Next-generation concrete: Combining load bearing and energy storage solutions

MIT ec^3 hub and MIT CSHub Research Brief
Damian Stefaniuk, James C. Weaver, Admir Masic,* Franz-Josef Ulm
*Corresponding Author, masic@mit.edu

A key concern facing the transition from a nonrenewable to a renewable energy economy is that several key renewable energy sources (e.g., solar and wind) generate electricity intermittently, and are therefore unable to meet the requirements for an uninterrupted power supply. To address these concerns, large-scale energy storage solutions that allow for excess energy produced during peak times to be stored and released when needed, are critically required.

To date, conventional battery and supercapacitor technologies have been used for renewable energy storage, but they often present environmental and cost challenges. For example, the production of conventional batteries involves the extraction and processing of raw materials (e.g., lithium, cobalt, and nickel) which may be subject to mounting market pressures and/or associated with negative impacts such as habitat destruction, water pollution, or the creation of social inequalities.

To address the need for a scalable, cost-effective solution for renewable energy storage, recent advancements at the MIT Concrete Sustainability Hub (CSHub) and the MIT Electron-Conducting Carbon-Cement-Based Materials Hub (ec^3 hub) have developed a multifunctional concrete that combines this intrinsically scalable, resilient structural material with energy storage and delivery capabilities [1]. Our approach consists of blending the inexpensive, and globally abundant raw materials of hydrophobic nanocarbon black (nCB), binder (e.g., Portland cement (PC)), aggregates, and water, together to create electron-conducting carbon concrete (EC^3) (Figure 1).

Key Takeaways

- Electron-conducting carbon concrete (EC^3) combines the intrinsically scalable, durable properties of concrete with energy storage and delivery capabilities.
- EC^3 technology uses inexpensive, globally abundant raw materials (hydrophobic nano-carbon black, binder, aggregate, and water) to create a scalable energy storage solution.
- EC^3 materials maintain a long-term stable capacitance, after thousands of charge-discharge cycles.
- EC^3 technology has potential applications in residential and industrial buildings, large-scale renewable energy storage, and transportation infrastructure. It could therefore enable the construction of off-grid shelters, self-charging roads for electric vehicles, and more stable electricity grids.

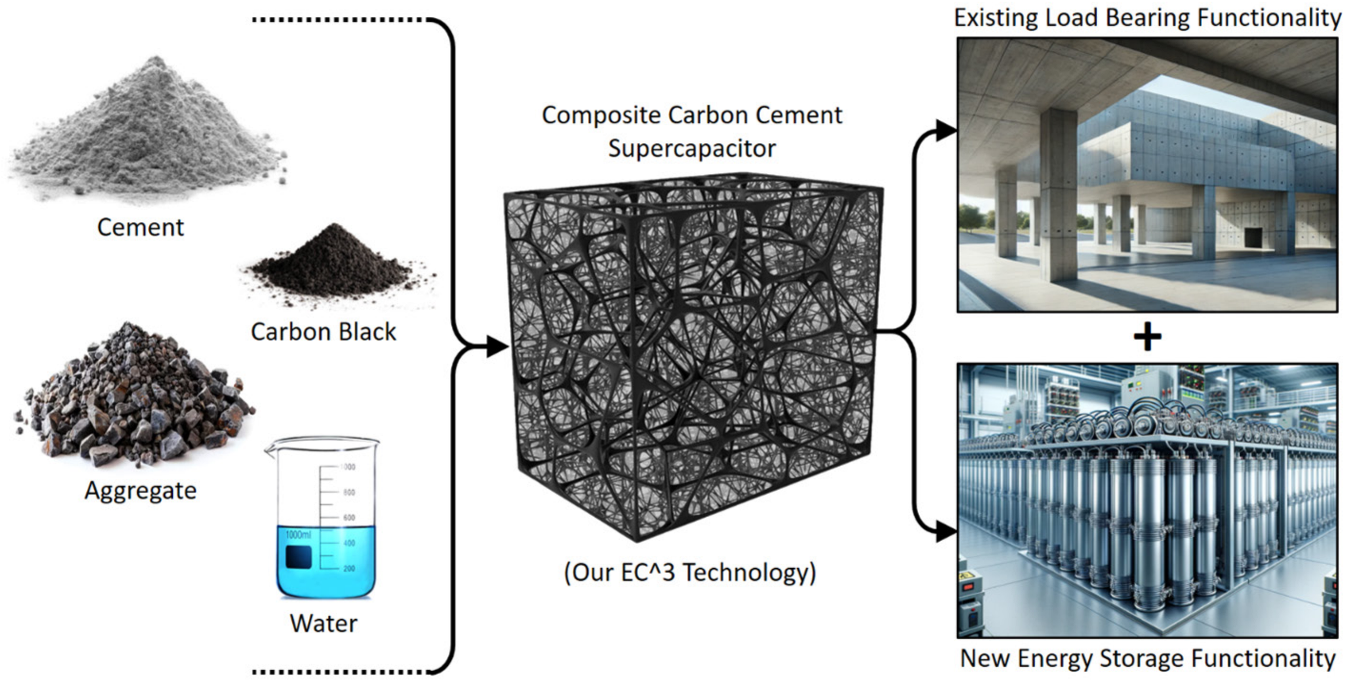

Figure 1. EC^3 (electron-conducting carbon concrete), a blend of carbon black, binder, aggregate, and water, simultaneously delivering energy storage functionality and load-bearing capacity [2].

Since EC^3 incorporates carbon black as a critical raw material, it provides an additional use for large quantities of carbon black produced as industrial byproducts such as in hydrogen production (i.e., via methane pyrolysis). Additionally, the ability to store energy within the building materials themselves offers a novel solution to energy management in urban settings, where space is often limited, and efficient energy use is critical.

Key Findings

Advancements in EC^3 technology at the MIT CSHub and the MIT ec^3 hub have led to the development of a 12-volt EC^3 supercapacitor. To date, the supercapacitor has demonstrated practical applications by powering small electronic devices such as LEDs and game consoles (Figure 2), and has shown promise for more energy intensive applications such as short-terms cell phone charging. Furthermore, recent developments have improved the material's resistance to energy leakage, maintaining its reference energy level for 6.5 times longer than the previous prototypes. With a current capacitance of 304 watt-hours per cubic meter and 50 farads, the EC^3 technology presents considerable opportunities for mass scaling. For example, it is estimated that approximately 33 cubic meters of EC^3 could supply the average daily energy demands of a residential house (~10 kilowatt hours). Notably, the initial estimate for this figure was 45 cubic meters [1], but technological advancements have since reduced this required volume by more than 30%.

Several key factors affect the viability of this technology, which are currently being explored for improved device efficiency. One is the minimum quantity of nCB required for the production of our EC^3 materials. Recent findings reveal a critical concentration for nCB at approximately 6-7% (by carbon mass vs. cement mass), beyond which, capacitance increases almost linearly with carbon content.

We also examined the impact of material aging on capacitance for samples aged 1 month and 30 months. These results demonstrate that the capacitance of EC^3 cells remain largely unaffected by aging, suggesting that the texture of the nCB network is stable long after the initial hydration phase (28 days). These findings imply that ongoing hydration does not significantly alter the energy storage capacity of the cement-carbon composites, confirming the stability of the nCB network over time.

Finally, a detailed electrochemical analysis was performed to test capacitance retention over time. These results demonstrate that over 95% of the capacitance remains after more than 10,000 charge-discharge cycles, as long as electrolyte saturation is maintained (for more details, see [1]).

Potential Applications

The versatility of our EC^3 technology – attributable to the diversity of applications for concrete – presents a wide range of applications across sectors. In both residential and industrial contexts, EC^3 technology may be used to build structures that are not only mechanically resilient, but also capable of storing and supplying energy on demand. These capabilities would enable the creation of energy-autonomous shelters, reducing dependence on external power sources. By integrating energy storage capabilities directly into building materials, energy losses typically associated with transmission and distribution would be minimized.

One of the most promising applications of EC^3 is storing intermittent energy from renewable sources such as wind, solar, and tidal power (left panel of Figure 3). By integrating energy storage capabilities into the structural components of wind turbines and tidal power stations, the EC^3 technology could help stabilize and enhance the reliability of the energy grid. Additionally, the integration of 3D printing technology unlocks considerable potential for diverse EC^3 applications. Through 3D printing, it is possible to fabricate bespoke structures that incorporate EC^3 technology in a wide range of application-specific and fully customizable form factors (middle panel of Figure 3). This approach allows for the rapid prototyping and production of energy-storing components, which can be tailored to specific architectural or engineering requirements. For example, 3D-printed building elements embedded with EC^3 materials could be used to create tailored, energy-efficient homes or commercial spaces. This method not only accelerates

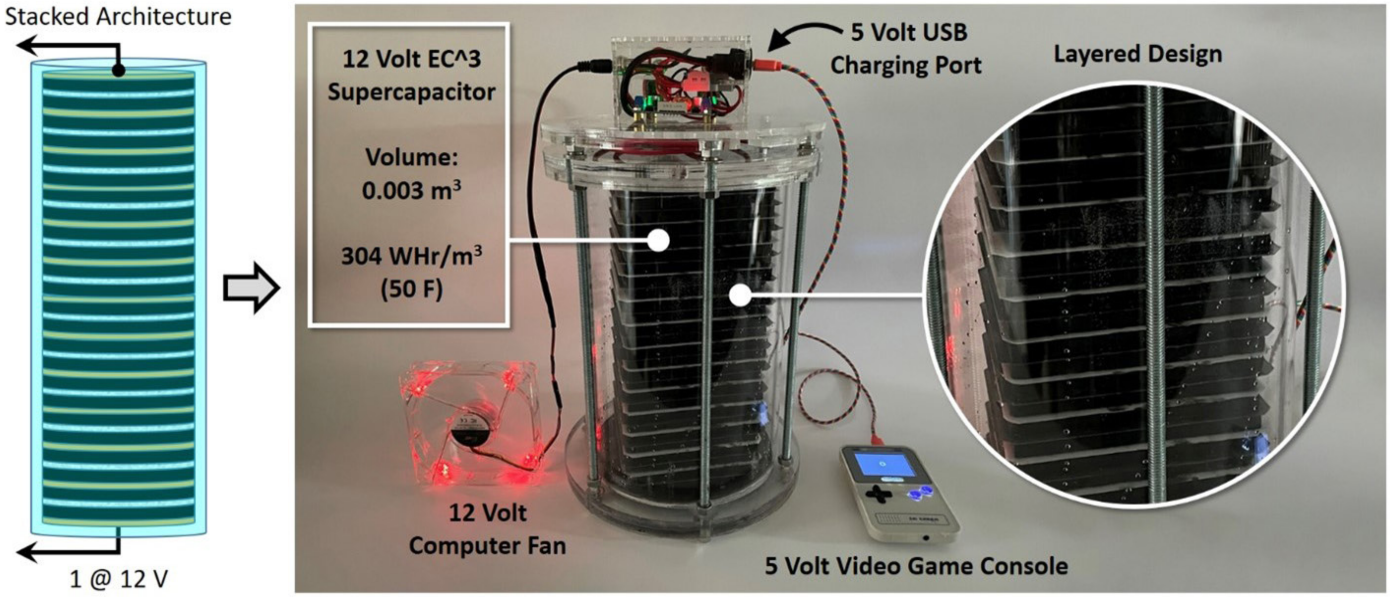

Figure 2. 12V meso-scale "battery" powering small electronic devices, such as a 12V fan and a 5V video game console, characterized by a rate-independent capacitance of 304 Wh/m3 and 50 F. For additional compositional details, see figure 4.

Figure 3. Conceptual representations of potential EC^3 functionalities [2]: Storage of intermittent energy from renewable sources (left), 3D-printed bespoke energy-storing residential and industrial buildings (middle), and self-charging roads for electric vehicles (right).

the construction process but also presents new opportunities for innovative design and sustainable construction practices.

EC^3 technology might also bolster transportation infrastructure systems by enabling the development of self-charging roads for electric vehicles (right panel of Figure 3). These roads could potentially harness and store energy and be used to wirelessly charge vehicles as they drive along them, reducing the need for external charging stations.

Conclusions

EC^3 technology leverages innovative material science to bridge the gap between structural support and energy storage, offering a potential solution for the future of construction and energy management. Through continued research and collaboration, EC^3 has the potential to create shifts in the construction industry, contributing to a more resilient, sustainable built environment.

Methodology

Electrical energy can be stored in various ways, including through battery and supercapacitor technologies. A supercapacitor is an energy storage device that stores energy through electrostatic separation of charges, as opposed to batteries that store energy through chemical reactions. This fundamental difference allows supercapacitors to charge and discharge much faster than batteries, but generally they store less energy in an equivalent volume. A typical supercapacitor consists of electrodes separated by an insulator, which are all soaked in an electrolyte (Figure 4). To create an effective carbon electrode, a conductive material with a high specific surface area is essential.

In our approach, we have demonstrated through correlative EDS-Raman spectroscopy, that the incorporation of a hydrophobic carbon phase into hydrophilic cement produces a high surface area electron-conducting carbon network (shown at different length scales in Figure 5) within the porous cement matrix. However, it is important to note that electron conductivity, while important, is not itself sufficient to develop energy storage capabilities. Supercapacitors also require internal porosity for ion diffusion, which is ensured by the interconnected hydration porosity in the cementitious matrix. In our fabricated supercapacitors, we use various electrolytes, such as a potassium chloride (KCl) solution, to facilitate this process. We have demonstrated the possibility of adding such electrolytes during the mixing stage or soaking the electrodes after casting.

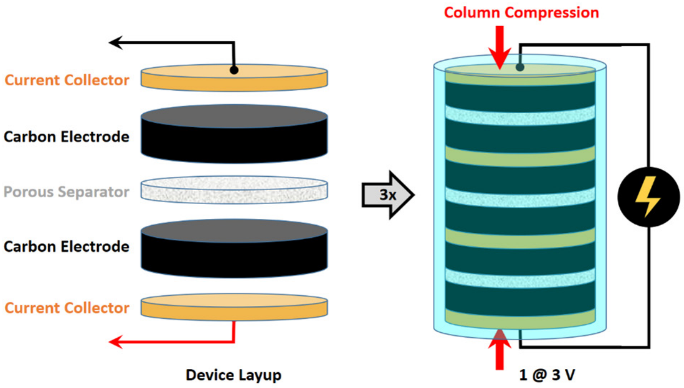

Figure 4. Schematic details of a representative modular unit (left) and an assembled 3-volt supercapacitor (right). For this column design, the localized axes of compression are denoted by the red arrows.

It is important to note that electrolyte chemistry critically determines the maximum potential operating window of a supercapacitor. For example, an aqueous electrolyte limits the voltage window to 1.23 volts, in order to prevent water electrolysis. To address this limitation, in our devices, we use electrodes that can be either monolithic or stacked in parallel or series to achieve the desired voltage and current. As a result, EC^3 technology can be easily incorporated into structural elements of various shapes, such as columns, walls, or platforms, which can support loads, while providing the desired energy storage functionality.

To measure the energy storage properties such as capacitance and capacitance retention, electrochemical tests such as cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) tests were conducted. For example, conventional CV tests were performed at different scan rates to test numerous samples with varied sizes, concentrations of nCB particles, water-to-cement ratios, and types of nCB with different specific surface areas. By combining these experimental tests with mathematical modeling,

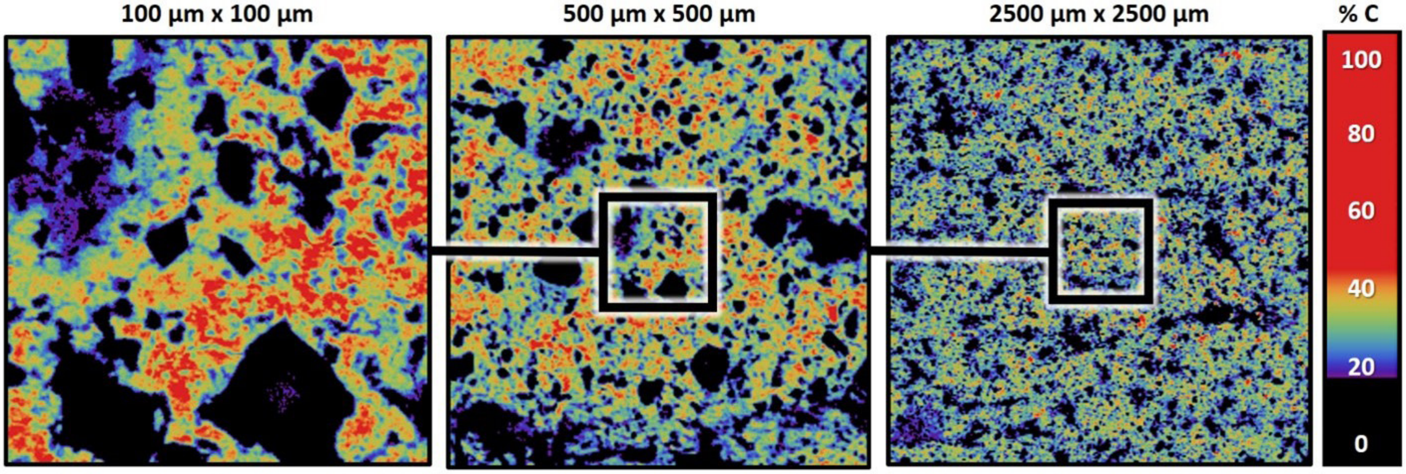

Figure 5. Carbon black particles create a conductive "wire" at different length scales (EDS data) and intermixed with hydration products.

we can demonstrate that the capacitance of carbon-cement can be reduced to an intensive quantity (rate-independent capacitance), whose magnitude is independent of the size of the system. This approach provides a measure for the high-rate capability as a function of electrode dimensions and constituent properties (for more details see [1]). As demonstrated from these discoveries, our porous carbon-cement composite materials thus represent a clear opportunity for scaling these energy storage properties from the electrode to the structural scale.

References

[1] Chanut, N., Stefaniuk, D., Weaver, J.C., Zhu, Y., Shao-Horn, Y., Masic, A., Ulm, F.-J. (2023). Carbon–cement supercapacitors as a scalable bulk energy storage solution. Proceedings of the National Academy of Sciences, 120, e2304318120. (2009).

[2] 3D renderings in figures 1 and 3 were created with the assistance of generative AI (OpenAI's DALL•E) and manually edited for clarity.