An Electric Freeway to the Future

High-carbon concrete offers electrifying possibilities

BY BRUCE W. RAMME AND STEVEN H. MILLER

Innovation begins with imagination. Imagine a city where people travel in small modules that drive themselves, navigating and negotiating traffic without input from the passenger. The passenger checks out a car from a corner docking station and inputs a destination. The car moves on electric power, navigating by GPS or by location markers on the street pavement. The car is, in fact, a simple autonomous robot that can "talk" to the other robot cars, negotiating with each other for perfect, accident-free traffic flow.

These electric cars carry extremely small batteries and run primarily on electric power they get from the roadway, but there are no embedded wires or metal rails. Instead, a ribbon of electrically conductive high-carbon concrete (HCC) cast into the roadbed charges the cars while they drive.

This future may not be so distant—every element of the scenario is currently in place or in development:

- Building on 10 years of research, electro-conductive concrete, with high compressive strength and good freezing-and-thawing resistance, is now available. Carbon from high-carbon fly ash (HCFA) and spent carbon sorbent—both by-products of coal combustion in modern power plants—make HCC a conductor. Initial HCC applications have included low-cost grounding for lightning-vulnerable structures, but a much wider range of use is envisioned, including electrical shielding, self-deicing bridges, induction-charging of electric vehicles, and pavements that function as storage batteries. It's a material in search of imagination and ingenuity to put it to work.
- The Korea Advanced Institute of Science and Technology (KAIST) is researching contactless charging vehicles that get energy from roadway-embedded power supplies. It has installed a prototype in Seoul Grand Park,[1] featuring power cables embedded in the road surface as part of an induction-charging system.
- The CityCar project underway at the MIT Media Lab[2] envisions semi-autonomous (self-parking) and autonomous (self-driving and self-organizing) vehicles. According to Ryan Chin, Director of the CityCar project: "Electro-conductive concrete could be potentially useful in the design of charging stations because it can reduce the total number of components required to install a station. Charging stations will also need to withstand the elements; thus, concrete would be a natural fit given its durability, weatherproofness, and cost. It's definitely worth considering as a possible material choice."

SLAB POWER

Electrically conductive concrete is not a new concept. It was investigated in the late 1970s and early 1980s,[3,4] and there are several patents for different approaches. The fundamental idea is that conductive materials mixed into the concrete form a sufficiently contiguous network for current flow. Materials such as carbon particles, carbon fibers, and steel fibers have been used.

Prototype applications include the Roca Spur Bridge on Nebraska Highway 77 South, about 24 km (15 miles) south of Lincoln. This three-span highway bridge is 46 m (150 ft) long and 11 m (36 ft) wide.[5] Completed in 2002, its deck incorporates a 100 mm (4 in.) thick conductive concrete inlay containing steel fibers and carbon materials, respectively comprising 1.5 and 25% of the total concrete volume. The inlay consists of 52 slab units—each 1.2 x 4.1 m (4 x 14 ft) in plan—that can be individually electrified. The resistance of the concrete is sufficient to generate heat when current is passed through it.

The deicing system was successfully tested in early 2004. The slabs were electrified in an alternating fashion to avoid a power surge, with each energized for 30 minutes. Slab temperature was kept at about 9°C (16°F) above ambient temperature, effectively deicing the surface. The first practical use of the system was during a 3-day winter storm in April 2004. It consumed about 3000 kW-hr of energy and remained ice free during the storm. Based on local energy costs, the 3-day event cost only $217. Running it continuously for 5 months of winter would cost less than $11,000.

Although the prototype proved the conductive concrete concept, monitoring of the system was discontinued after July 2009. According to Amy Starr, Research Engineer for the Nebraska Department of Roads, the deck surface had a rough finish and was therefore milled. This exposed the steel fibers, which rusted and caused surface deterioration.

COAL, CARBON, AND CONCRETE

HCFA is a material of relatively recent origin. The Federal Clean Air Act of 1990 mandated changes that altered the way some power plants burn their coal to reduce ozone-forming NOx emissions. The changes sometimes led to a less complete burn of the coal, leaving higher proportions of carbon in the fly ash that is collected by flue gas particulate removal systems.

HCFA is defined as fly ash that exhibits loss on ignition (LOI) of greater than 12%, but the material used for the tests described in this article had LOI values exceeding 20%.

While fly ash has been used for years as a pozzolanic additive in concrete and other applications, this and other uses do not keep pace with production. According to the most recent available figures, about 60% of U.S. fly ash production is landfilled.[6]

HCFA has proved more difficult to use in concrete than conventional fly ash, in part because of its dark color and also due to issues with admixtures. Ironically, its potential conductivity has been another barrier to use because concrete is normally expected to have high electrical resistance. As a result, a much higher proportion of HCFA is landfilled than conventional fly ash.

Activated carbon sorbent is used to capture mercury from the flue gas stream. Powdered activated carbon is injected into flue gas, where it absorbs mercury and collects ultrafine fly ash. By mixing it into a cementitious material, the mercury is bound and a useful material can be produced.

According to research carried out at the University of Ohio and sponsored by the Electric Power Research Institute, concretes made with Class C fly ash and concretes with carbon sorbents release only minute quantities of mercury during curing and in subsequent leaching tests. In leaching tests on crushed concrete samples, mercury measured just 0.25% of the EPA standard for acceptable mercury levels in drinking water. Moreover, the mercury leached from ordinary portland cement concrete was higher on each test than mercury from any of the fly ash concretes, with or without carbon sorbent.[7]

Unlike buff-colored conventional Class C fly ash (right), the dark color of HCFA has been a barrier to beneficial use in concrete *(photo courtesy of We Energies)*

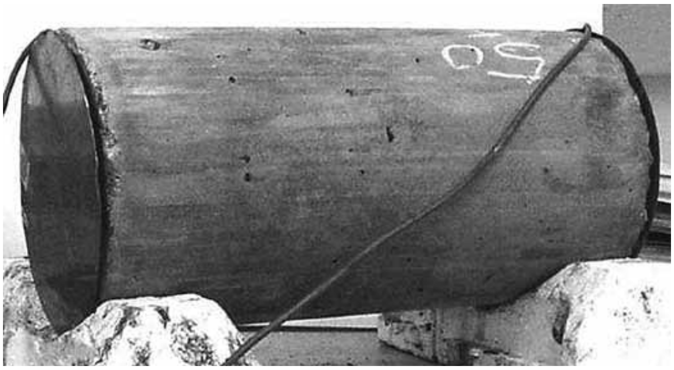
Initial developments using HCFA

Initial experiments conducted from 2000 to 2003 by We Energies, a Wisconsin electric and gas utility, focused on electro-conductive controlled low-strength materials (CLSMs or flowable fill). These cementitious mixtures have compressive strengths of less than 8.3 MPa (1200 psi). A flowable fill incorporating a combination of HCFA and carbon fibers had resistance as low as 2.2 ohms after curing and air drying for 28 days. A study conducted at the University of Wisconsin-Milwaukee in 2006[8] concluded that achieving similar conductivity using carbon fibers alone (no HCFA) requires about 300% more carbon fiber in the cementitious mixture.[9] Apparently, the carbon fibers both reduce microcracking during drying shrinkage and form "backup" electrical bridges across microcracks so that the HCFA remains conductive. Thus, the combination of HCFA and carbon fibers makes concrete that is both electrically conductive and cost effective. Electrically conductive concrete and CLSMs are now covered by U.S. patents 6,821,336 and 7,578,881.

Structural HCFA concrete

Current HCFA concrete mixtures can achieve 62 MPa (9000 psi) at 1 year. While this could allow the use of the material for structural applications, it would be prudent to provide corrosion protection for the reinforcement.

It should also be noted that carbon tends to absorb admixtures and render them ineffective. This is a significant issue with air-entraining admixtures, but substitute materials have been found to provide freezing-and-thawing



A cylinder of electrically conductive HCC, with electrodes on either end, is tested for conductivity *(photo courtesy of We Energies)* resistance. Residual solids from pulp and paper mills contain cellulose microfibers that have been shown to act as distributed reinforcement in concrete.[10,11] The fibers also create small voids that behave like entrained air, protecting concrete from freezing-and-thawing cycles. Concrete made with HCFA and fibrous residuals has been shown to survive more than 150 freezing-and-thawing cycles, and concrete made with carbon sorbent and fibrous residuals survived more than 210 cycles. In these mixtures, high-range water-reducing admixtures (HRWRAs) were used successfully, but dosages were increased by about 5.5 times what would be used in conventional concrete; batches with higher quantities of fibrous residuals required additional increases in dosages of HRWRAs.

FIRST APPLICATION

The first practical project using HCFA concrete was a telecommunications tower in Rudolph, WI. As with most electrical towers in the region, this tower was frequently struck by lightning.

To protect electronic equipment, such towers must be well grounded, providing a path of least resistance from the strike point into the earth that channels the energy away from the equipment. The grounding system must comprise a conductor with sufficient conductivity and cross section to handle the energy of a strike, and the interface between the conductor and earth must have sufficient surface area to transfer the energy into the ground. Because the earth is not a good conductor, the interface must be large.

The subject tower was originally grounded with a buried ring of 25 mm (1 in.) diameter copper wire encircling the tower and an adjacent building. Additional grounding was provided by six radial copper wires, each about 75 m (250 ft) long, connecting the ring to the moorings of each of the six tower guylines.

HCFA is added to a concrete mixture. This batch was used for a grounding contact for a telecommunications tower in Rudolph, WI. It was the first practical application of electrically conductive high-carbon fly ash concrete *(photo courtesy of We Energies)*

To provide the tower with more effective grounding, the existing copper ring and radials were augmented with HCFA concrete. A 300 mm (1 ft) wide x 150 mm (6 in.) deep trench was dug along the buried wires and the trench was filled with HCFA concrete. This increased the surface area of the ground interface by more than 1000%. To provide a similar increase using copper, the costs would have been orders of magnitude greater.

FUTURE POTENTIAL

The future potential of HCC may be limited only by our imaginations. The following concepts could be only the beginning.

Grounding and shielding

In addition to grounding communication and electrical towers, HCC can be used to construct facilities housing sensitive communications equipment and data-processing equipment, as these also require electrical shielding. It may be possible to build HCC grounding into the structure of the building and eliminate conventional copper grounding entirely. We Energies currently has research in progress to define electrical design parameters for conductive concrete foundations located in clay, sand, and rock.

Incorporating HCC into the structure of buildings has several potential benefits. At its simplest, the material can provide electrical grounding and shielding. Electrically sensitive equipment and data could be protected from stray electrical fields by making conductive walls that channel charges around the structure and into the earth. Shielding could also provide security for data signals that could otherwise be intercepted or disrupted by unauthorized parties outside the structure.

Storage battery pavement

By adding a strip of zinc to the side of an HCC slab, an entire road or highway pavement could become a massive, low-cost electrical storage system. In this case, HCC would form the cathode; zinc the anode; and calcium chloride (road salt), sodium hydroxide, or potassium hydroxide would serve as the electrolyte. Such storage would complement renewable electrical generation systems

A trench was dug around the existing copper grounding ring and backfilled with HCC *(photo courtesy of We Energies)* (such as solar panels or wind turbines) that are typically widely dispersed, and the stored power could be used to light highways and parking lots.

Bar codes, data storage, and data transmission

Strips of HCC could be cast into pavements, acting as a magnetic barcode and positively identifying locations on roads or airport runways. Motor vehicles or aircraft could "read" the code magnetically as they pass.

A broad range of resistances can be developed by varying the HCC mixture designs. It's therefore possible to make concrete that would be classified as a semi-conductor, opening the possibility of large-scale data storage in HCC.

HCC cast into a building's superstructure or cladding could also function as a wireless antenna. In hospitals, for example, wireless devices are now used to monitor patients' vital signs and to communicate that information to mobile doctors and nurses, as well as nurse's stations. Distributing and collecting wireless signals inside buildings requires either a very powerful, centrally located antenna or a lower power distributed antenna system. Signal deteriorates rapidly with distance, so a central antenna's broadcast power must be set high enough to reach the worst reception areas.

A more distributed antenna system needs less power to operate effectively, and less power is used by the wireless devices it serves. Incorporating conductive concrete in the superstructure, floor decks, or exterior cladding, rather than post-installing expensive metal wiring, could efficiently serve even the most remote areas of a structure. It would also allow for the future addition of wireless services, such as devices that monitor security systems and building performance.

NEXT STEPS

Clearly, more research is needed to make such applications a reality. The leap from well-founded theory to workable solutions or manufacturable products can be a large one. The realization of the potential of such a material will depend—as it always does—on imaginative designers who expand the range of applications to be pursued.

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Selected for reader interest by the editors.

Bruce W. Ramme, FACI, is Vice President—Environmental at We Energies in Milwaukee, WI. He received his BS, MS, and PhD in engineering and his EMBA, all from the University of Wisconsin-Milwaukee. He has more than 33 years of experience as a civil engineer and has published numerous technical reports and papers and a handbook on the use of coal combustion products.

Steven H. Miller, an award-winning Writer and Photographer specializing in issues of the construction industry, has written extensively on advanced forms of concrete. He works with Chusid Associates, a technical and marketing consulting firm dedicated to bringing advanced building products into the marketplace.