and cement within ECC enables us to precisely adjust any of the elements to accommodate variations in the others." Lepech explains. An experimental version of ECC that uses a combination of cement kiln dust and green foundry sand to replace some or all of the ordinary cement and sand actually performed better than a version that used the ordinary materials. Cement kiln dust is a by-product of the portland cement production process. Green foundry sand is a by-product of the metal casting process. Both materials are produced in large quantities in Michigan, and both have historically been disposed of in landfills.

"It's great to be able to put these otherwise useless and even environmentally damaging materials to use like this," Lepech says. "We're constantly on the look out for different recycled materials to try in ECC."

Lower Environmental Impact, Less Expensive Over Time

The results of a study conducted by Keoleian, Kendall, Lepech, and Li (2006) provide another indication that ECC could play a key role as a material in sustainable transportation infrastructure applications. This study used life cycle modeling techniques to compare the sustainability performance of a bridge that uses traditional steel expansion joints to that of a bridge that uses ECC link slabs.

Life cycle modeling is completed in two parts. The first involves performing a life cycle assessment, which provides a measure of environmental and social impacts of using a product, system or technology. The second part is a life cycle cost analysis, which uses life cycle assessment data to calculate costs from various perspectives.

The study showed that bridge decks with ECC link slabs have a lower impact on the environment and cost less over a 60-year service life than those using steel expansion joints (see Table 1).

Bearer of Cost	Steel Expansion Joint	ECC Link Slab	ECC Cost Advantage
Agency	$ 640,000	$ 500,000	22%
User	$ 21,300,000	$18,200,000	14%
Environment	$ 34,000	$ 26,000	22%
Total	$ 22,000,000	$ 19,000,000	15%

Table 1. Total Life Cycle Costs.

Research is Improving Clarity

When describing the process of discovery that is playing out in the area of sustainable transportation infrastructure today, Dr. Lepech uses an analogy from a book, *Educating the Reflective Practitioner* (1987). The book was written by the late Dr. Donald Schön, a renowned organizational development expert and professor of philosophy at MIT. "In the varied topography of professional practice, there is a high, hard ground overlooking a swamp," Schön writes. "On the high ground, manageable problems lend themselves to solution through the application of research-based theory and technique. In the swampy lowland, messy, confusing problems defy technical solution." In the book, Schön goes on to describe how problems often present themselves not as well-formed structures, but rather as "messy, indeterminate situations."

Today the work of researchers in the "swampy lowlands" is filtering the previously murky water. As a result, we're beginning to see relationships more clearly and to understand for the first time, how links between "high and hard" islands of understanding can provide exciting and fascinating solutions to problems that, up until now, seemed unsolvable. Like a 300-yard drive straight down the fairway, each of these solutions requires a combination of actions strung together in precisely the right way. The results are smooth and elegant, powerful and intense; beautiful to see. And you don't have to be an engineer to appreciate them.

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