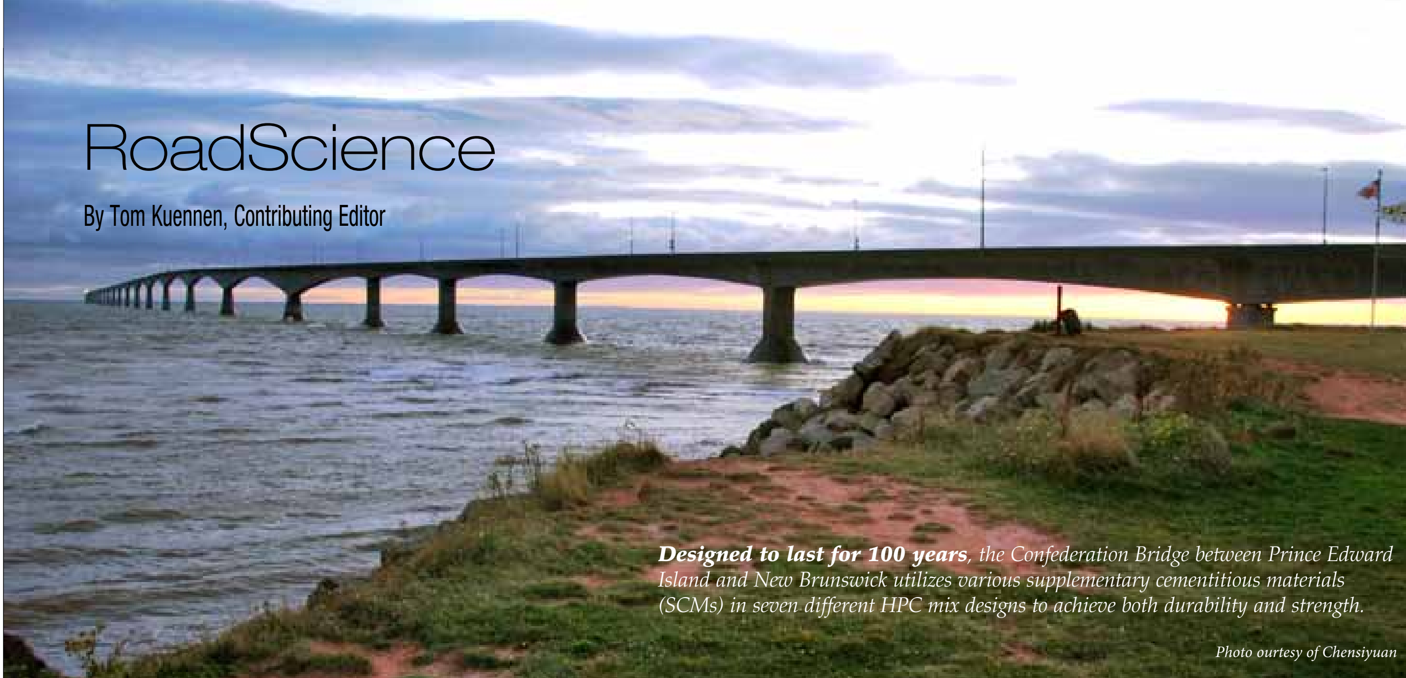


RoadScience

By Tom Kuennen, Contributing Editor

***Designed to last for 100 years**, the Confederation Bridge between Prince Edward Island and New Brunswick utilizes various supplementary cementitious materials (SCMs) in seven different HPC mix designs to achieve both durability and strength.*

Photo ourtesy of Chensiyuan

Ternary Concrete Mixes Offer High Performance

Reclaimed industrial byproducts play role in high-performance and ultra-high-performance mixes

Ternary and quaternary portland cement concrete mixtures – those incorporating three or four products into their cementitious components – are providing transportation infrastructure owners more durable, longer-lasting structures while incorporating industrial byproducts that in an earlier day were landfilled.

As such, they contribute to a "greener" or more environmentally sustainable transportation infrastructure, while adding value to the basic construction materials and providing a long-term lower cost for a structure, despite initial higher costs.

Ternary concrete mixtures include three different cementitious materials, including portland cement, and reclaimed industrial byproducts like ground, granulated blast furnace slag, silica fume or fly ash, to achieve high-compressive strengths, low permeability and corrosion resistance, resistance to sulfate and alkali-silica reactivity deterioration, and reduction of thermal cracking.

These mixes comprise today's High Performance Concrete (HPC), the mix design of choice for precast, prestressed bridges, beams and decks, and for some portland cement concrete pavements.

The importance of ternary concrete mixes is such that the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University has made them a high priority for research, with work continuing in two phases in 2011 (see below).

'Think Three'

A ternary mix has three cementitious components in the mix, according to Tim Cost, P.E., a senior technical service engineer for Holcim. "In general, [a ternary mix] includes portland cement and two of the following – slag cement, fly ash and silica fume – and often allows a higher total portland replacement."

How can three components be better than one or two? "There are practical limits and potential side effects from individual supplementary cementitious materials (SCMs)," Cost said at a recent presentation to the Alabama Concrete Industries Association. "Ternary blends allow the designer to best optimize mix properties for the project, for design and construction."

This includes optimization of a concrete mix for strength, permeability, durability, heat of hydration and plastic properties, including finishing, pumping, segregation and bleeding. They also may result in higher total cement replacement in a mix, with improved mix economics and implications for sustainability, he says.

Indeed, ternary mix components fly ash, slag cement and silica fume are 100-percent recycled content. Cost says they reduce the clinker content of concrete, thus lowering associated CO_2 emissions and embodied energy, and reduce landfill disposal of industrial byproducts.

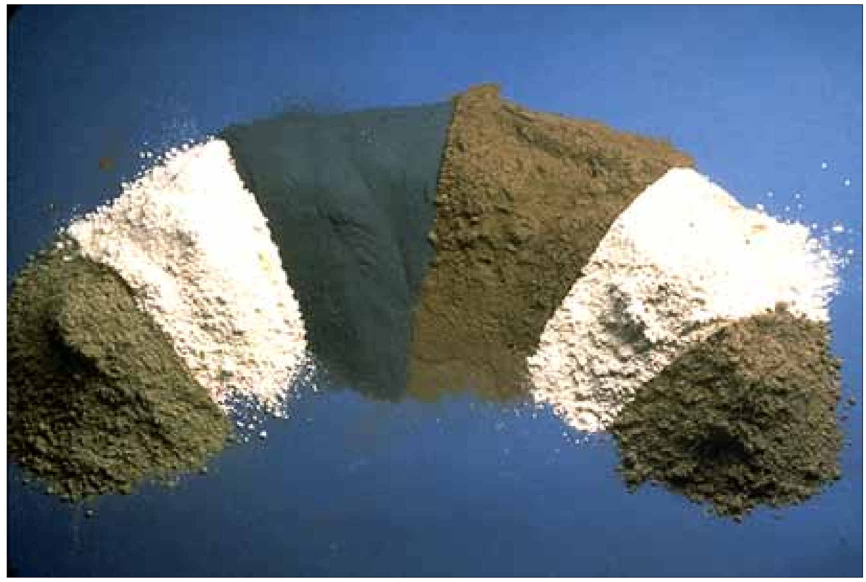
HPC, also referred to in the literature as "durable concrete," is an engineered concrete made up of the classic components of water, portland cement, and fine and coarse aggregates, but with a twist. With HPC, materials and admixtures are carefully selected and proportioned to realize high early strengths, high ultimate strengths and high durability beyond conventional concrete.

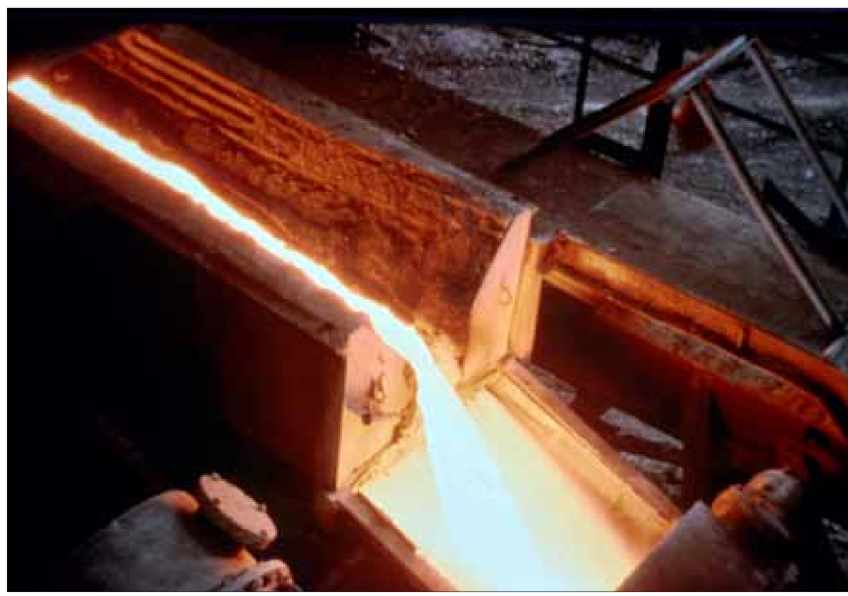
Reclaimed industrial byproducts are integral to HPC mixes. HPC describes a set of specialized concrete mixes that provide added durability for concrete structures, ease of placement and consolidation without affecting strength, long-term mechanical properties, early high strength, and longer life in severe environments, all the while using less material. As such, HPC might potentially permit fewer girders in a design, with reduced maintenance, extended life cycle, and if designed well, enhanced aesthetics.

HPC was a component of the Strategic Highway Research Program (SHRP), specifically the Concrete and Structures section. Under SHRP, four types of HPC were developed:

- **Very Early Strength (VES, 2,000 psi at 6 hours),**
- **High Early Strength (HES, 5,000 psi at 24 hours),**
- **Very High Strength (VHS, 10,000 psi at 28 days), and**
- **Fiber-reinforced HES, with steel or poly fibers added to control shrinkage cracks.**

Originally, HPC was targeted at bridge sub- and superstructures, but since then HPC has migrated into pavements, and even precast pavement panels. More information about HPC for bridges and pavements is available from *http://knowledge.fhwa.dot.gov/cops/hpcx.nsf/home*.





Supplementary cementitious materials (SCMs) *(top) for ternary or quaternary concrete mixes. From left to right, fly ash (Class C), metakaolin (calcined clay), silica fume, fly ash (Class F), slag, and calcined shale.*

Photo courtesy of Portland Cement Association

Jet process granulator *(bottom) produces slag in a glassy, amorphous state that complements portland cement concrete.*

Photo courtesy of Holcim (US) Inc.

Enhancing Cementitious Component

While the Federal Highway Administration reports that 94 percent of pavements in the United States are surfaced with asphalt, without question concrete is the most widely used construction material in the nation.

Conventional performance of cement and concrete can be boosted through alterations in the chemical composition of clinker – the fused lumps derived from the pyroprocessing of raw limestone (lime), clay (alumina) and sand (silica) – which is fine-ground to make cement.

But it's easier to improve the performance of concrete via additives. Some of the additives – like coal fly ash, high-reactivity metakaolin and silica fume – are pozzolans that exhibit cementitious properties in the presence

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of calcium hydroxide, which is formed when cement combines with water and begins to cure.

Other additives – like ground granulated blast furnace (GGBF) slag – are cementitious on their own, and in the form of GGBF slag cement actually can substitute for cement in large percentages of the cementitious component, up to 70 percent, according to the Slag Cement Association.

But because the pozzolanic reaction may be slower compared to the rest of the cement hydration reactions, the early strength of concrete made with materials such as slag cement may not be as high as concrete made only with portland cement. But GGBF cement mixes gain strength over longer periods, resulting in concrete with compressive strengths exceeding 10,000 psi or even 13,000 psi, such as in the case of Reliant Stadium in Houston.

Alternately, highly reactive pozzolans – such as silica fume and high-reactivity metakaolin – produce high early strength concretes that increase the rate at which concrete gains strength.

For the cement producer, it's more practical to promote ternary blends of cement, as they reduce the amount of cement that's required for a fixed amount of concrete. This equates to, all things being equal, longer lifetimes for quarry extraction sites, lower pyroprocessing costs, a lower carbon footprint for the same tonnage of blended cement, perhaps an elimination of the need to expand a plant, which is difficult in today's permitting environment, and more portland cement to go around when the inevitable cement shortages occur in construction boom times.

There is another advantage of ternary concrete mixes incorporating industrial byproducts: their use in concrete is recognized by the *Leadership in Energy and Environmental Design* (LEED) system of the U.S. Green Building Council, to which the building industry has turned to evaluate the degree of "green" design a structure or development incorporates. Thus, a ternary mix can help a project earn desirable LEED certification, or help a certified project achieve coveted Silver, Gold or Platinum levels.

Reclaimed, recyclable industrial byproducts – which in past years would have been dumped in landfills – now are key components to the high-performance concrete mixes of today.

Fly Ash from Coal

Fly ash, termed a CCB (coal combustion byproduct), is the residue of the burning of pulverized coal in thermal power plants. The ash particles are collected mechanically or by electrostatic precipitators. Generally, 15 to 20 percent of burned coal takes the form of ash.

Fly ash is a pozzolan, meaning it is a siliceous and aluminous material that, in the presence of water, will combine with an activator (lime, portland cement or kiln dust) to produce a cementitious material, according to *Fly Ash Facts for Highway Engineers*, a publication of the FHWA, and authored by the American Coal Ash Association (ACAA).

Initially, this ash went right up the stack, but as awareness of the problems with air pollution increased, technologies were developed to make it easier to remove the ash from the stack stream. This material mostly was landfilled, but high landfill costs – along with the need to develop profit centers – spurred electric utilities to find markets for the pozzolanic material.

The American Society for Testing and Materials (ASTM) classifies fly ash into Class C and Class F categories. Class C, with a higher calcium oxide content (CaO, or "lime"), comes from the burning of western sub-bituminous or lignite coals, and Class F is derived from bituminous eastern coals. Research indicates that Class F fly ash is better suited for fighting alkali-silica reactivity, the common malady of concrete.

Silica Fume for HPC

Another industrial "waste" byproduct that would otherwise be landfilled - silica fume – has a most useful role as a component of durable concrete.

Silica fume is a byproduct of the reduction of high-quality quartz with coal or coke and wood chips in an electric arc furnace, during the production of silicon metal or ferrosilicon alloys. The fume is condensed from gases escaping from the furnace and mostly consists of superfine, spherical silicon dioxide particles.

From 1977 on, silica fume began to find its way into U.S. high-rise construction as an additive to concrete, to which it imparts durability and strength. In the 1980s, it was used extensively in high-profile high-rise projects, in some cases producing concrete that exceeded 14,000-psi compressive strengths.

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▲ ***Relative appearance*** *of fly ash and portland cement in micrographs.*

Photo courtesy of Portland Cement Association

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Silica fume is used in bridge structures and decks, where it enhances compressive strengths while boosting durability by blocking migration of chloride ions to reinforcing steel.

One such bridge is the eight-mile-long Confederation Bridge connecting Prince Edward Island with New Brunswick in Canada's Maritimes Region. This signature bridge is exposed to some of the world's most extreme weather conditions, including significant amounts of ice that are constantly moving, high winds that result in salt water splash and spray zones on the piers, and frequent cycles of freezing and thawing.

To protect the structure against corrosion and to achieve a 100-year service life, the bridge was constructed with seven different concrete mix designs incorporating various supplementary cementitious materials – including silica fume and fly ash – to achieve low permeability, high early strength, low heat rise, and resistance to freezing and thawing.

GGBF Slag Cement

Like fly ash, use of blast-furnace slag in concrete has been practiced in Western Europe and Japan since the early 1940s. Blast furnace slag is the byproduct of the manufacture of molten iron, resulting from the fusion of limestone and other fluxes with the ash from coke and silica and alumina from iron ore.

While air-cooled slag has been used for decades for noncritical applications such as railroad track ballast, or landfilled or left in heaps at steel mills, in a processed state as ground granulated blast-furnace slag (GGBF) it takes on much higher value as an admixture to concrete.

According to ASTM, GGBF slag is a cementitious, glassy, granular material formed when molten blast-furnace slag is rapidly chilled by immersion in water. This chilling creates a granular product that is then ground to spec and used as an admixture in concrete where it provides improved performance over conventional concrete.

A major mass pour for a bridge pier spread footing was a major application of GGBF slag cement for the Missouri DOT. There, GGBF slag cement – in a 70-percent substitution for Type II portland cement – was being used to lower the heat of hydration in a 2,600-cubic-yard pour for a pier footing for the Phase 1 extension of Page Avenue (S.R. D) in St. Louis County. Ultimately more than 100,000 yards of the mix – representing about 10,000 tons of slag cement – would go on the job over a year and a half.

Control of heat of hydration was the prime purpose for GGBF slag cement being used. The mass pour concrete mix design called for 50 calories per gram heat of hydration.

The ready-mix producer wanted to achieve crack-free concrete, and devised a 70-percent slag cement/30-percent Type II low-heat cement mix that met the criteria. For this project,

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GGBF slag cement – *in a 70 percent substitution for Type II portland cement – is being used to lower the heat of hydration in a 2,600-cubic yard mass pour for a pier footing for the Phase 1 extension of Page Avenue in St. Louis County.*

Photo courtesy of Tom Kuennen

MoDOT had a crack specification of 0.03 millimeters.

The pours were averaging 4,100 psi in 28 days, and 4,500 in 56 days. In addition to the 70/30 slag/Type II cement content, the mix design included MoDOT-approved river sand and No. 67 (3/4-inch) MoDOT gradation D limestone, using W.R. Grace air entrainment admixture. Four additional mass pours of this size would be placed.

The same mix design as the mass footings was used for the columns atop the footings, with the exception that a high-range water reducer was added to enable placement of a concrete with a 5- to 6-inch slump around the steel. The spec was written as a performance spec, enabling the contractor to meet or exceed the specification of the heat spec, which specified 160°F maximum internal temperature. That's extremely hard to do conventionally, without going to extremes such as insulated forms and liquid nitrogen.

Option of Quaternary Mix

While ternary mixes are more and more common, a quaternary mix is seen less often.

A quaternary mix was used in the *Revive Wacker Drive* project in Chicago. This was a unique quaternary mix, with all four elements of cement, slag, Class F fly ash and microsilica added. The city was looking to attain the optimum mix for durability, and the proportions and composition of the mix complement one another to attain a 75- to 100-year life cycle on this project.

Quaternary concrete mix *is used for Revive Wacker Drive project for City of Chicago.*

Photo courtesy of Tom Kuennen

The quaternary HPC mix for Wacker Drive incorporated strength of 6,000 psi in 28 days, with 4,200 psi at post-tensioning in three to four days. The mix was designed to control shrinkage and thermal contraction to minimize cracking, and provide long-term resistance to attack from alkali-silica reactivity (ASR), alkali-aggregate reactivity and delayed ettringite formation, in addition to resistance to chloride penetration. After placement, the deck was covered with a latex-modified concrete (LMC) driving course that serves as an impervious, sacrificial friction layer.

Ongoing Research in Iowa

The importance of ternary concrete mixes is such that the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University has been studying these mixes in highway pavements, within the context of the *CP Road Map* (see *CP 'Road Map' Not Set in Stone*, August 2010, pp 24-33, or *visit www.betterroads.com/road-science-3/*).

This important project, the three-phased *Performance Properties of Ternary Mixtures for Concrete Pavements*, began with a scope of work study in 2004. The first fruit of this research was the December 2007 publication, *Development of Performance Properties of Ternary Mixtures: Phase I Final Report.*

The project enjoys a broad base of sponsors, including: the Federal Highway Administration; a pooled fund study uniting California, Illinois, Kansas, Mississippi, New Hampshire, Pennsylvania, Wisconsin and Utah, with Iowa as lead state; the Portland Cement Association; Headwaters Resources;-, the American Coal Ash Association; and the Slag Cement Association.

The project is a comprehensive study of how SCMs can be used to improve the performance of concrete mixtures. The initial stages of this project considered several sources of each type of supplementary cementitious material (fly ash, slag, and silica fume) so that the material variability issues can also be addressed. Several different sources of portland cement and blended cement also were used in the experimental program.

Goals included development of quantitative guidance for state DOTs on how to optimize the technical properties, lifecycle value and constructability of ternary mixes; information on the effect of these SCMs on slump, entrained air and admixture dosage; solutions to cold-weather placement issues, such as set time, early-age strength development and potential for deicer salt scaling of ternary mixes; definition of optimal use of ternary mixes in rapid-strength applications; and definition of performance guidelines for use of ternary mixes.

Phase I of the study consisted of a 24-month laboratory program that studied the influence of multiple combination and proportions of cement, slag, silica fume and fly ash on specific performance properties of mortar specimens. These experiments included more than 100 different mixtures, and the overall project is being conducted in three different phases. The December 2007 report also contains a brief literature study to summarize the state of the practice in ternary mixtures, including field applications by the Ohio DOT, New York State DOT, Pennsylvania DOT and Iowa DOT.

"Takeaways" from Phase I include the fact that ternary combinations with pozzolans between 40 and 50 percent of the total cementitious materials are performing well in moderate to hot weather environments, and small quantities of silica fume and metakaolin provide early age boosts to cold weather applications.

The Phase I report identified materials combinations that were to be explored in Phases II and III. Phase II is ongoing through March 2011 and is evaluating cementitious materials combinations that will perform well in different environmental and climatic conditions. Phase II is focused on concrete mixtures that have the right properties in both the construction and hardened phases in cold weather, hot weather, freeze-thaw cycle conditions, and where road salts and corrosion may be factors in the life cycle of the concrete elements.

Phase III, started in June 2009, continues into June 2011 with field applications of ternary mixes in Utah pavements, Pennsylvania bridge decks, and potentially other applications in New Hampshire, Illinois, Mississippi, California, Iowa, Kansas and Wisconsin.

The complete Phase I report can be downloaded at *http://www.intrans.iastate.edu/reports/ternary_mixes_phase1.pdf* and a PowerPoint presentation from October 2009 on Phase I by Dr. Paul J. Tikalsky, P.E., chair and professor, Department of Civil and Environmental Engineering, University of Utah, may be downloaded at *www.cptechcenter.org/t2/documents/03Tikalsky-TernaryMixes.pdf*

Ternary Blends and Sawing

An earlier CP Tech Center study, *Crack Development in Ternary Mix Concrete Utilizing Various Saw Depths*, was funded by the Iowa Highway Research Board and was released in 2009.

Early entry sawing, which uses a lightweight machine to apply earlier and shallower cuts than conventional sawing, is believed to increase sawing productivity and reduce costs, the report says. But some early entry saw joints in Iowa have experienced delayed cracking, including delays of weeks or months after sawing.

"An urgent concern is whether early entry sawing could lead to late-age random cracking," the report says. "This study was designed to investigate whether delayed random cracking may occur in pavements constructed using early entry sawing."

Because cracking is related to stress development in concrete, the specific objective was to examine the stress levels that develop at pavements' early entry sawing joints. The study found:

- Although most joints made using the early entry sawing method cracked later than the joints made with conventional sawing, all 30 joints examined in this study cracked within 25 days after paving.
- No random cracking was observed in the test section two months after construction.
- The average joint cracking time for early entry sawing was 12.3 days.

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The average joint cracking time for the joints made with the conventional sawing method was 2.2 days.

With the results of this study, agencies and the paving industry can identify potential late-age random cracking problems in pavements constructed with early entry sawing. Download the study at *www.intrans.iastate.edu/reports/sawing.pdf*

Ultra-High Performance Concrete

New concretes with high percentages of cement and silica fume, low water/cement ratios, and including steel fiber reinforcement, are being investigated by the FHWA.

Compressive strength in these new concretes is more than seven times that of conventional concrete, while tensile cracking strength is three times greater, FHWA reports. This emerging technology, known as Ultra-High Performance concrete (UHPC), has the potential to significantly impact the U.S. highway system.

Challenges remain, however, limiting widespread implementation of projects using this new technology, FHWA said in 2009. Among them are the lack of design code provisions, inadequate industry familiarity with the product, and high initial costs. "Addressing these issues will require significant knowledge transfer, industry support and buy-in, and greater reliance on life cycle costing," FHWA says.

The first UHPC I-girder bridge opened to traffic in 2006 was the Mars Hill Bridge in Wapello County, Iowa. A second UHPC superstructure bridge opened to traffic in October 2008: the Cat Point Creek Bridge in Richmond County, Va. Also, a UHPC-decked girder bridge that opened to traffic in November 2008 was the Jakman Park Bridge in Buchanan County, Iowa.

UHPC in North America is sold under the name of *Ductal*, jointly developed and patented by the French firms Lafarge and Bouygues. Ductal is an innovative technology that covers a family of UHPCs with exceptional characteristics in terms of mechanical resistance (compressive strengths up to 29,000 psi or 200 Mpa, flexural tensile strength beyond 5,800 psi or 40 Mpa), durability, abrasion-resistance, and resistance against chemical and environmental attack from freeze/thaw cycles or chloride penetration.

This cementitious material consists of cement, sand, silica fume, silica flour, admixture, water and high-strength steel fibers, but no aggregates. Its durability properties are those of an impermeable material, better than conventional HPC, the maker says.

In structural applications, Ductal is used without any passive reinforcing bars. Very fine, high-strength steel fibers are provided to withstand secondary tensile stresses due to shear, tension, small bending moments and concentrated loads. ❖