Carbon-cement supercapacitors: A disruptive technology for renewable energy storage

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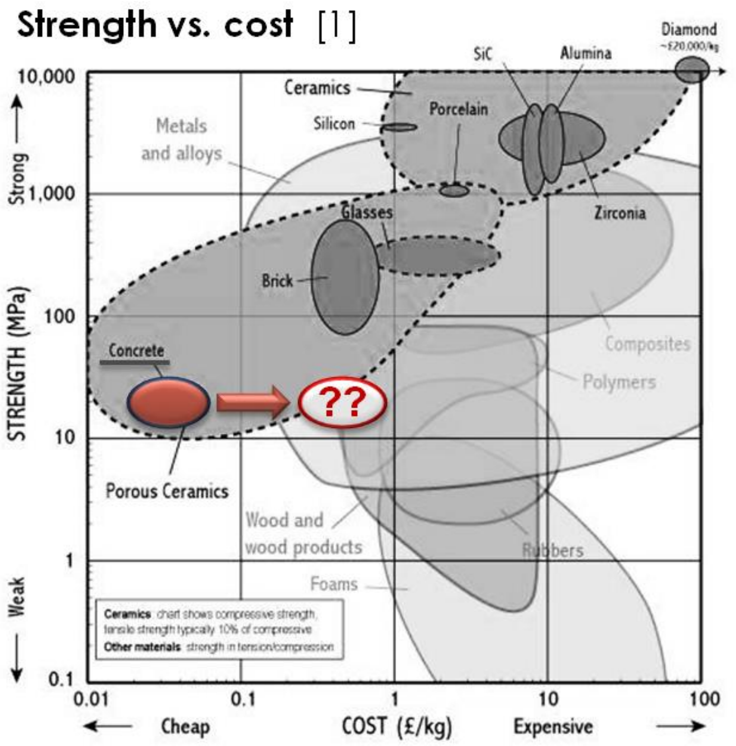
How to reduce the environmental footprint of concrete and address energy storage challenge?

Environmental footprint of concrete



Near future: $200 per ton carbon tax [2]

Energy storage challenge

The pace of the transition from fossil fuel-based economy to a renewable energy economy will strongly depend on the availability of bulk energy storage solutions.

[1] http://www-materials.eng.cam.ac.uk
[2] https://www.greencarcongress.com/2022/05/20220506-epic.html
[3] https://www.amakella.com/from-fossil-fuel-to-renewable-energy/1111

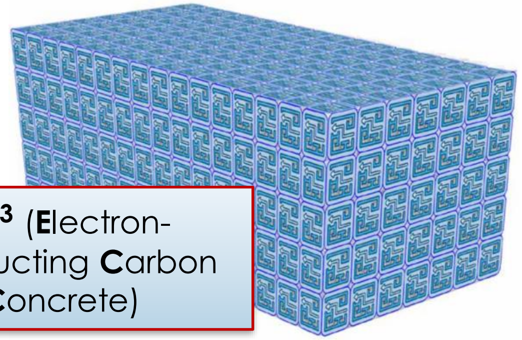
EC^3, besides its natural load-bearing capacity, brings new high-impact functionalities into concrete

Multifunctional concrete

Concrete

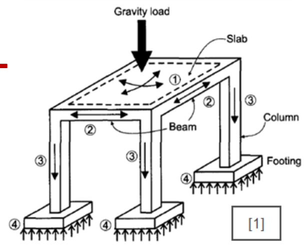
+

nano Carbon Black (nCB) particles



EC^3 (**E**lectron-**C**onducting **C**arbon **C**oncrete)

Load bearing

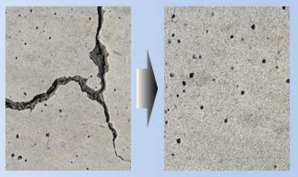


+

Freeze-thaw resistance

Hydrophobicity

Longevity of structures



Shielding against HPEM* impulses

Faraday cage effect

Military structures

Data storage

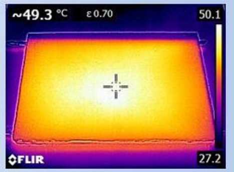
*High Power Electromagnetic

Self-heating

Joule effect

De-icing bridges, sidewalks, airport runways

Radiant floor heating

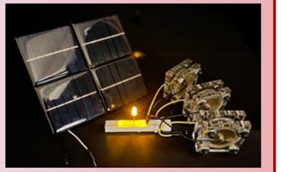


Energy storage

Structural supercapacitor

Renewable energy buffer

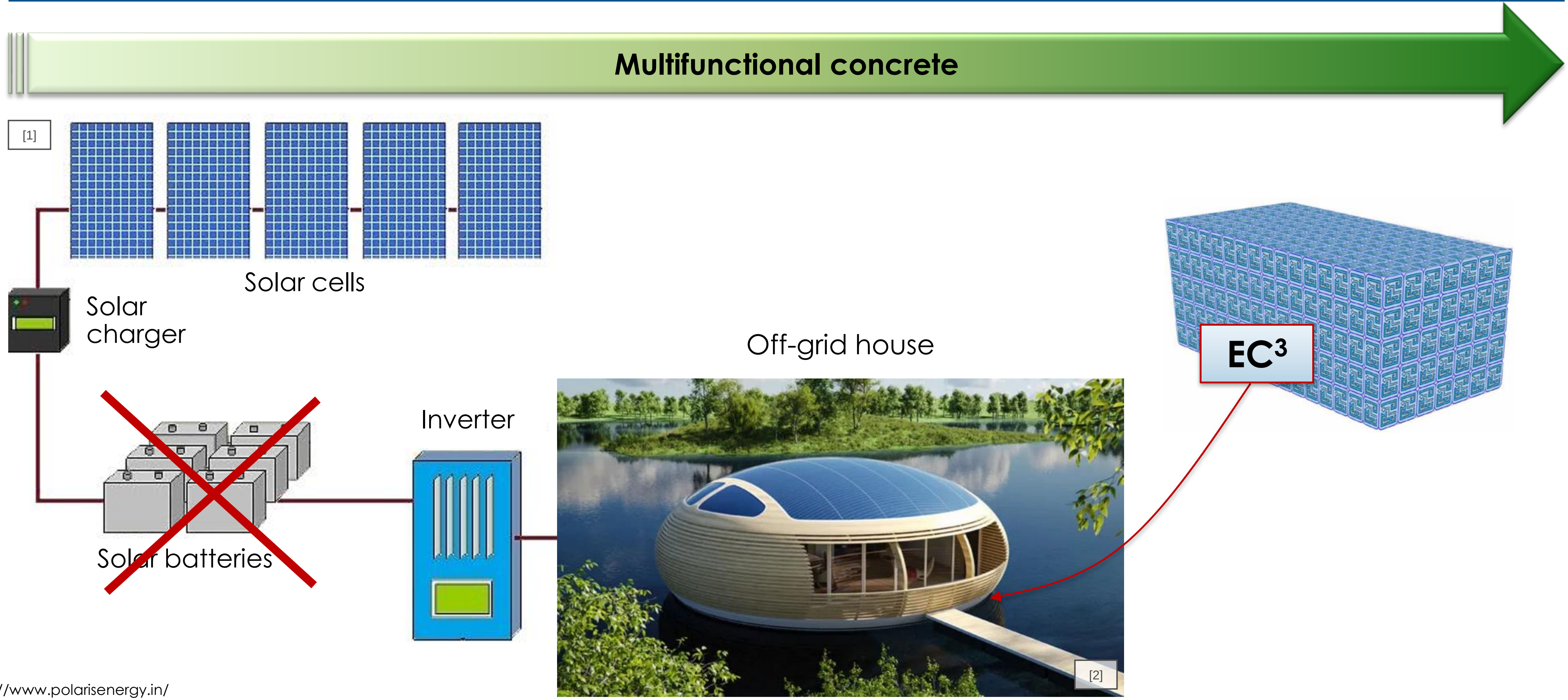
Smart charging roads



[1] https://www.engineersdaily.com/

[2] The New York Times; Photographs by SCIEPRO and mikroman6, via Getty Images

EC³ can reduce (or even replace) currently used batteries



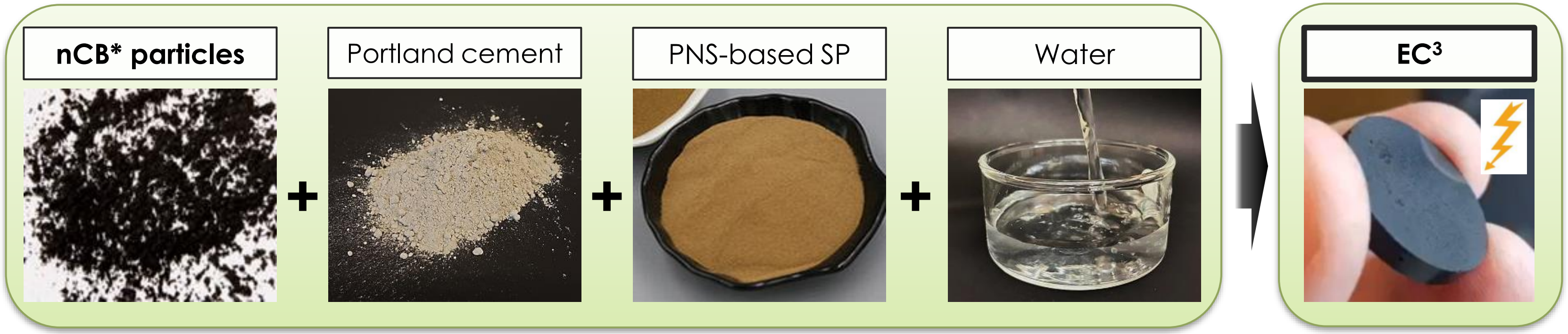
[1] https://www.polarisenergy.in/
[2] https://offgridworld.com/5-cutting-edge-off-grid-homes-modern-amenities/

The technology has already been developed but the scalability of EC^3 still needs to be addressed

Previous efforts:

Achieved functionalities:
Heat conductivity & energy storage!

Optimized:
nCB type and superplasticizer.



***nCB – nano Carbon Black**

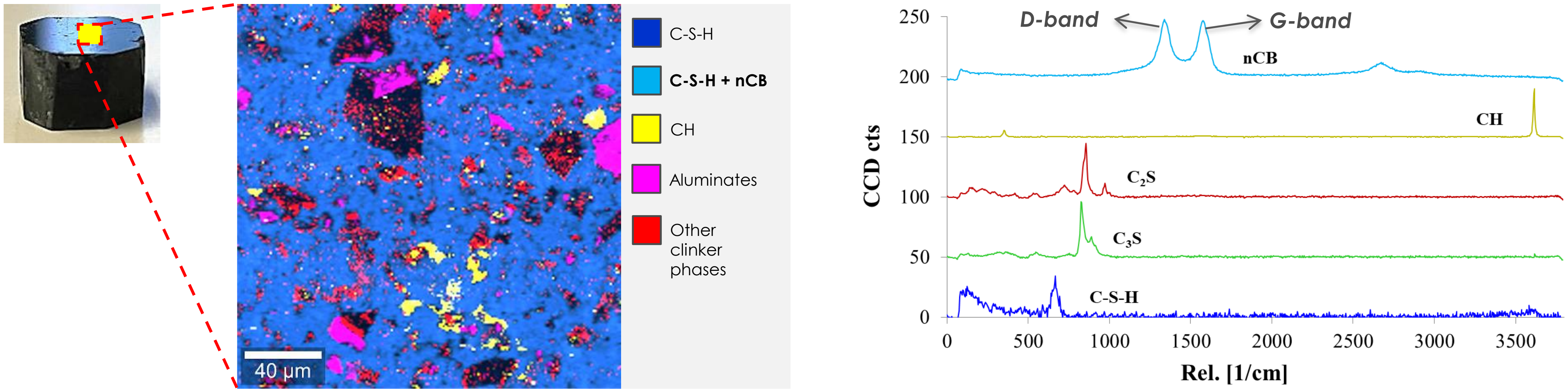
Publications:

Pellenqu *et al*. (2018-2020). Electron conducting carbon-based cement, method of making it as supercapacitator. Patent.
Soliman *et al*. (2020). Electric energy dissipation and electric tortuosity in electron conductive cement-based materials. *Physical Review Materials*.

SCALABILITY

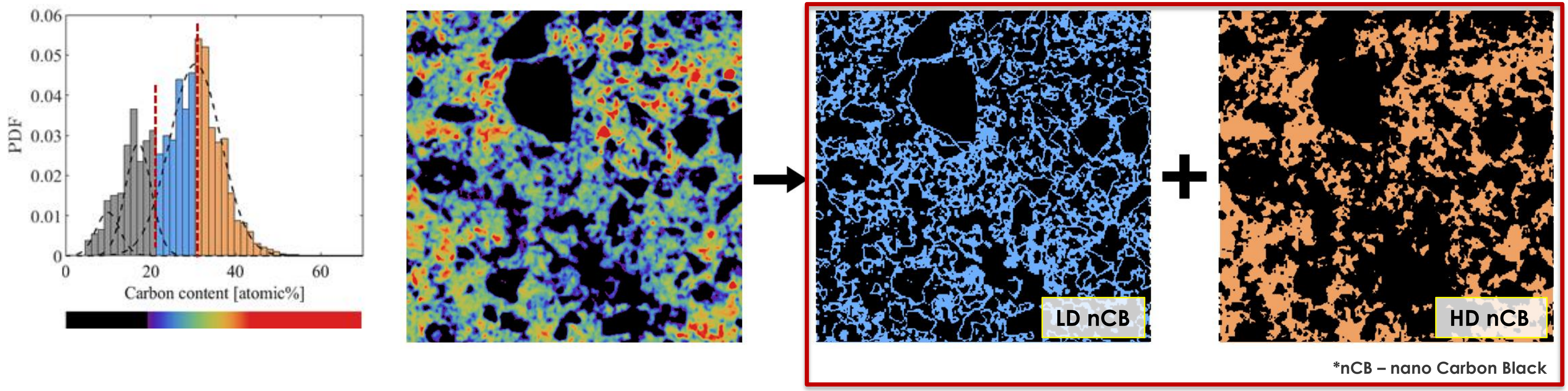
Correlative EDS–Raman Spectroscopy allows to distinguish nCB from carbonated products

Raman Spectroscopy map and Raman spectra of different phases:



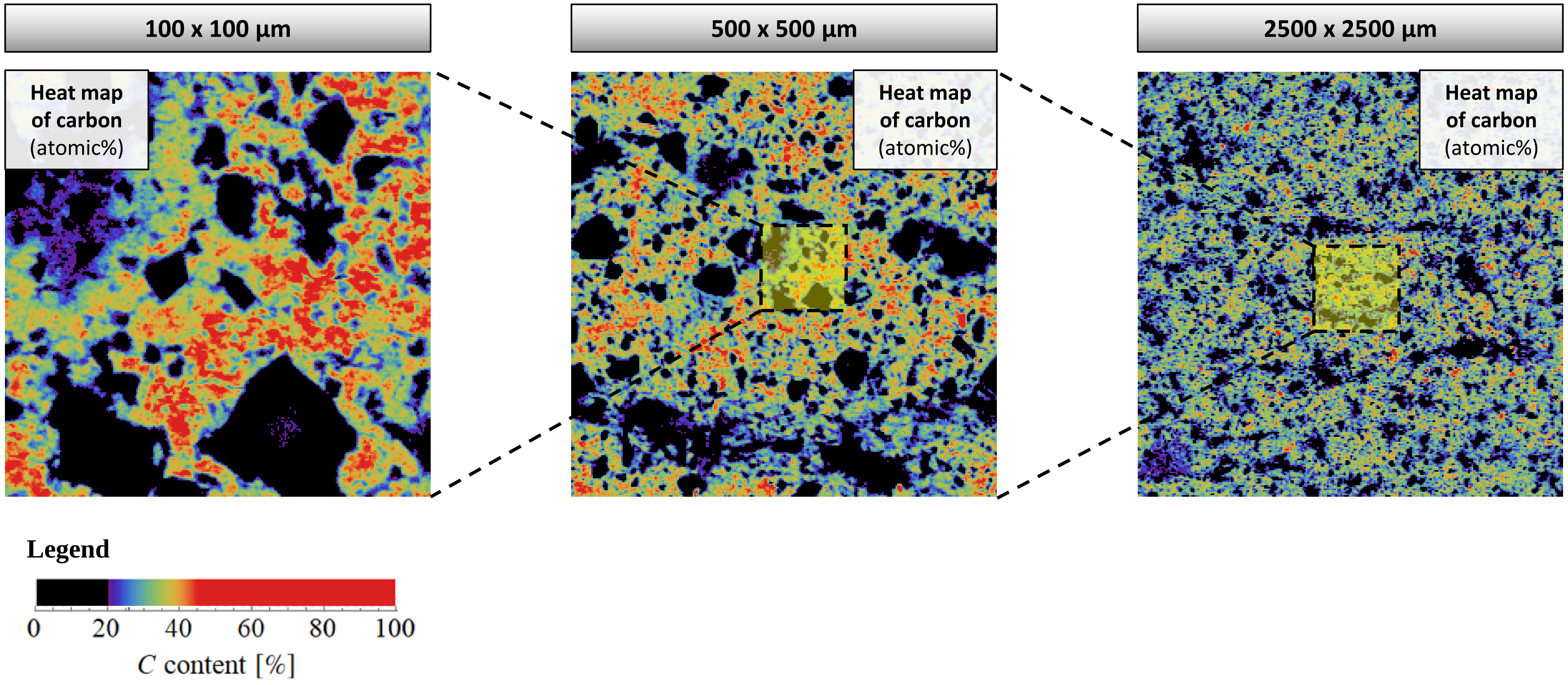
Hydration of cement with water in the presence of carbon phase generate a space-filling volumetric wire

Further analysis of nCB particles network reveals **low- and high-density (LD & HD) nCB phases**:



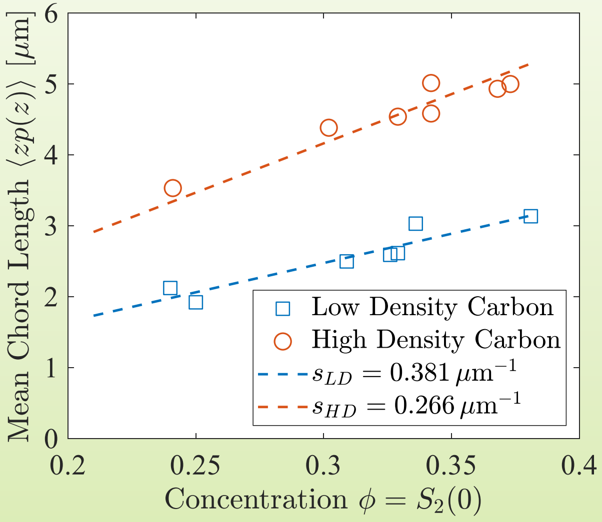
A space-filling volumetric wire can be visible at different length scales

Carbon black particles distribution at different length scales (EDS data):



Low- and high-density (concentration) nCB phases have a unique specific texture

A linear scaling of mean chord length with phase concentration is indicative of a **unique specific (texture) surface** of LD and HD nCB phases:



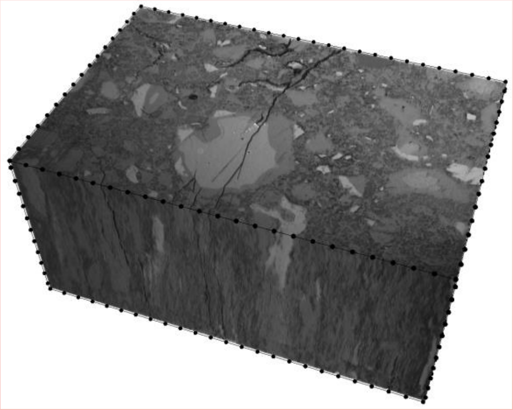
*nCB – nano Carbon Black

Ongoing efforts:

FIB SEM/EDS

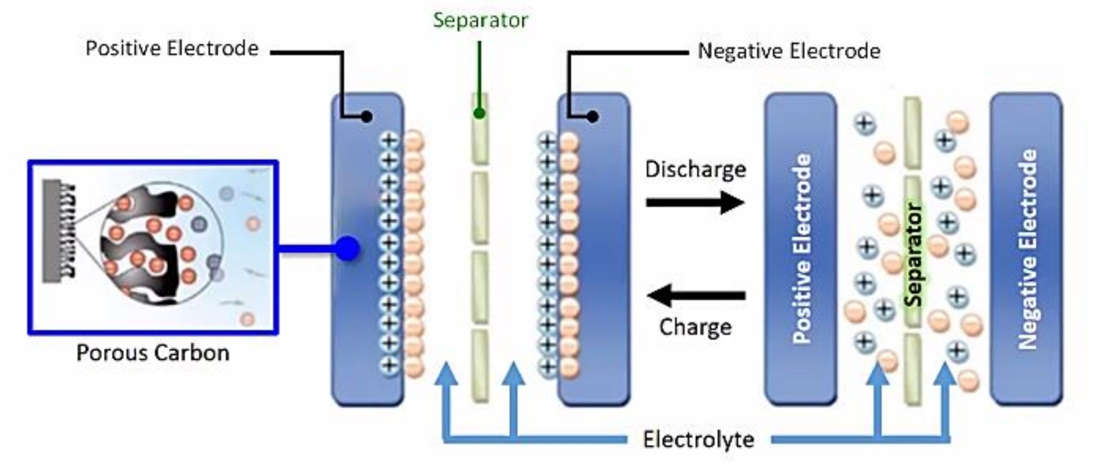
Imaging:
2D → **3D**

Resolution
400 nm → **10 nm**



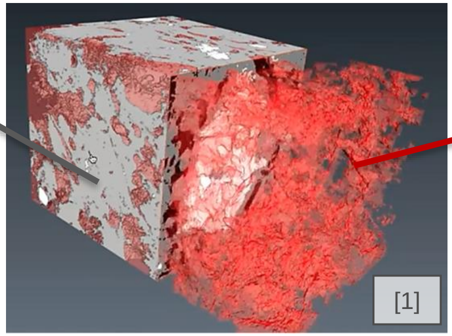
How EC^3 works as a supercapacitor

Schematic of the supercapacitor:



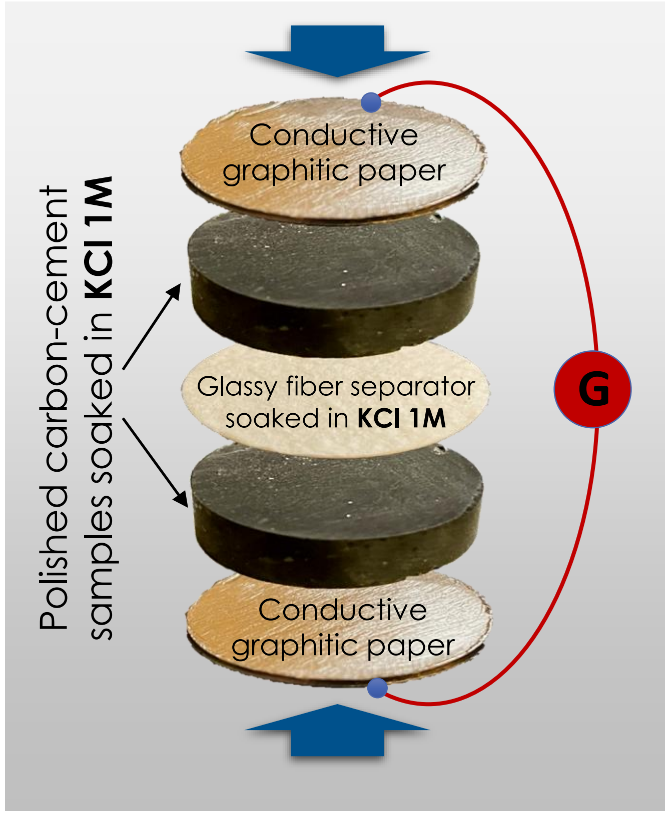
CONCRETE AS “structural” SUPERCAPACITOR:

Carbon-cement composite for energy storage **(electrode)**



Hydration porosity for transport **(electrolyte)**

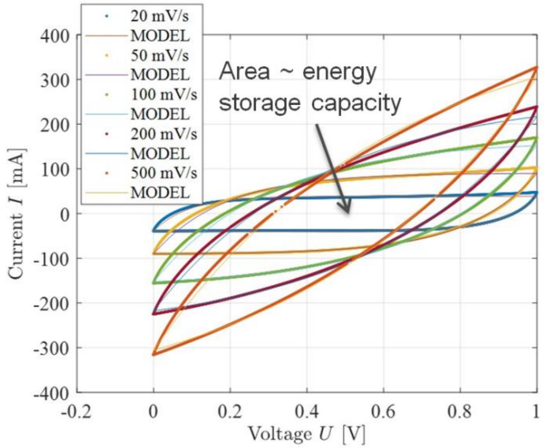
Supercapacitor testing cell:



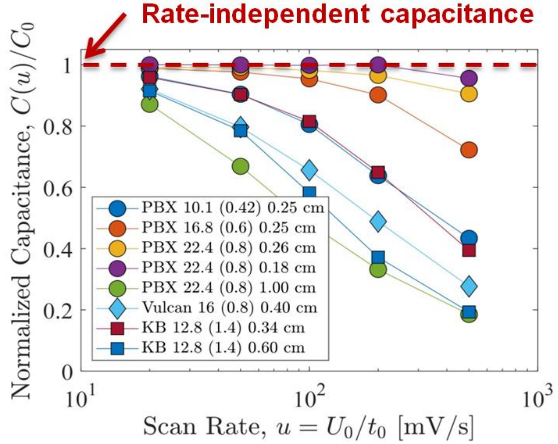
[1] CT scan by J. Perrin, Soleil synchrotron Paris

45 m^3 of EC^3 is sufficient for an average need of a residential house (average volume of foundation)

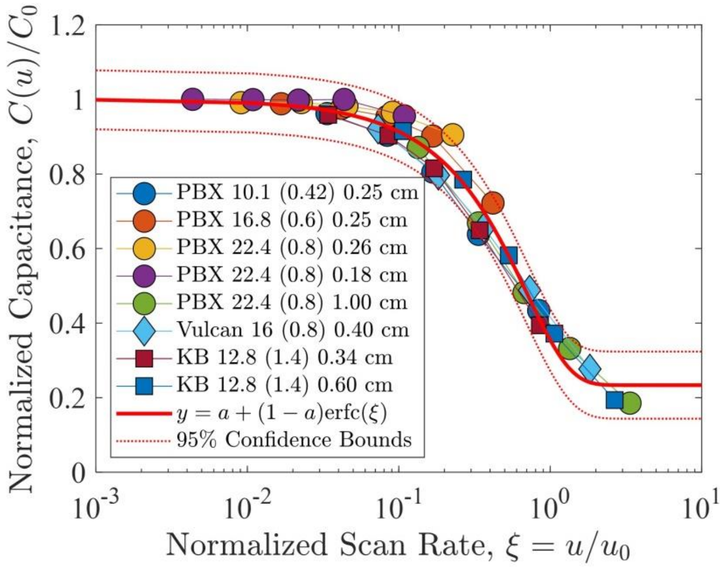
Energy storage capacitance:



Rate-independent capacitance



Rate-dependent capacitance scaled with **ξ**:



Classical dimensionless diffusion variable:

$$\xi = \frac{d^2\,\phi_C\,\rho_C\,S_{\mathrm{BET}}}{s_{LD}\,t_0\,\gamma D_0}\left(\frac{W}{C}\right)^{-3}$$

- d – electrode thickness
- $\phi_C\,\rho_C$ – nCB concentration
- S_{BET} – specific surface of nCB
- s_{LD} – texture specific surface
- t_0 – charge time
- $\gamma\,D_0$ – fitted diffusion coefficient
- W/C – water-to-cement ratio

Estimated capacitance: **20-220 Wh/m^3**

While we have several electrolytes to choose from, we are seeking to identify a cost-effective one with specific properties

What is needed:

- high diffusion coefficient,
- high ionic conductivity,
- negligible effect on the EC[3],
- relatively low cost.

"No perfect electrolyte has yet been developed" [1]

Electrolytes

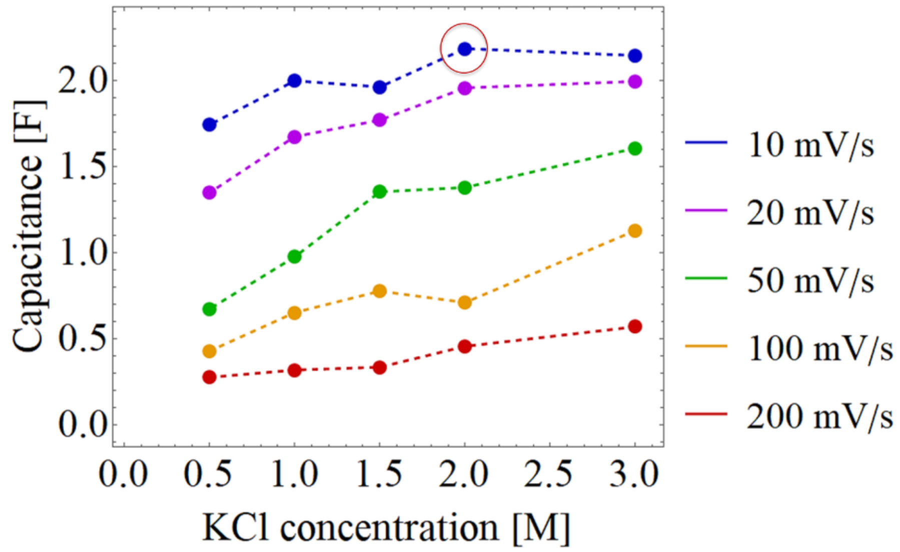
Aqueous	Organic solvents	Ionic liquids	Gel-like
Potassium chloride (KCl) Potassium hydroxide (KOH) Sodium sulfate (Na_2SO_4) Sulfuric acid (H_2SO_4) Sodium hydroxide (NaOH)	Acetonitrile (ACN) **Propylene carbonate (PC)** Dimethyl sulfoxide (DMSO) Ethylene carbonate (EC) Tetrahydrofuran (THF)	[EMIM][Tf2N] (1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide) [EMIM][BF4] (1-ethyl-3-methylimidazolium tetrafluoroborate) [BMIM][BF4] (1-butyl-3-methylimidazolium tetrafluoroborate) Ethylammonium nitrate (EAN)	Gel form of any liquid electrolyte, e.g.: **Gel form of KCl solution** 

[1] Raza, W., Ali, F., Raza, N., Luo, Y., Kim, K. H., Yang, J., ... & Kwon, E. E. (2018). Recent advancements in supercapacitor technology. *Nano Energy*, 52, 441-473.

Electrolyte concentration and its type highly affects the EC^3 supercapacitor performance

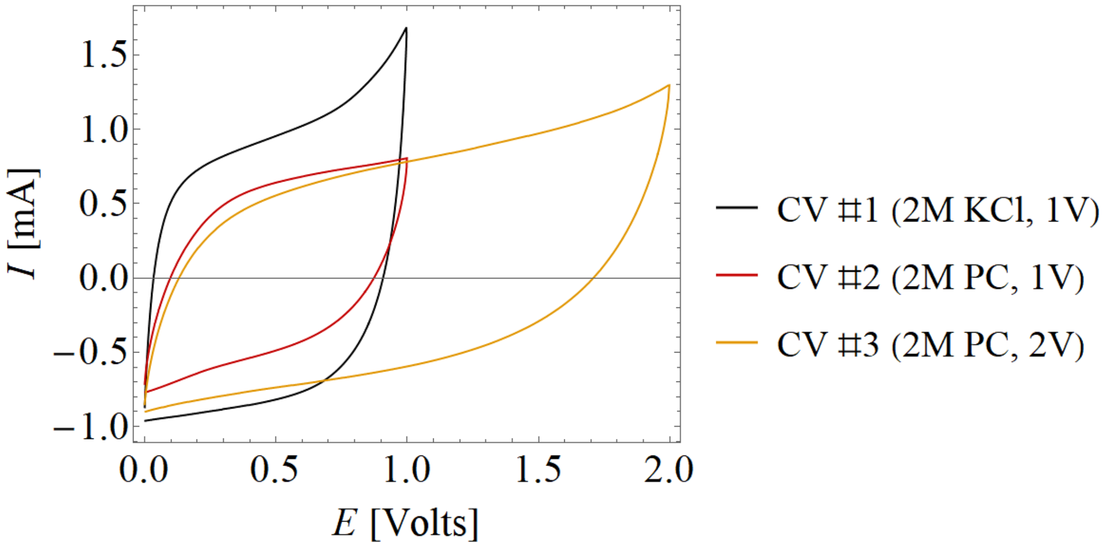
An influence of the electrolyte concentration:

- Higher molarity → **higher** ionic conductivity
- Higher molarity → **lower** diffusion coefficient



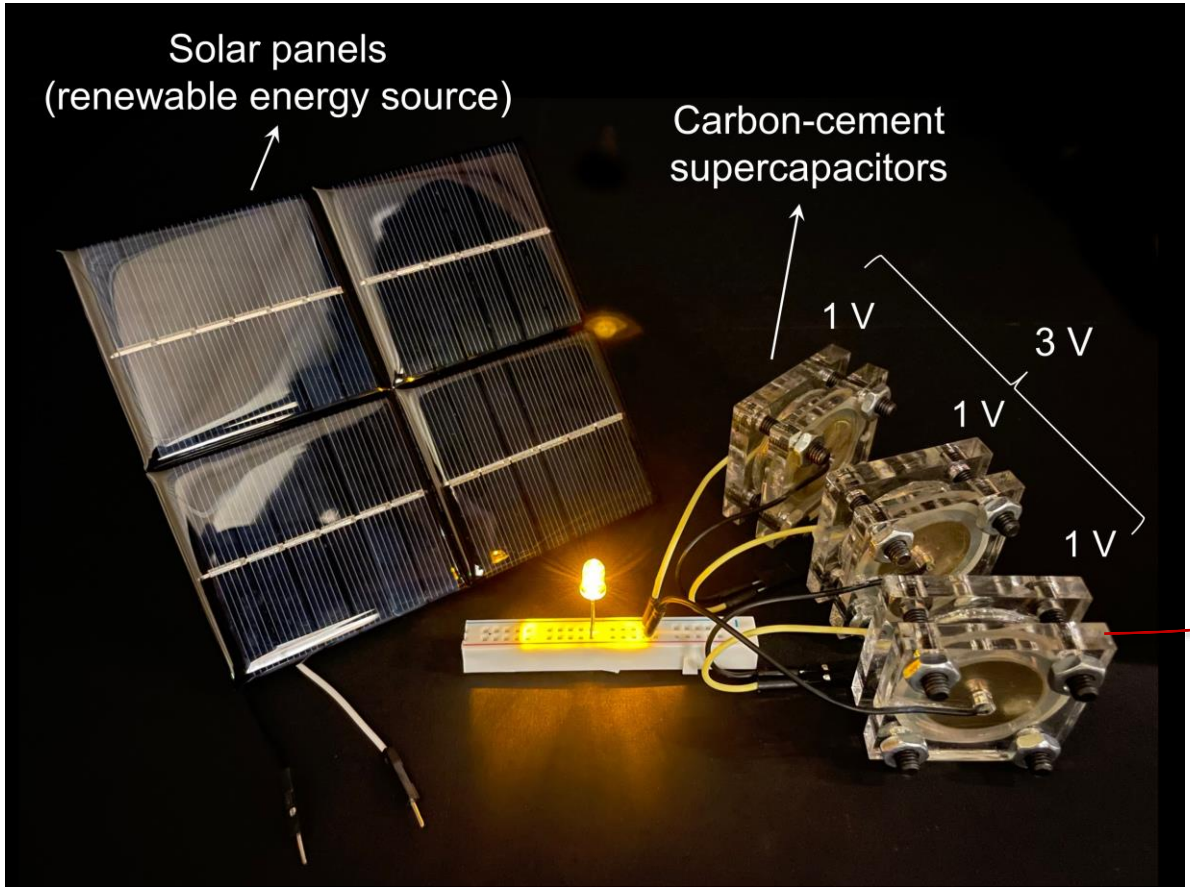
Aqueous vs. organic:

- Organic → **lower** capacitance
- Organic → **higher** voltage window



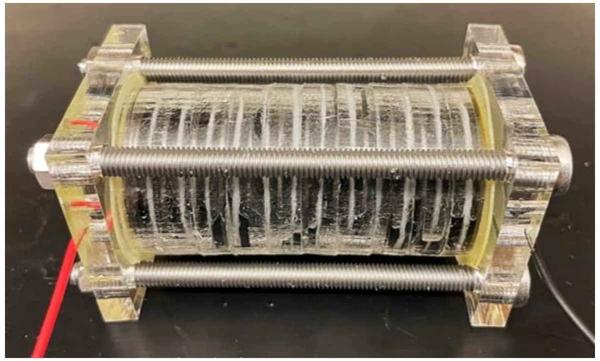
Proof of concept: lighting an LED with EC^3

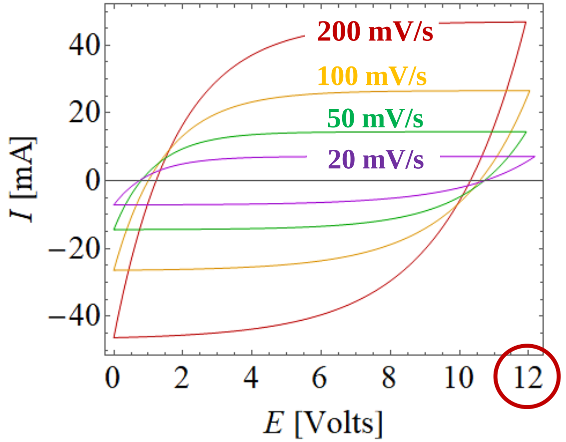
Functional carbon-cement supercapacitors (connected in series) charged by solar panels:



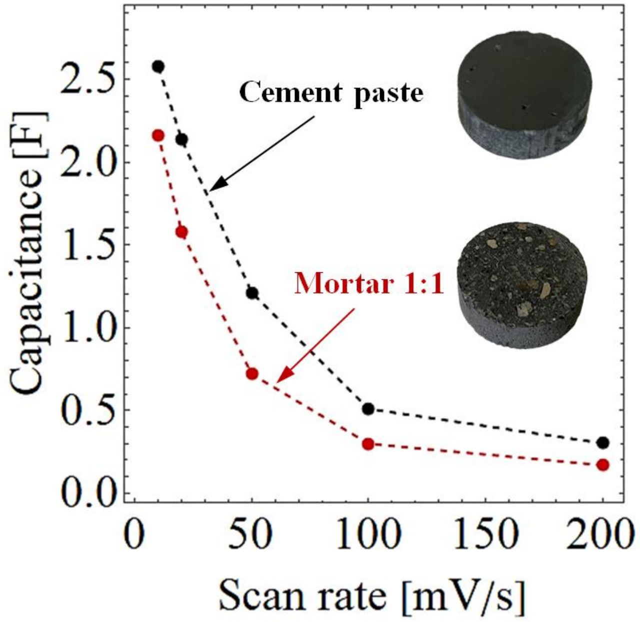
EC^3 was successfully scaled up to 12V “battery” and to a mortar scale

12V supercapacitor:



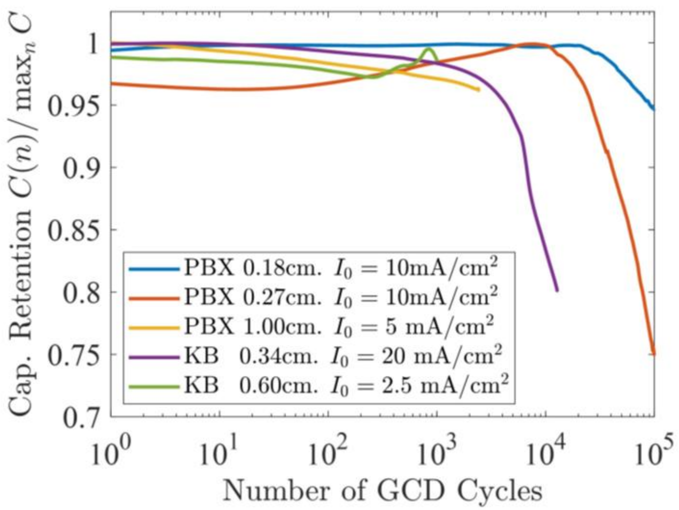


EC^3 scaled up from cement paste to mortar scale:

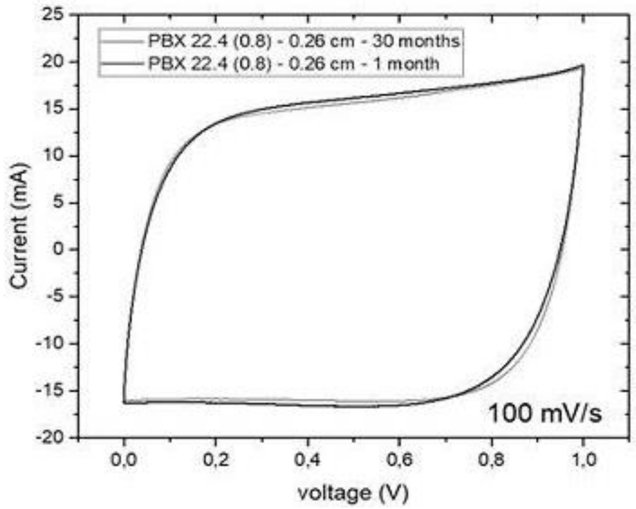


EC3 supercapacitors show a great performance due to its long lifetime, resistance to aging, and low percolation threshold of nCB

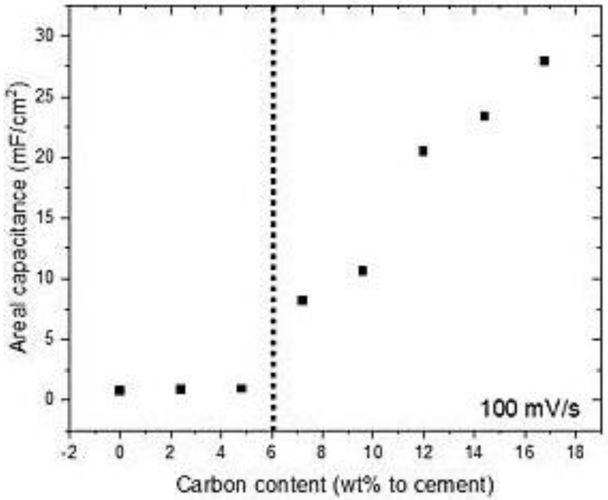
An influence of the **number of charge-discharge cycles**:



An influence of the **hydration time**:

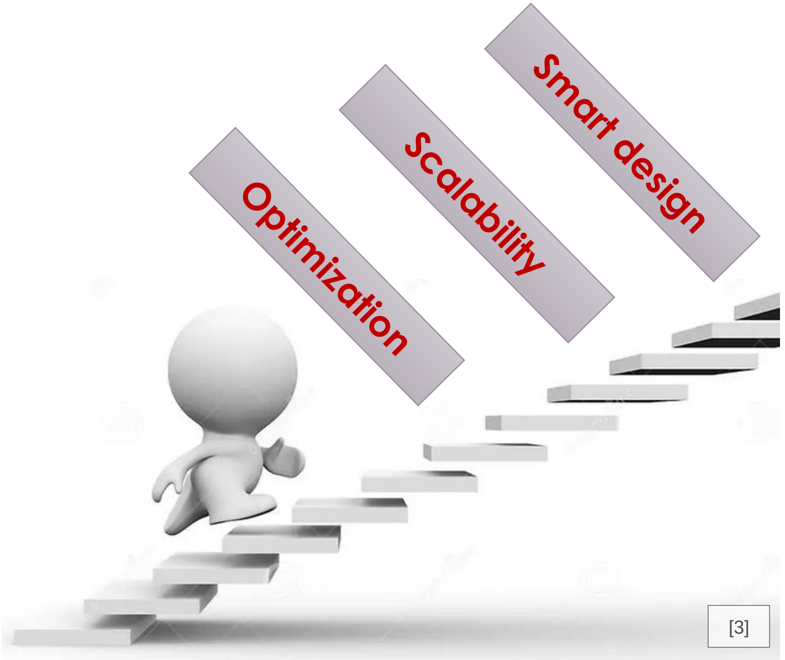


An influence of the **carbon black content** (by mass):



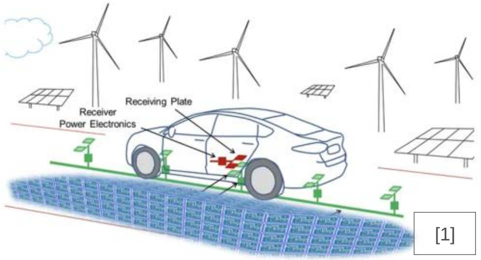
Conclusions and perspectives

EC³ technology exhibits promising scalability, spanning voltage levels from 1V to 12V and encompassing scales from cement paste to mortar. This versatility widens its range of potential applications, bringing us closer to the transition from a fossil fuel-based economy to renewables.



Future large-scale applications

Smart charging roads



Off-grid houses

Energy buffer for renewables

[1] Courtesy of Admir Masic and James Weaver
[2] https://offgridworld.com/5-cutting-edge-off-grid-homes-modern-amenities/
[3] https://www.dreamstime.com/stock-illustration-white-d-human-character-running-up-stairs-three-dimensional-stylized-image69269838

Questions?

Additional questions:

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Photo by Andrew P. Laurent

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