CONCRETE INNOVATIONS

Session 15
September 13th 2023

On the multifunctional future of concrete

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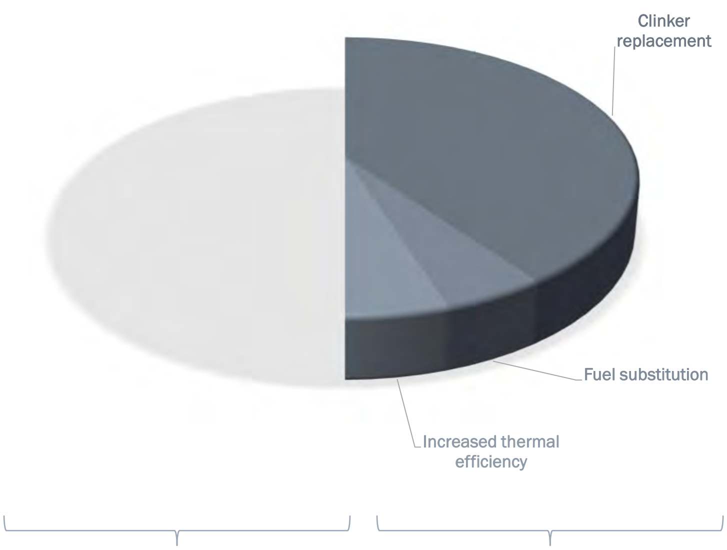
Why Materials Matter?

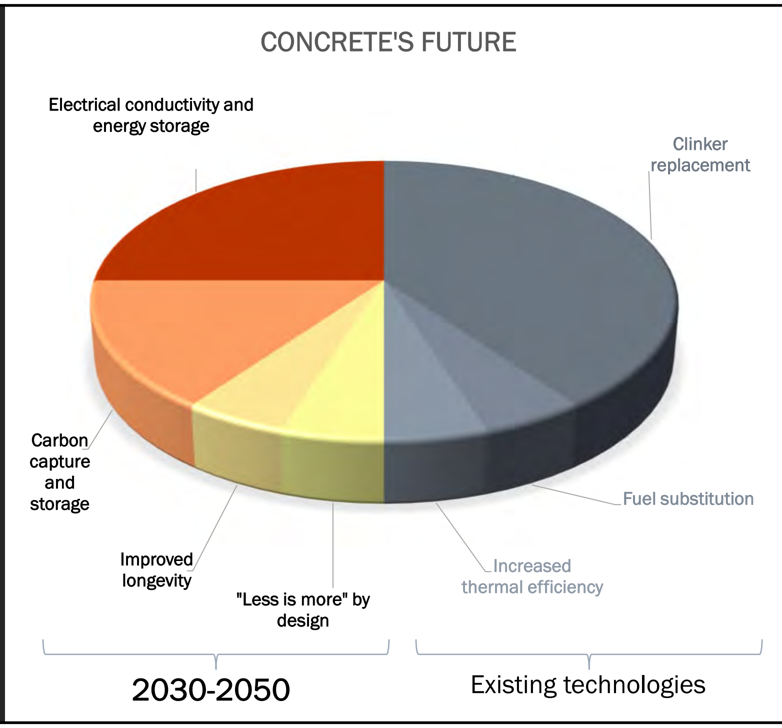
Portland Cement Association released in October 2021 the industries' 2050 carbon neutrality roadmap

CONCRETE'S FUTURE



CONCRETE'S FUTURE:

Multifunctionality!



Multifunctional concrete

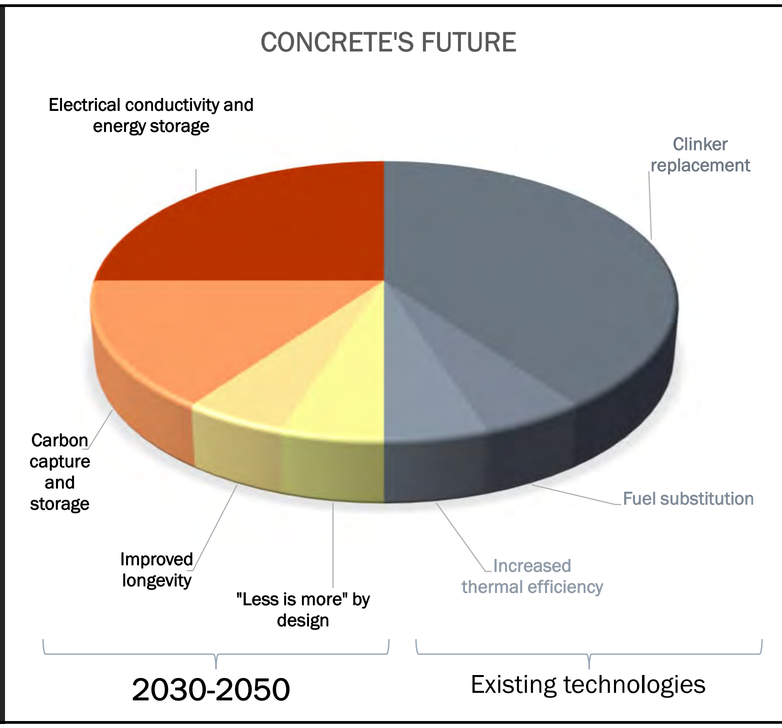
CLIMATE CHANGE

ENERGY TRANSFORMATION

RESILIENCE

SUSTAINABILITY

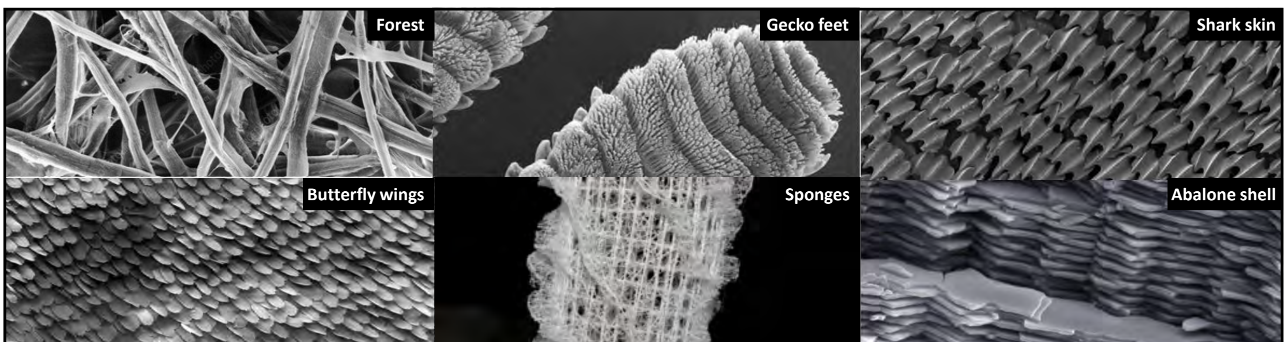
SOCIAL JUSTICE



Biological materials/structures

- Organisms have evolved over millennia
- Hierarchical structure: from nano to macro
- Self-assembly
- Self-healing
- Synthesis under mild conditions (room temperature)

MULTI-FUNCTIONAL!



Biological materials/structures

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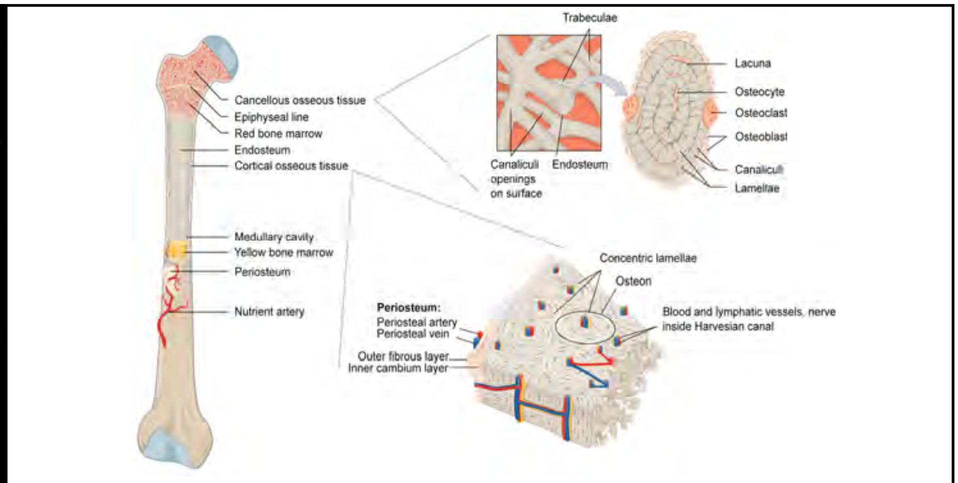
MULTI-FUNCTIONAL!

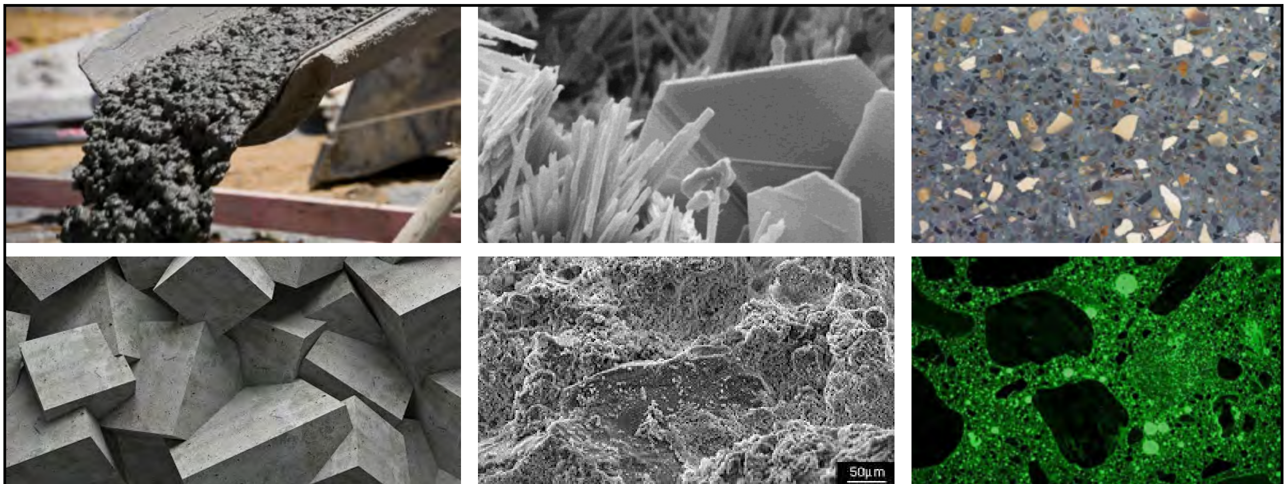


Bone as a MULTI-FUNCTIONAL material

Minerals=strength
blood vessels=energy supply
cells=self-healing
canaliculi = signaling

MULTI-FUNCTIONAL!

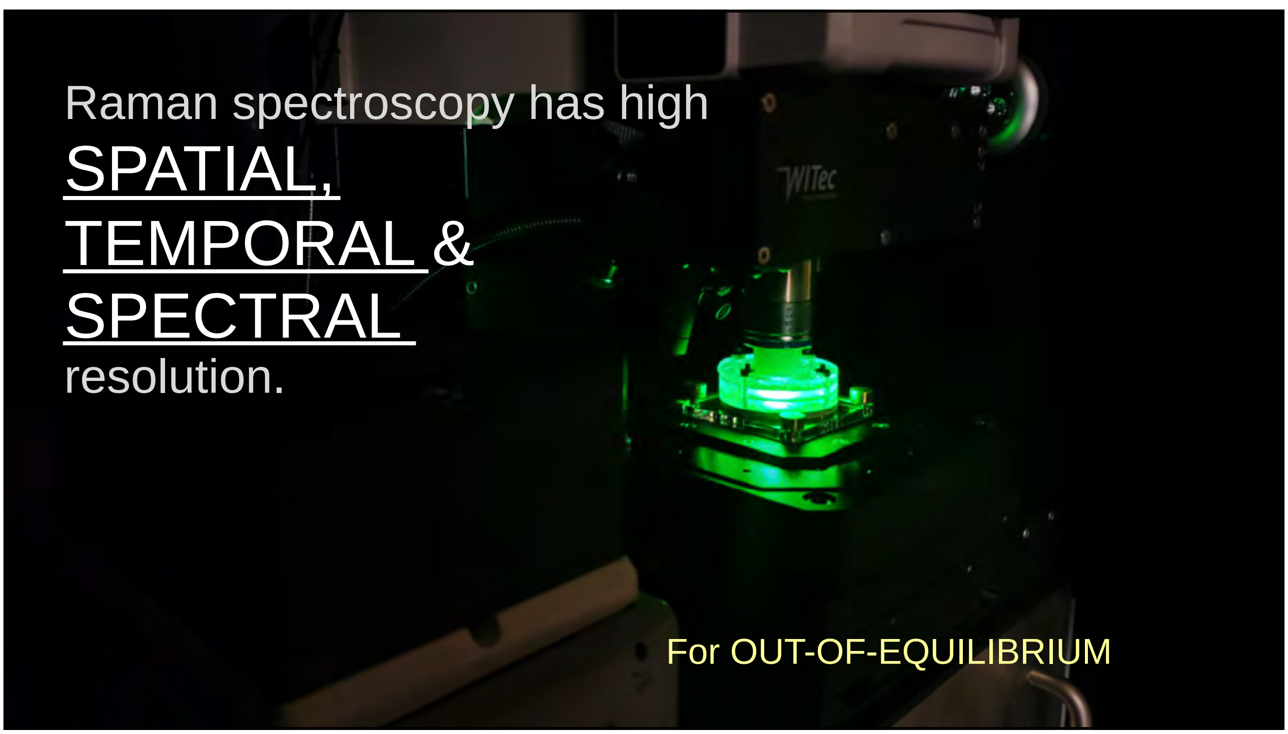
Concrete and multifunctionality



Capitalizing on cement chemistry: OUT-OF-EQUILIBRIUM

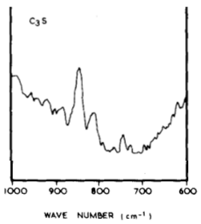
Concrete is a remarkably rich deposit of interesting and contemporary research questions, all contained in its ambiguities: granular or continuous?, liquid or solid?, crystalline or glassy?, smooth or rough?, “porous”, brittle or ductile?, material or process?

Henri Van Damme, CCR (2018)

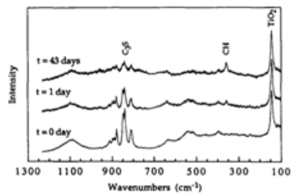


+ Optical microscope, CCD | + Confocal microscopy | + Underwater Raman

Clinker components

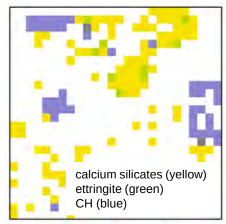


Hydration products



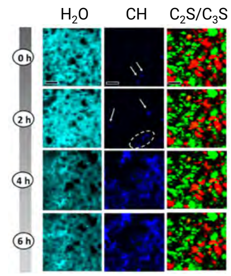
Bensted, JACerS (1976)
Tarrida et al., ACBM (1995)

Raman mapping



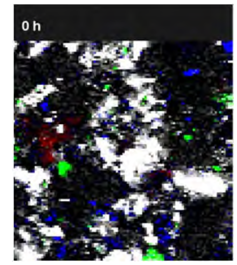
Liu and Sun, Front. Struct. Civ. Eng. (2016)

***In-situ* monitoring**



Torres-Carrasco et al., JRS (2019)

Operando
Real-world condition



Loh et al., Langmuir (2021)

Raman spectroscopy + Cement chemistry

Raman spectroscopy had limited applications due to its poor signal-to-noise ratio

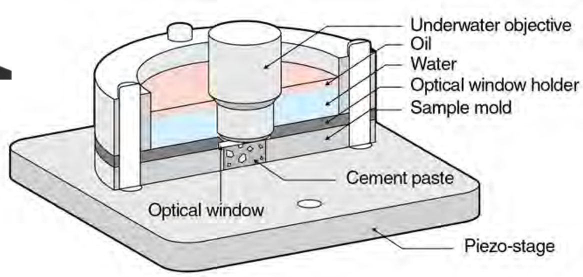
Optical microscope added the **spatial resolution**

Confocal Raman micro-spectroscopy enabled fast acquisition → **temporal resolution**

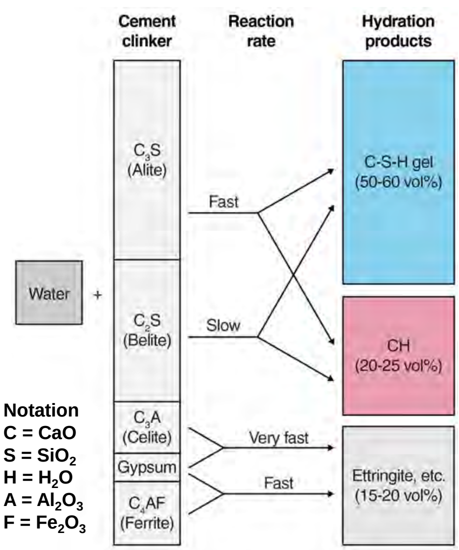
Underwater Raman enabled monitoring in **real-world conditions** with **higher temporal resolution**

In-situ underwater Raman stage for cement hydration monitoring

Hyun-Chae Loh



- Allows *in-situ* Raman while the sample cures underwater
- Water dissipates heat and prevents sample damage
- Close to the real-world curing (hydration) conditions



Notation
C = CaO
S = SiO_2
H = H_2O
A = Al_2O_3
F = Fe_2O_3

Loh et al., *Langmuir* (2021)

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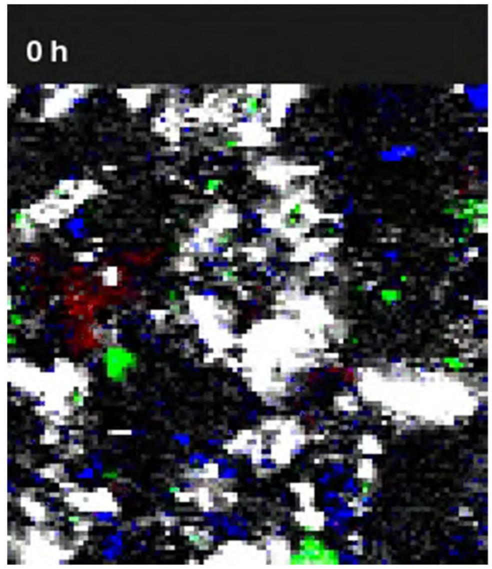
Raman spectroscopy + Cement chemistry

Underwater Raman enabled monitoring in **real-world conditions** with **higher temporal resolution**

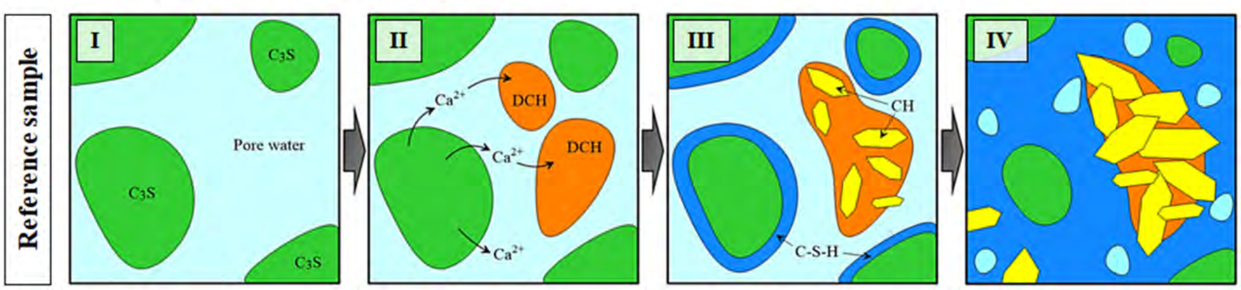
+ Underwater Raman

Operando **real-world condition** OPC w/c=0.4



Loh et al., Langmuir (2021)

Schematic representation of early stage hydration



Loh et al., Langmuir (2021)

Early stages of cement hydration

Discovery of OUT-OF-EQUILIBRIUM/transient phases

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Multifunctional concrete

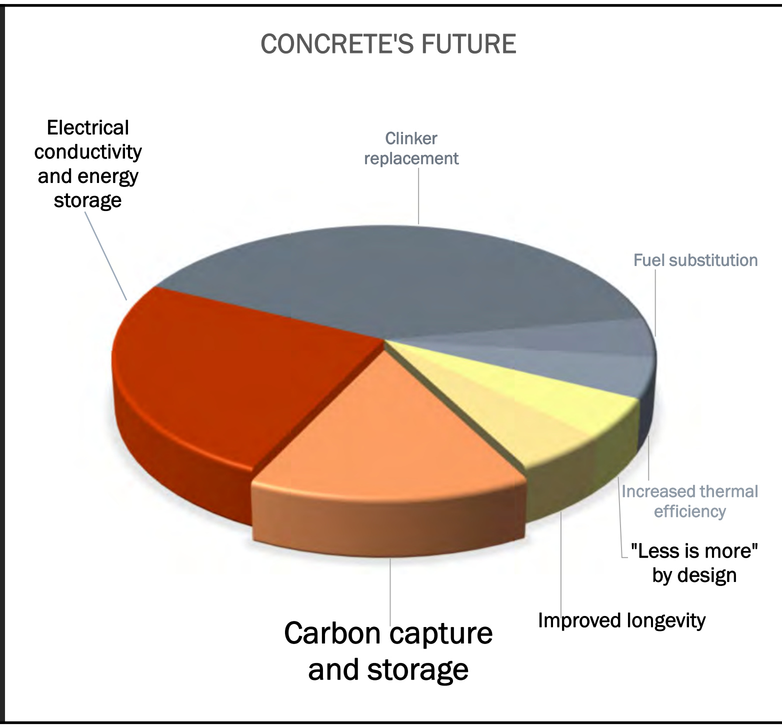
CLIMATE CHANGE

ENERGY TRANSFORMATION

RESILIENCE

SUSTAINABILITY

SOCIAL JUSTICE

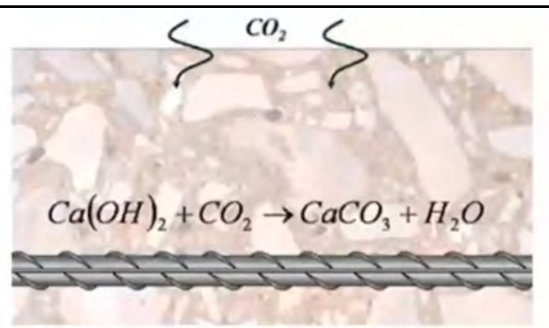


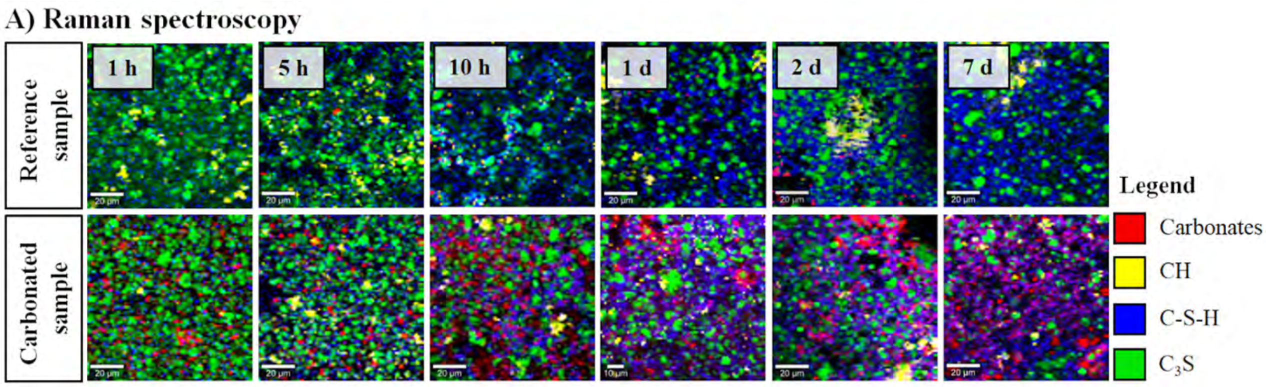
CO_2 uptake in concrete over time: problem or opportunity?

Late-stage carbonation leads to pH drop associated with reinforcement corrosion and concrete spalling.

But:
CARBONATION = CARBON SINK!

How to reconcile the two phenomena





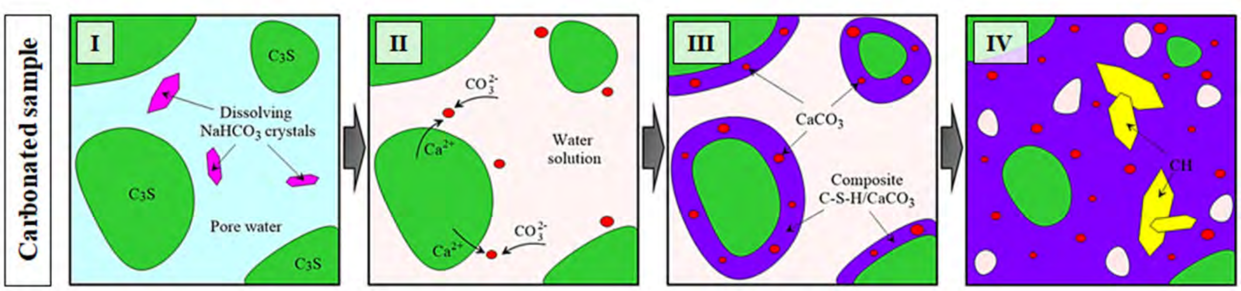
Stefaniuk et al., PNAS Nexus, 2023

Fresh concrete carbon capture and storage: cementing CO_2 into C-S-H

- Carbon capture
- Permanent carbon storage
- Early strength development due to seeding

MULTI-FUNCTIONAL!

Schematic representation of early-stage carbonation



Stefaniuk et al., PNAS Nexus, 2023

Cementing CO_2 in concrete

Up to 15% of total CO_2 emissions can be permanently stored in cement

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Multifunctional concrete

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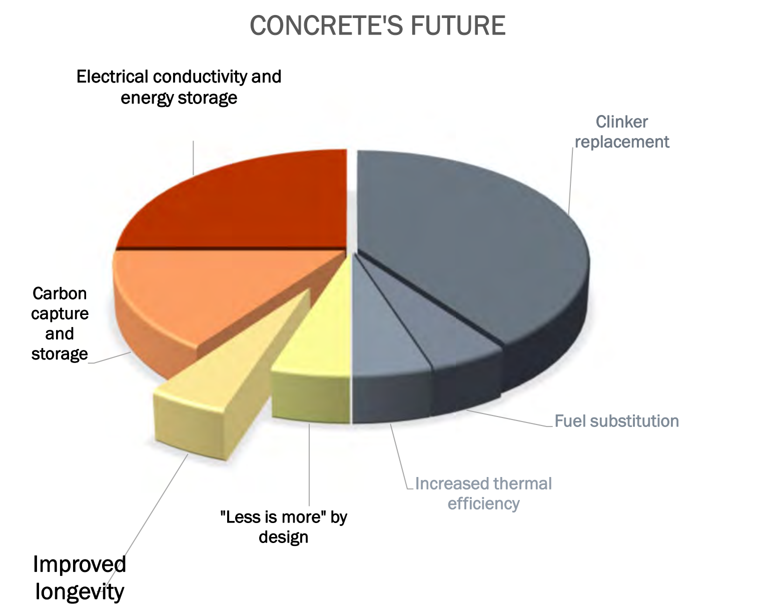
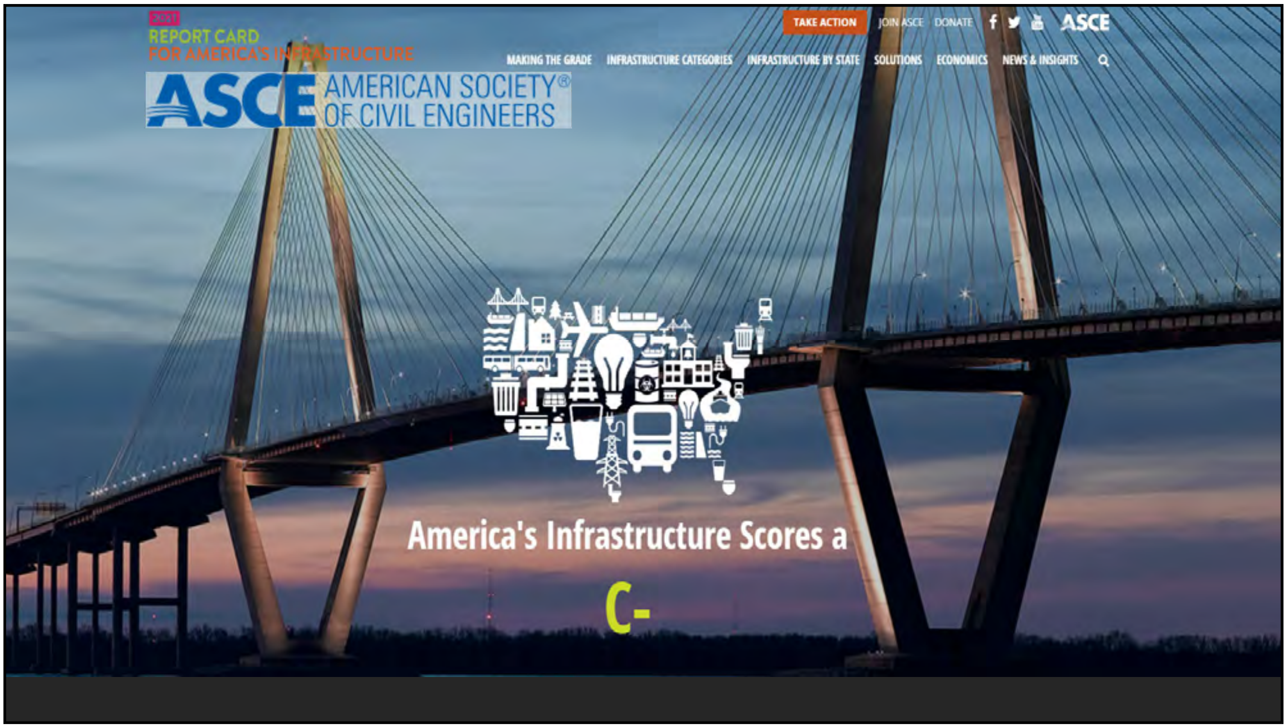


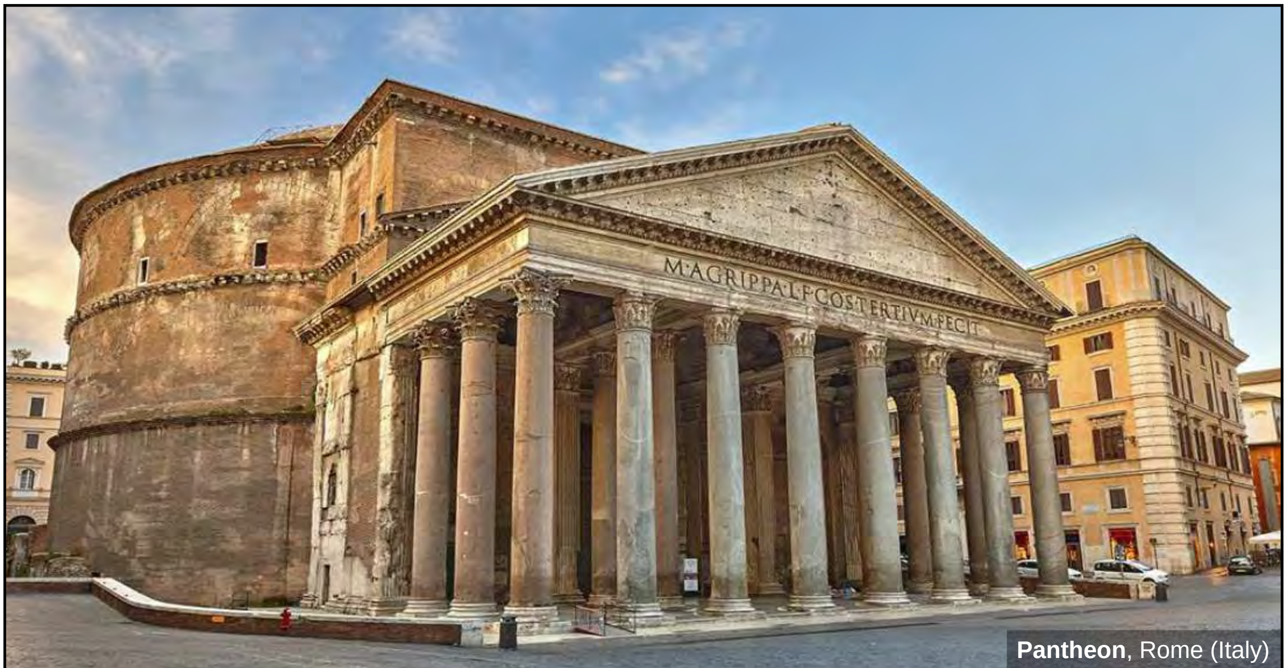
Morandi bridge

Genova – Italia
August 14 2018

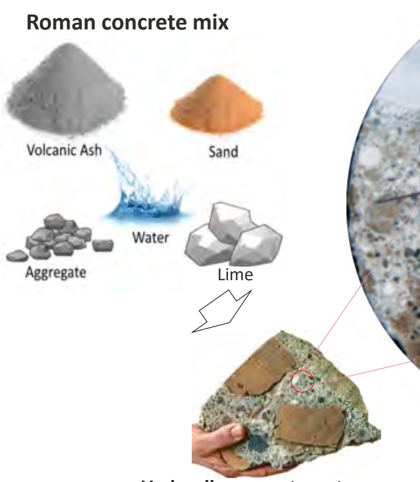


Roman aqueduct Pont du Gard

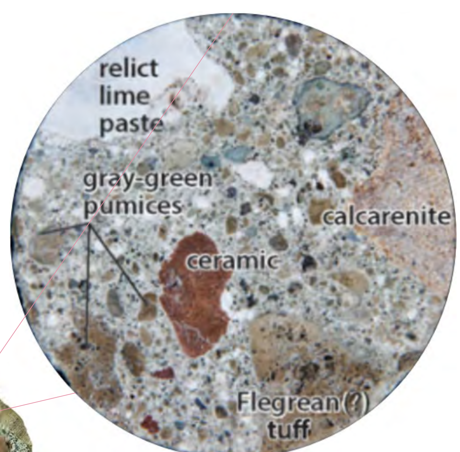
France 60 AD - today



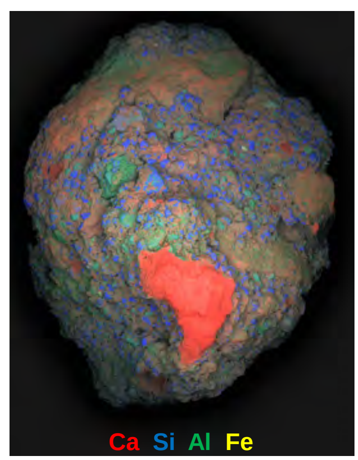
What are the origins of extreme long-term durability of ancient Roman concrete?



Hydraulic cement mortar
Calcium-aluminum-silicate-hydrate (C-A-S-H)

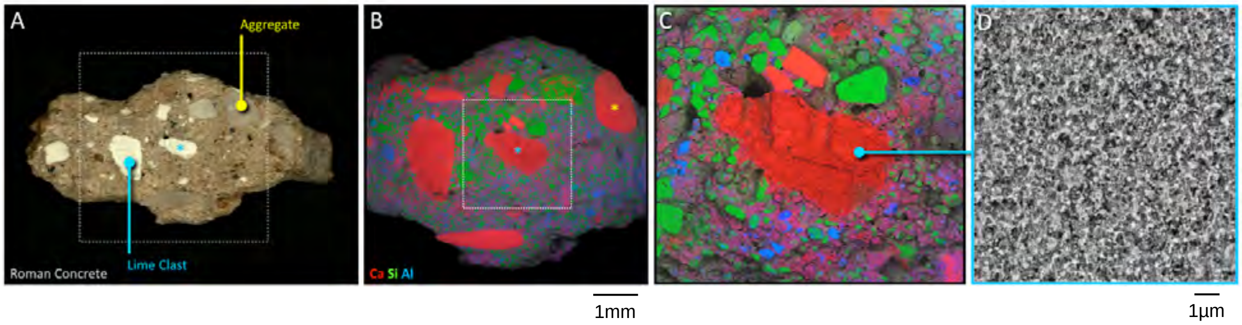


Jackson et al. (2016)



How relict lime clasts are formed in ancient samples and can they be the missing link in “self-healing” picture?

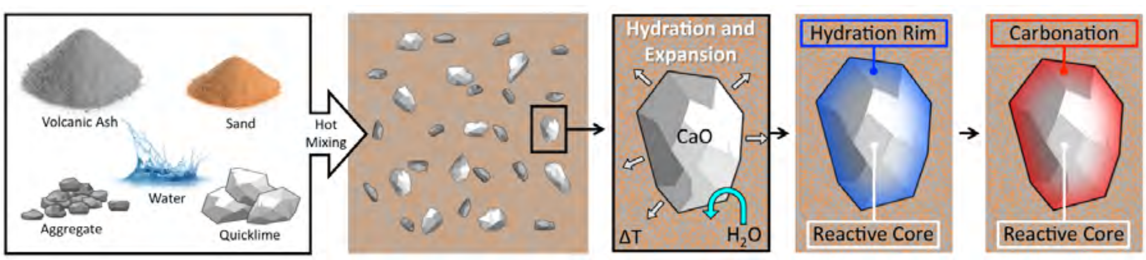
Roman concrete: Long-lasting, self-healing ancient materials



Hypothesis: Relict lime clasts serve as the long-term source of reactive calcium

Seymour et al., Science Advances, 2023

Hot-mixing could create low-humidity conditions in lime clasts



Hot mixing using quicklime

Exothermic hydration of quicklime in the mortar:
- Creates low-humidity conditions around lime particles preventing the dissolution.
- Promotes and accelerates hydraulic reactions (solving the issue of Roman concrete setting time)

Seymour et al., Science Advances, 2023

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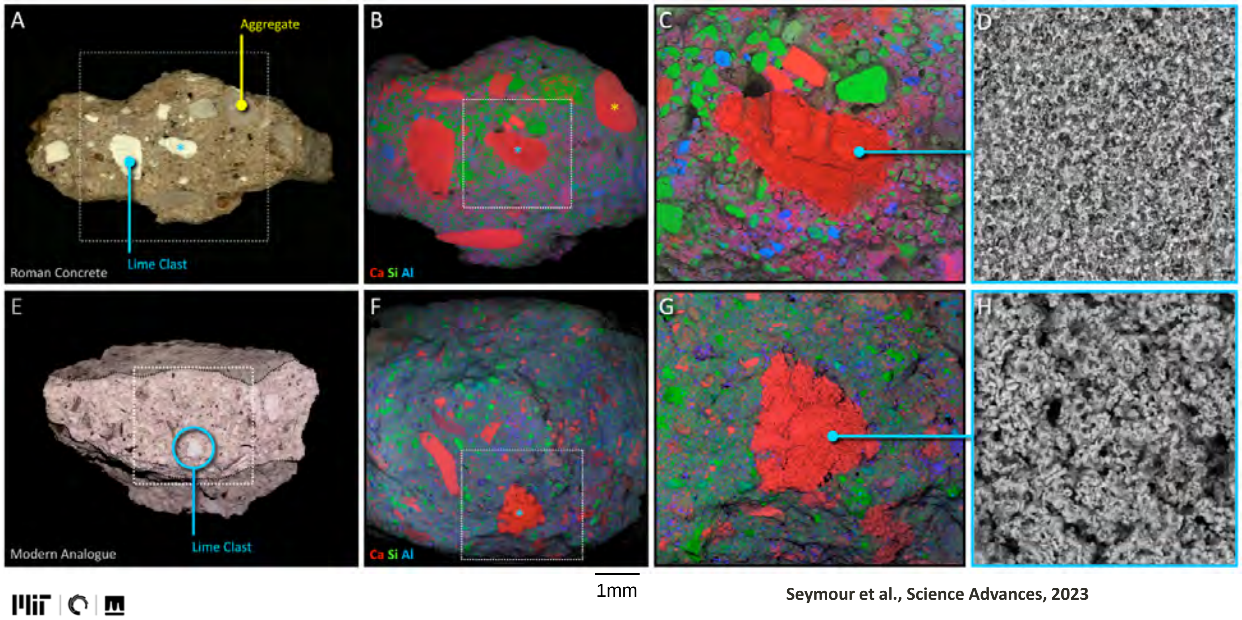
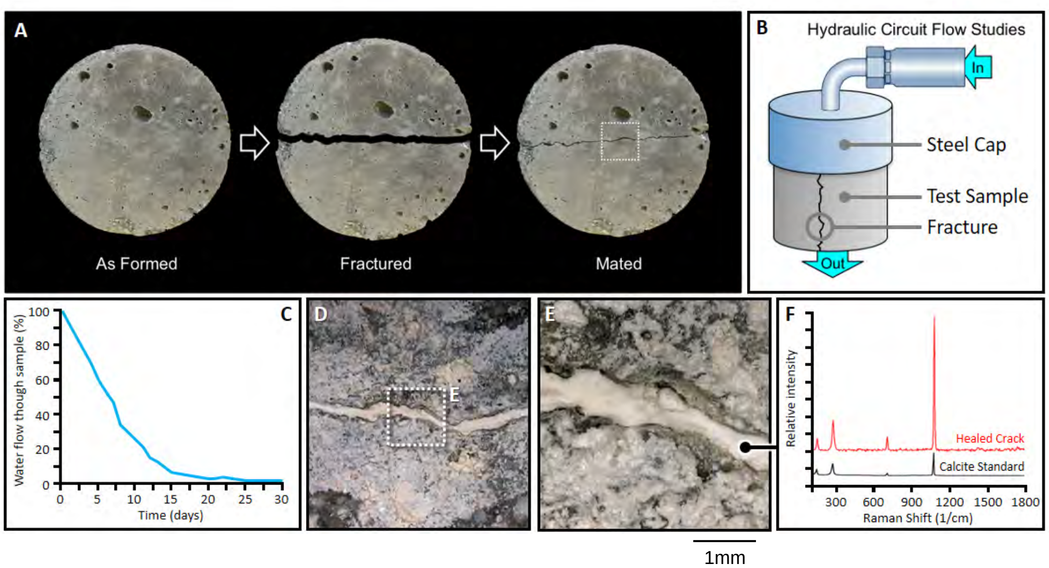
Roman concrete: Long-lasting, self-healing ancient materials



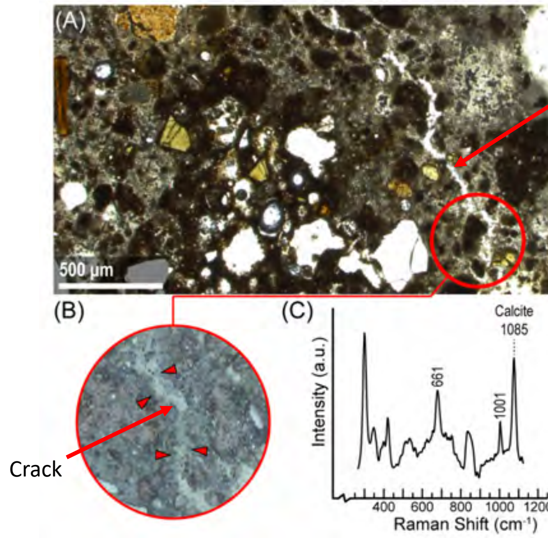
Seymour et al., Science Advances, 2023

Design of self-healing modern concrete incorporating hot-mixing strategy



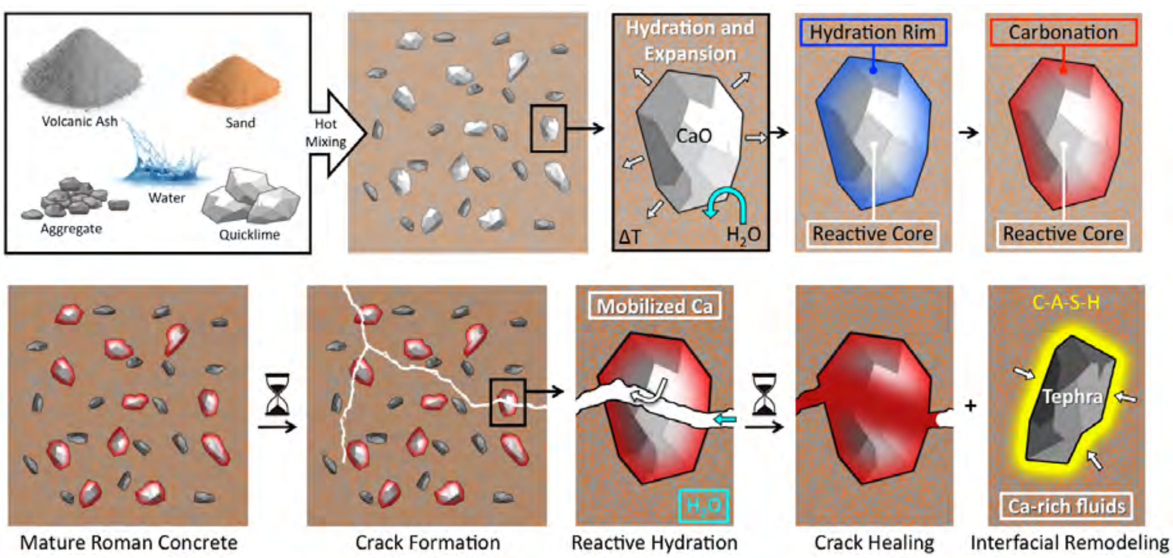
Seymour et al., Science Advances, 2023

2,050-year-old Roman tomb offers insights on ancient concrete resilience

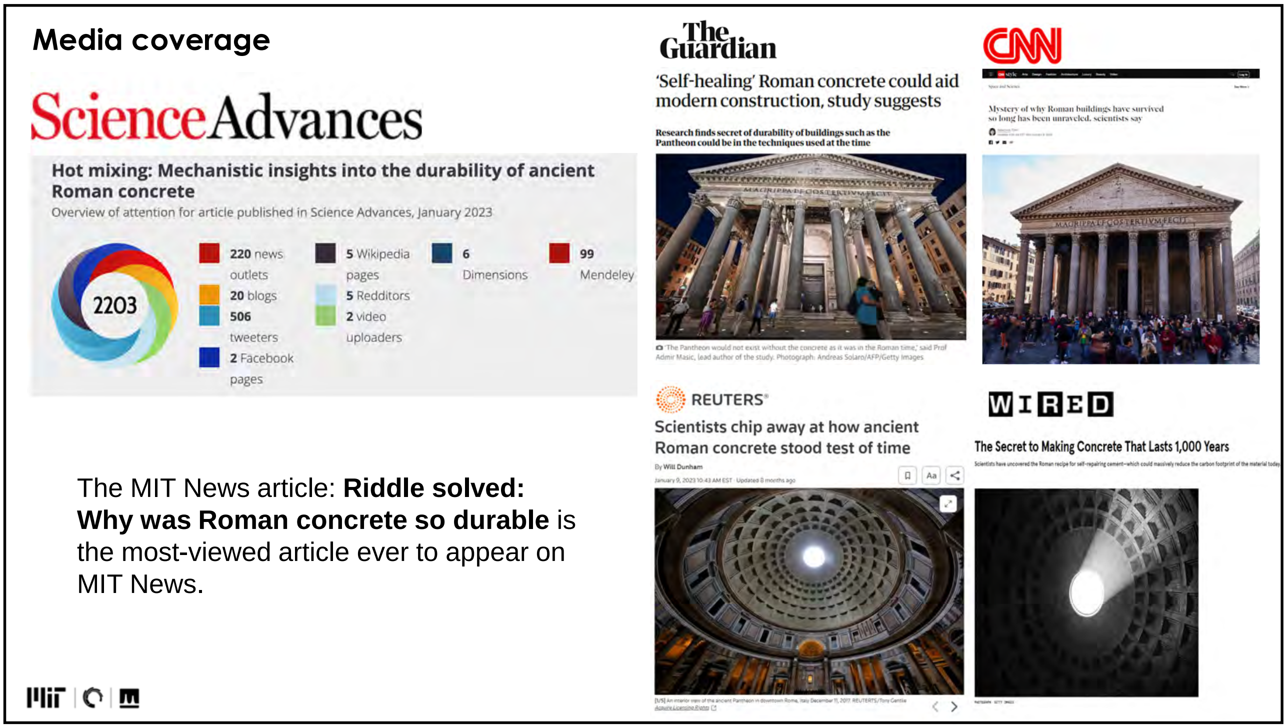


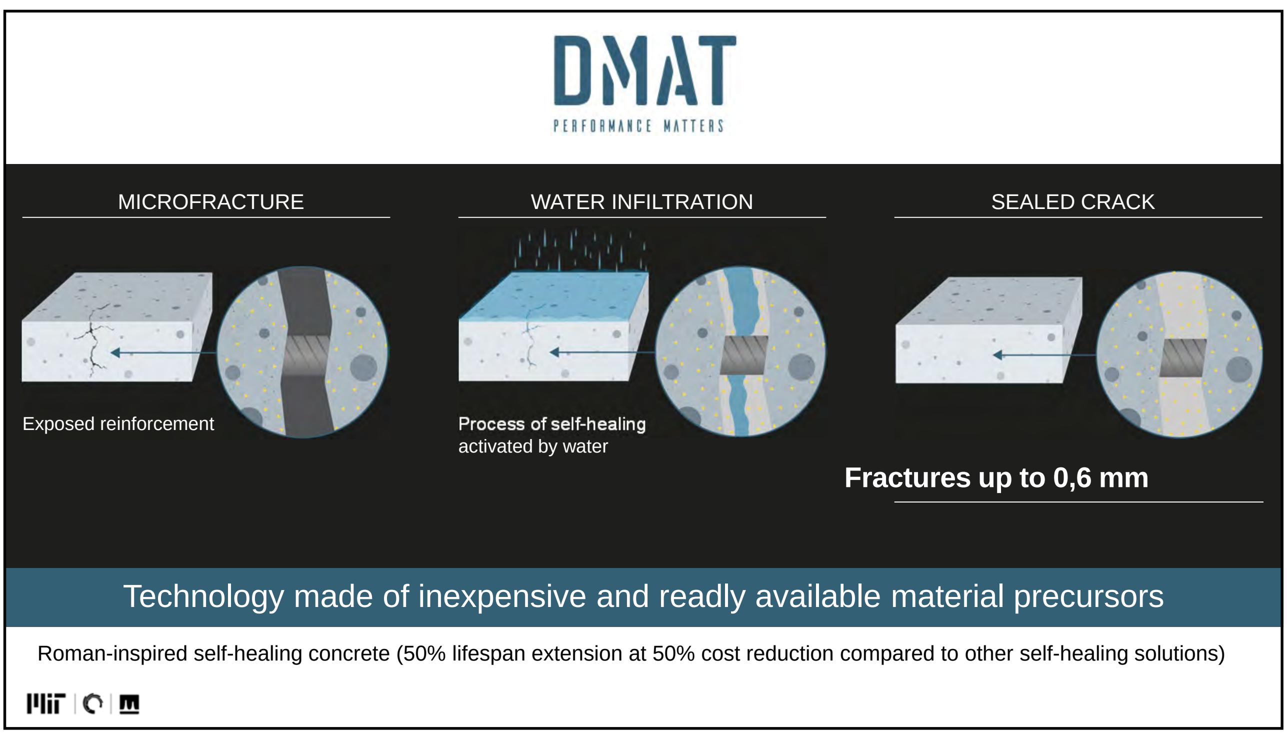
Seymour et al., JACerS, 2021

Self-healing mechanism



Seymour et al., Science Advances, 2023


Media coverage
ScienceAdvances
Hot mixing: Mechanistic insights into the durability of ancient Roman concrete
Overview of attention for article published in Science Advances, January 2023
2203
220 news outlets
20 blogs
506 tweeters
2 Facebook pages
5 Wikipedia pages
5 Redditors
2 video uploaders
6 Dimensions
99 Mendeley
The MIT News article: **Riddle solved: Why was Roman concrete so durable** is the most-viewed article ever to appear on MIT News.
The Guardian
'Self-healing' Roman concrete could aid modern construction, study suggests
Research finds secret of durability of buildings such as the Pantheon could be in the techniques used at the time
CNN
Mystery of why Roman buildings have survived so long has been unraveled, scientists say
REUTERS
Scientists chip away at how ancient Roman concrete stood test of time
WIRED
The Secret to Making Concrete That Lasts 1,000 Years


DMAT
PERFORMANCE MATTERS
MICROFRACTURE
Exposed reinforcement
WATER INFILTRATION
Process of self-healing activated by water
SEALED CRACK
Fractures up to 0,6 mm
Technology made of inexpensive and readily available material precursors
Roman-inspired self-healing concrete (50% lifespan extension at 50% cost reduction compared to other self-healing solutions)

Multifunctional concrete

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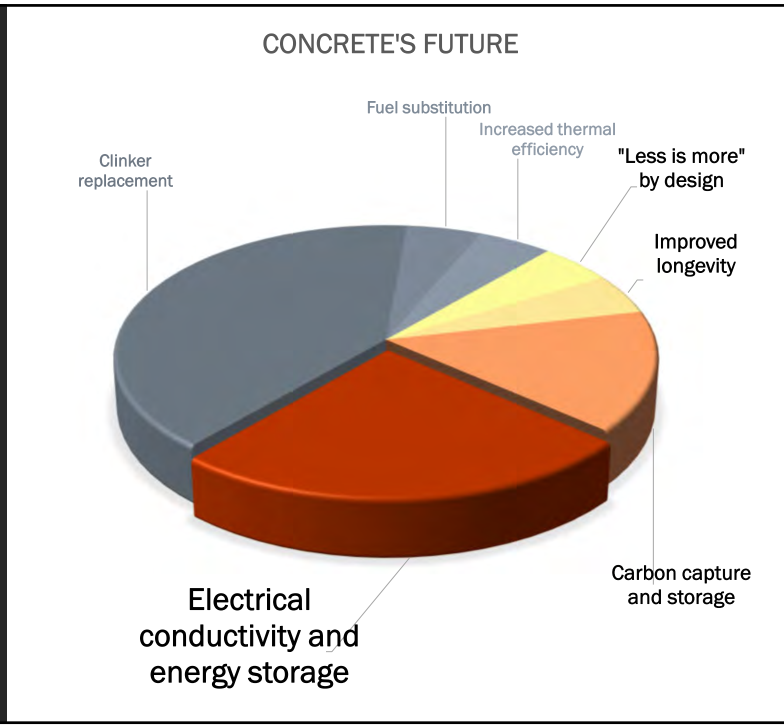
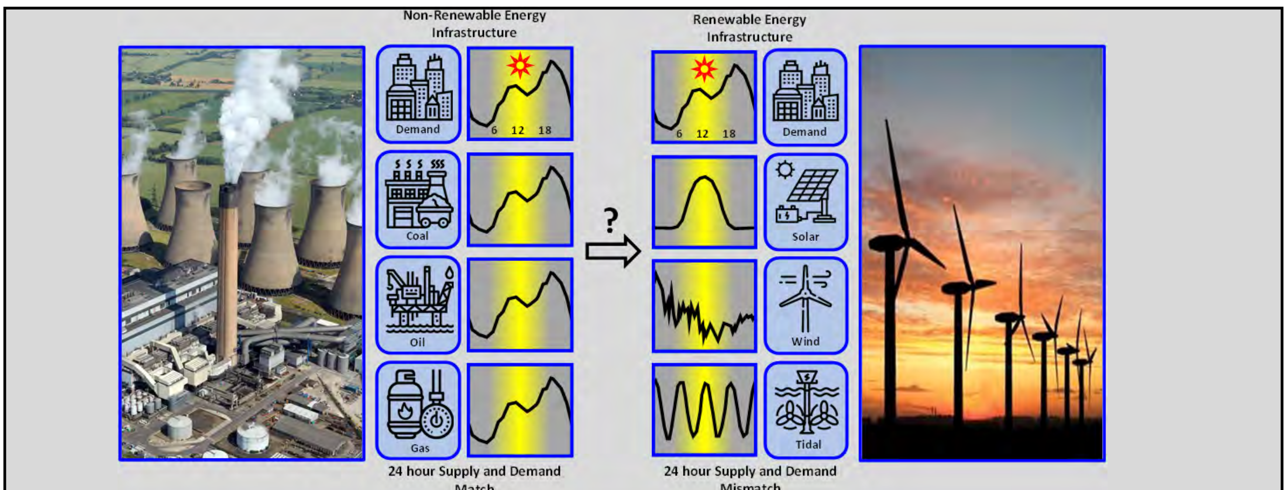




Challenge: Shift to green energy requires massive storage solutions & structures

Current Battery Technology NOT scalable | Need for NEW Bulk Storage Solutions

Electron Conductivity? –

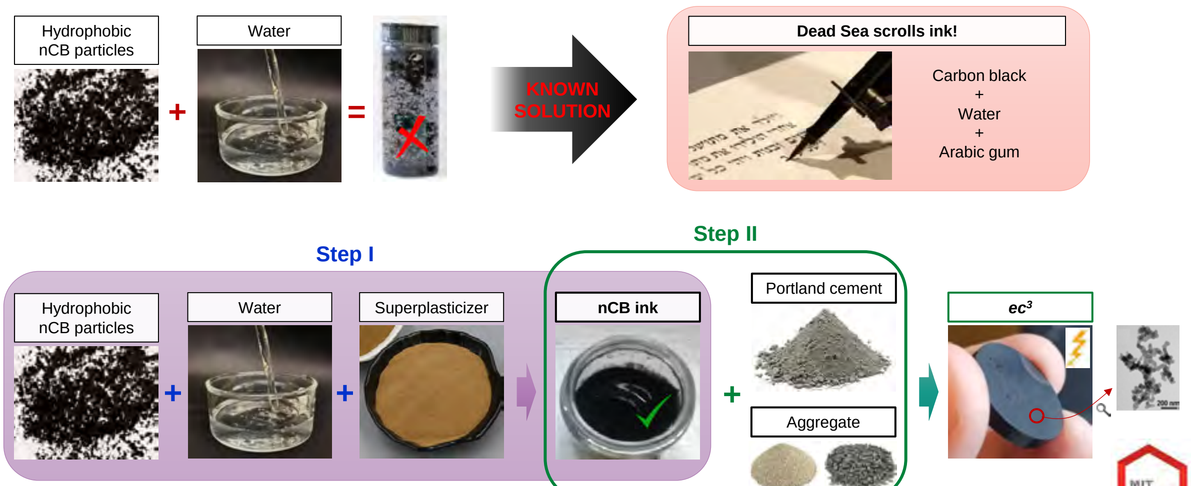
Get Real: Concrete is Strong, Everybody can make it… & it has a huge environmental footprint.

But it's an Insulator –

IS THERE ANY CHANCE TO ADD THIS FUNCTIONALITY TO CONCRETE?

Know how: a proper dispersion of nCB particles is the key

How to mix and disperse hydrophobic nCB particles in water?



Highly repetitive due to the physical chemistry driven process

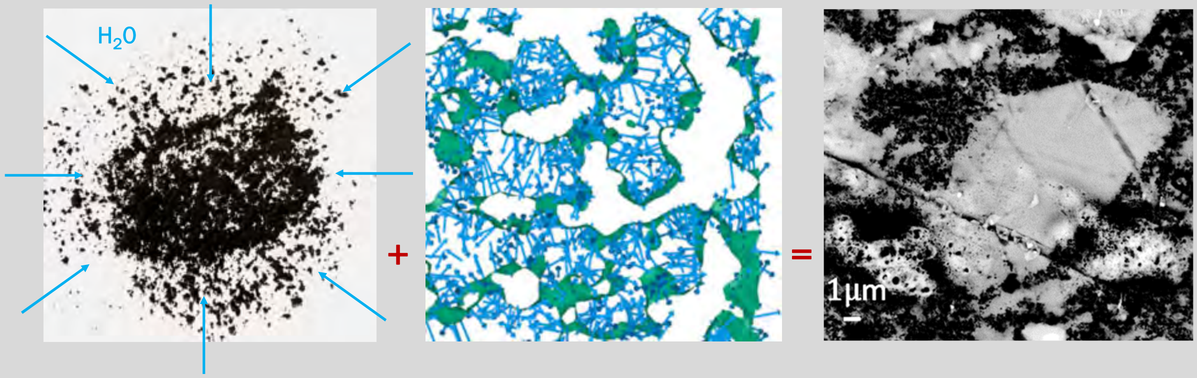
[1] Pellenqu *et al.* (2018-2020). Electron conducting carbon-based cement, method of making it as supercapacitator. Patent.

Slide **36**

Hydrophobicity of Carbon Leads to clumping

Hydrophilicity of Cement leads to Hydration (solid formation w water)

Competition of (1) and (2) lead to Volumetric Wire



Percolation of a Volumetric Wire through a load-bearing cement skeleton

A Physical Chemistry Driven Process = Highly Repetitive

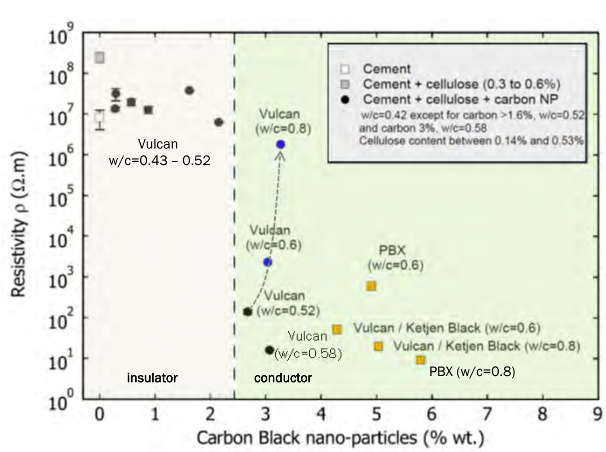
Patent pending

PROPERTY:

Electron Conductivity

At 2-3%wt VOLUMETRIC WIRE percolates through the solid skeleton

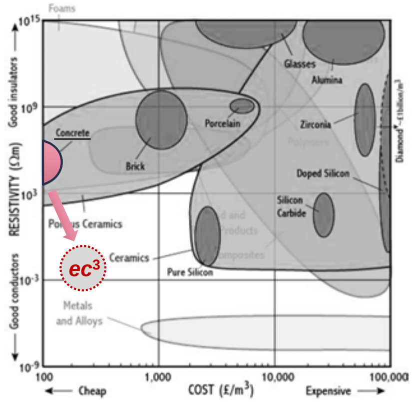
Electron Conductivity ~ 1/Resistivity

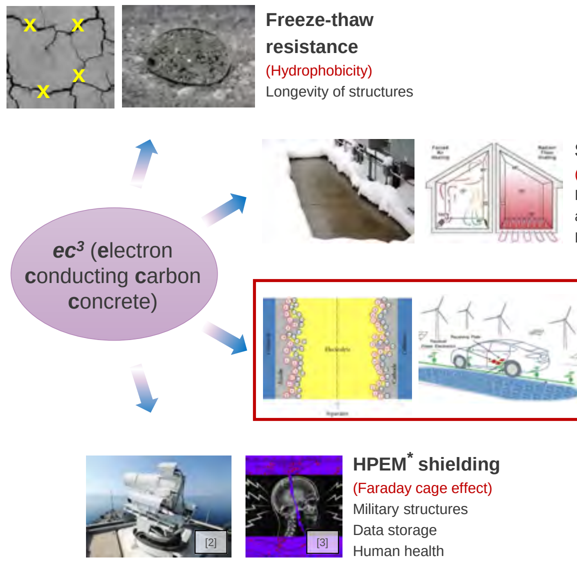


Patent pending

Opportunities of electron conducting carbon concrete *ec³*

Resistivity vs. cost [1]





Freeze-thaw resistance
(Hydrophobicity)
Longevity of structures

Self-heating
(Joule effect)
De-icing bridges, sidewalks, airport runways, etc.
Radiant floor heating

Energy storage
(Structural supercapacitor)
Renewable energy buffer
Autonomous housing
Smart charging roads

HPEM* shielding
(Faraday cage effect)
Military structures
Data storage
Human health

*High Power Electromagnetic impulses

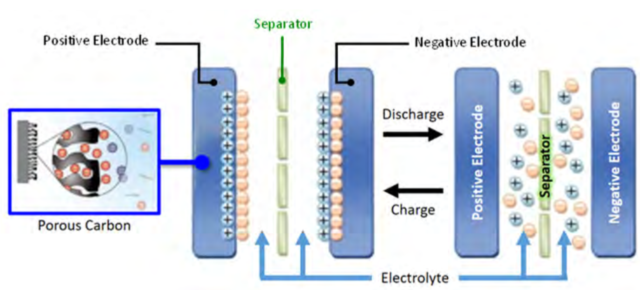
References
[1] http://www-materials.eng.cam.ac.uk
[2] https://www.militaryaerospace.com/power/article/14072339/
[3] The New York Times; Photographs by SCIEPRO and mikroman6, via Getty Images

Cement + Carbon + Porosity = Supercapacitor

Battery = Change electrical energy into chemical energy

Supercapacitor = Electrical Charge stored in a shell around the carbon (no chemical reaction)

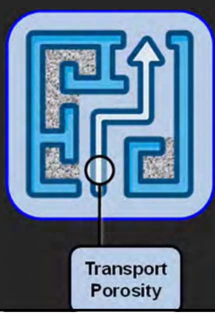
HOW DOES A SUPERCAPACITOR WORK?



CONCRETE AS “structural” SUPERCAPACITOR:

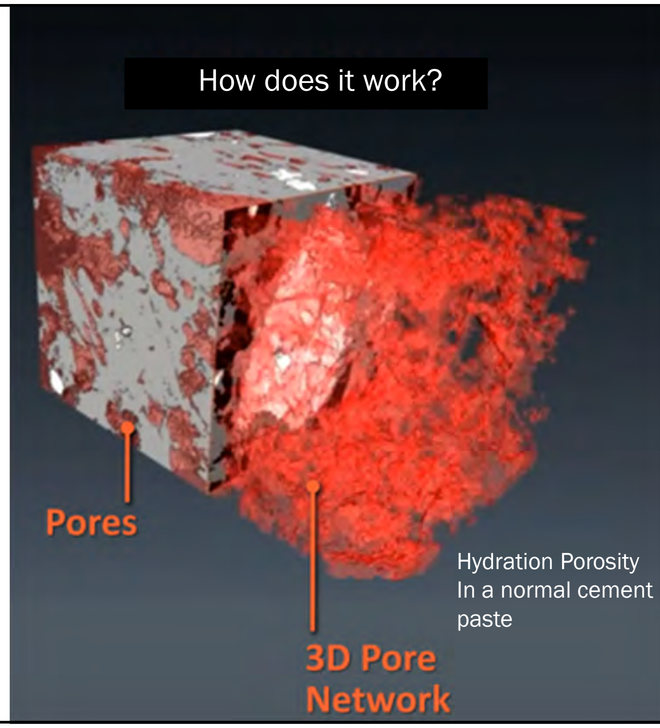
- Porosity of cement paste (for Electrolyte)
- Carbon-Cement Composite for Energy Storage

We use the "natural" porosity of cement as transport porosity (electrolyte)



Patent pending

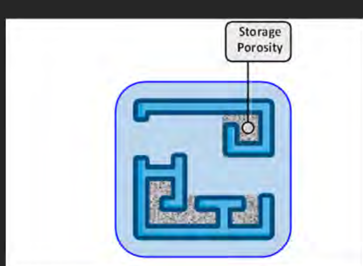
How does it work?



Hydration Porosity
In a normal cement paste

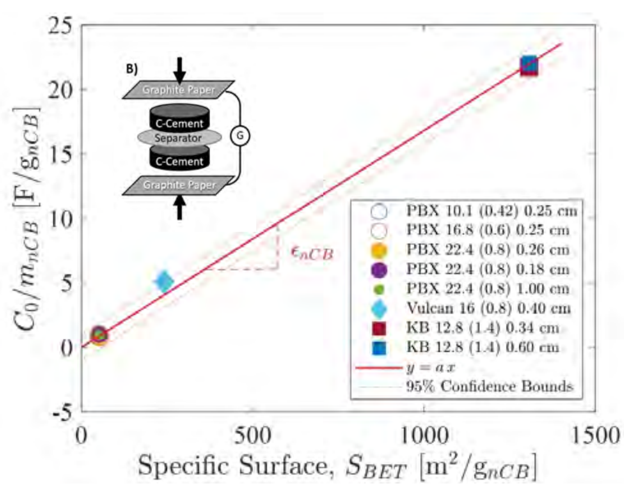
How does it work?

We use the nanoporosity of carbon black for charge storage



Patent pending

Energy Storage Capacity Increases linearly with surface area of disordered nanocarbon.



~ ENERGY STORAGE CAPACITY

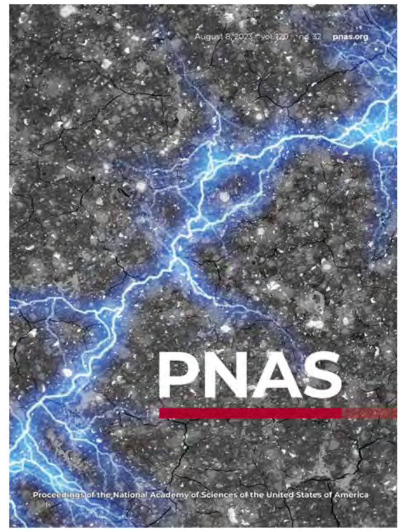
For more details see the recent paper in PNAS (Proceedings of the National Academy of Sciences)

RESEARCH ARTICLE | ENGINEERING

Carbon–cement supercapacitors as a scalable bulk energy storage solution

Nicolas Chanut, Damian Stefaniuk, James C. Weaver, Yunguang Zhu, Yang Shao-Horn, Admir Masic, and Franz-Josef Ulm | Authors Info & Affiliations

Edited by Yonggang Huang, Northwestern University, Glencoe, IL; received March 23, 2023; accepted June 22, 2023
July 31, 2023 | 120 (32) e2304318120 | https://doi.org/10.1073/pnas.2304318120



PNAS cover by **James C. Weaver**

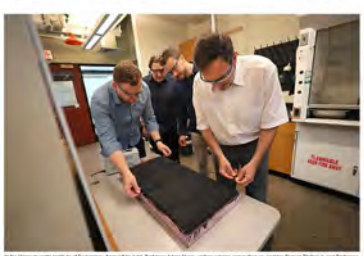
Slide **43**

Increasing global interest

The Boston Globe

Is cement the solution to storing renewable energy? Engineers at MIT think so.

Supercapacitors could make powering your home and electric vehicles easier and more sustainable



MIT researchers say they have developed an energy storage system that could allow homes to store their own power without external batteries and highways to charge electric vehicles as they traveled on the road — no charging stations needed.

And the best part, the researchers say, is their system, called a supercapacitor, could be built from three of the world's most abundant materials: cement, water, and carbon.

The researchers, who work at MIT's Concrete Sustainability Hub, recently reported their breakthrough in the Proceedings of the National Academy of Sciences, a peer-reviewed scientific journal. They detailed how a tiny prototype — around 1 centimeter wide and 1 millimeter thick — powered an LED light at least 10,000 times.

WORLD ECONOMIC FORUM

World Economic Forum
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These scientists are using widely available materials to create an alternative to batteries

Learn more about sustainable battery chains: https://ow.ly/phaE50PAlte

Massachusetts Institute of Technology

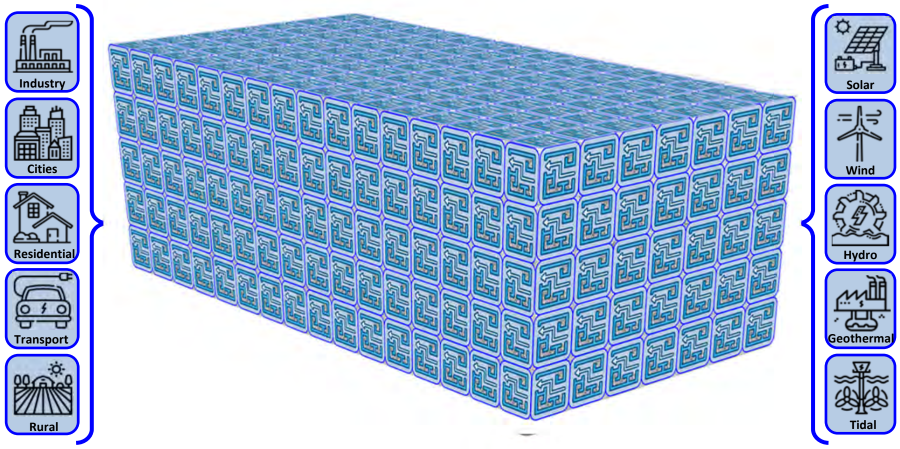
MIT News
ON CAMPUS AND AROUND THE WORLD

MIT engineers create an energy-storing supercapacitor from ancient materials

Made of cement, carbon black, and water, the device could provide cheap and scalable energy storage for renewable energy sources.

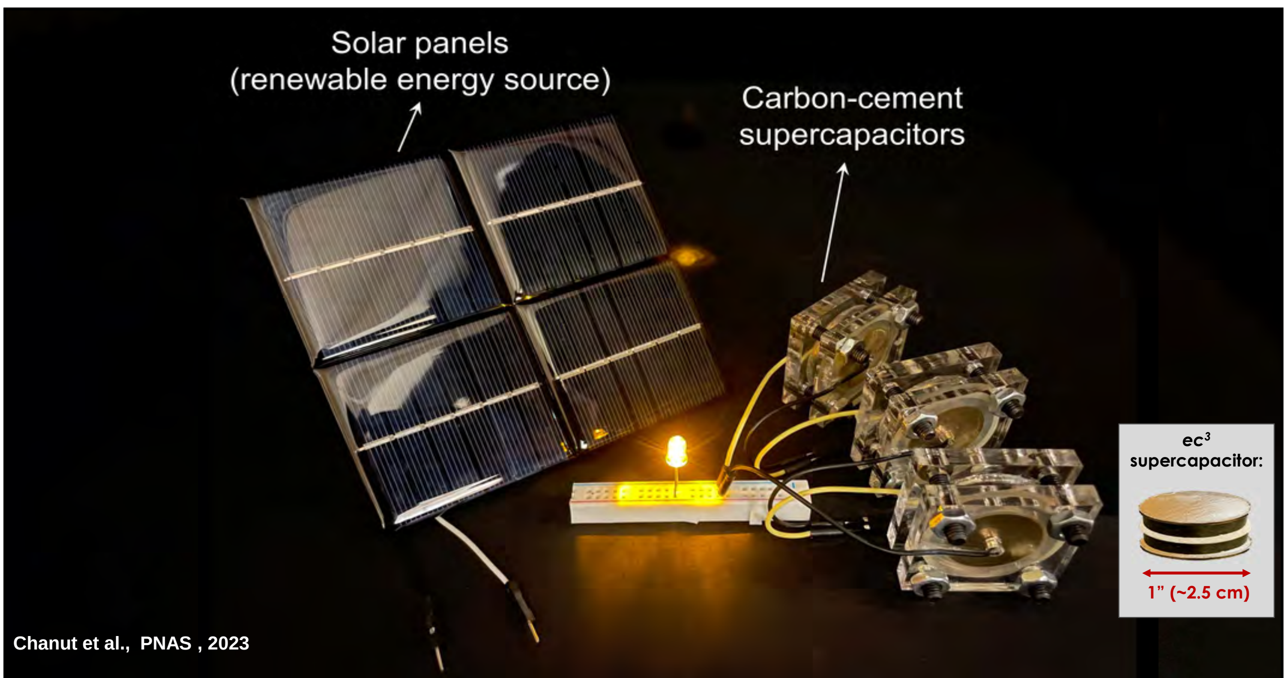
David L. Chandler | MIT News
July 31, 2023

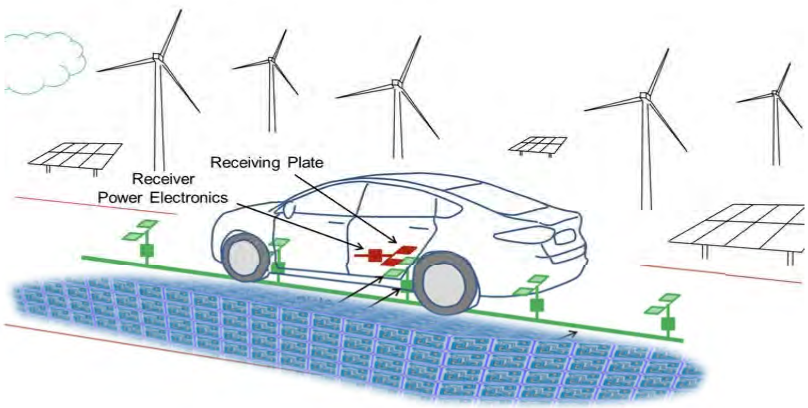
Slide **44**



Multifunctionality: Concrete as a “Battery”

Electron-Conducting Cement-Based Materials

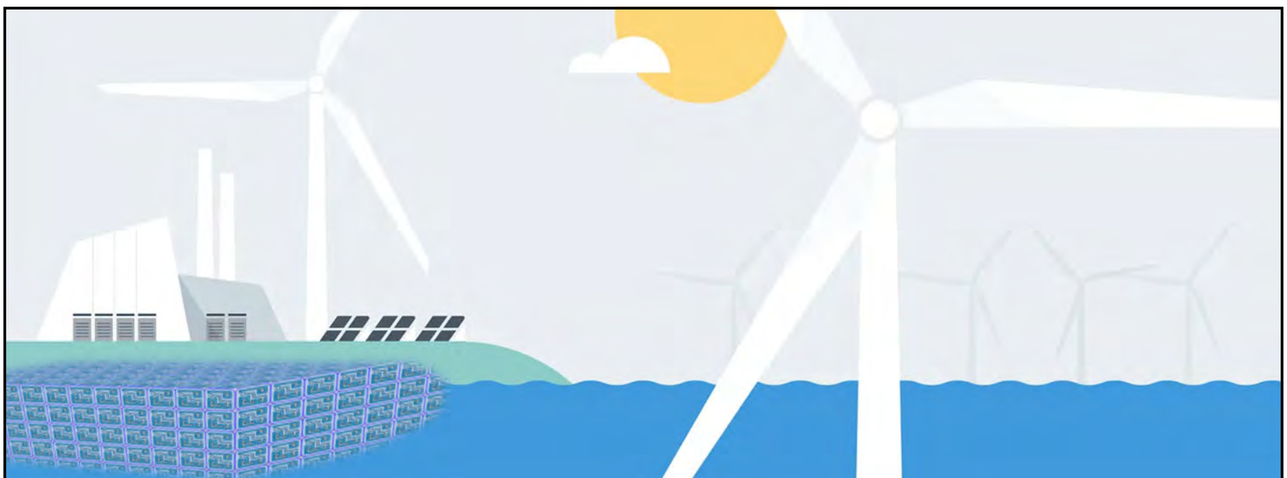




https://www.businessinsider.com/charge-electric-car-while-driving-technology-cornell-2021-5

Future: Smart charging roads

Road as a renewable energy storage
Wireless charging of cars



Future: Energy Storage Everywhere

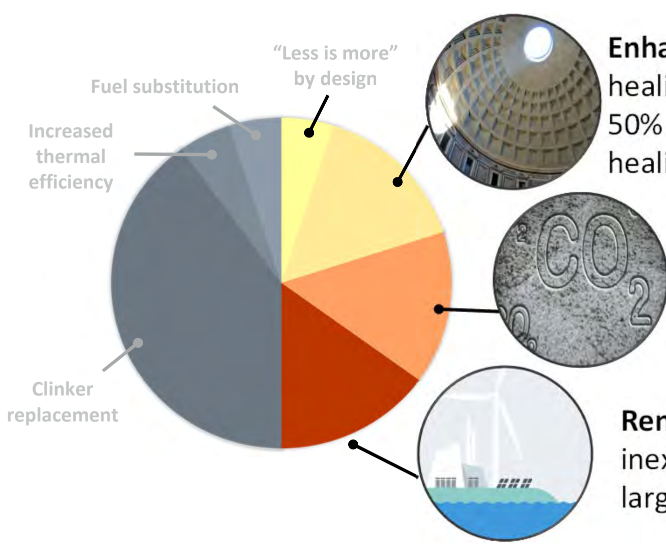
Scalable bulk supercapacitors for renewable energy storage

Future: decentralized electrical energy supply

Integrated Vascular Networks | Home foundations and walls as batteries

For reference:
Daily residential energy consumption: ~10 kWh ~ 40 m^3 EC^3-Concrete

Multifunctional concrete



Enhanced durability: Roman-inspired self-healing concrete (50% lifespan extension at 50% cost reduction compared to other self-healing solutions)

Early-age CO_2 sequestration in cement: up to 15% of total CO_2 emissions associated with cement production could be mineralized.

Renewable energy storage: scalable and inexpensive carbon-cement composites for large energy storage applications.

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THANK YOU!

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