nanoCarbon Black (nCB) in UHPC
Effect on Conductivity and Mechanical Properties

Nancy Soliman, A. Omran, Daniel Gracious, Paige Martinez

TEXAS A&M UNIVERSITY CORPUS CHRISTI | COLLEGE OF ENGINEERING

American Concrete Institute
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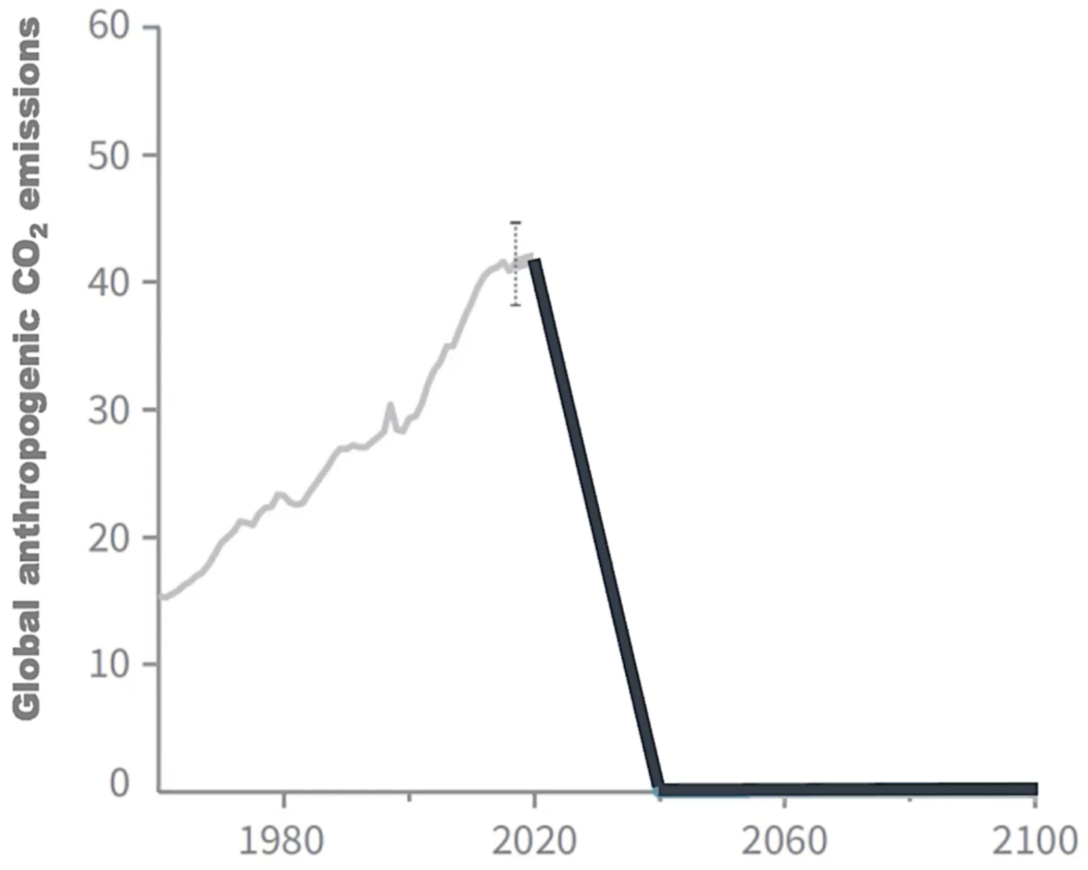
Motivation

A radical change is needed:
Cut CO_2 emission by 50% in the next 10 years (stay below temperature rise of 1.5 ^oC); reach net zero in 2050

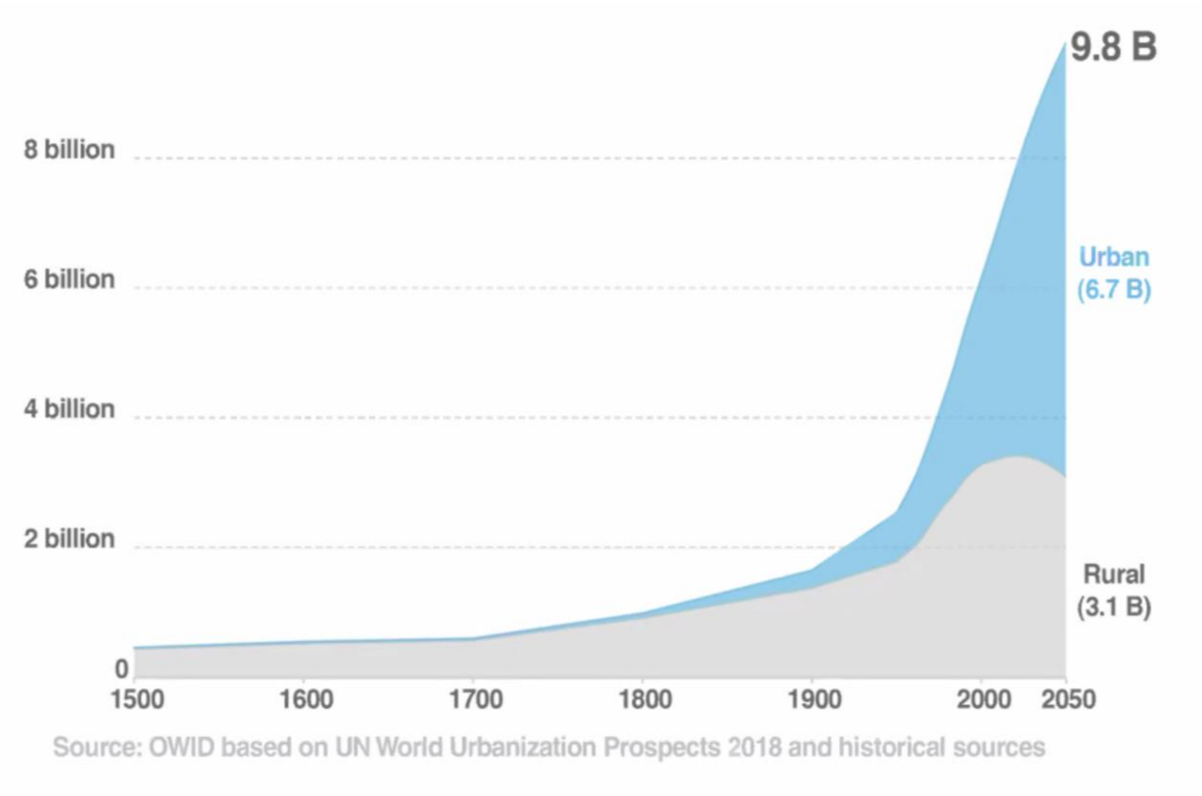


USA has joined over 120 countries in committing to be net-zero emission by 2050

IPCC 2021. 1.5oC report

Urbanization: concrete usage increases exponentially

By 2050 more than **two thirds (6.7 billion)** of the world's population will live in **urban areas**

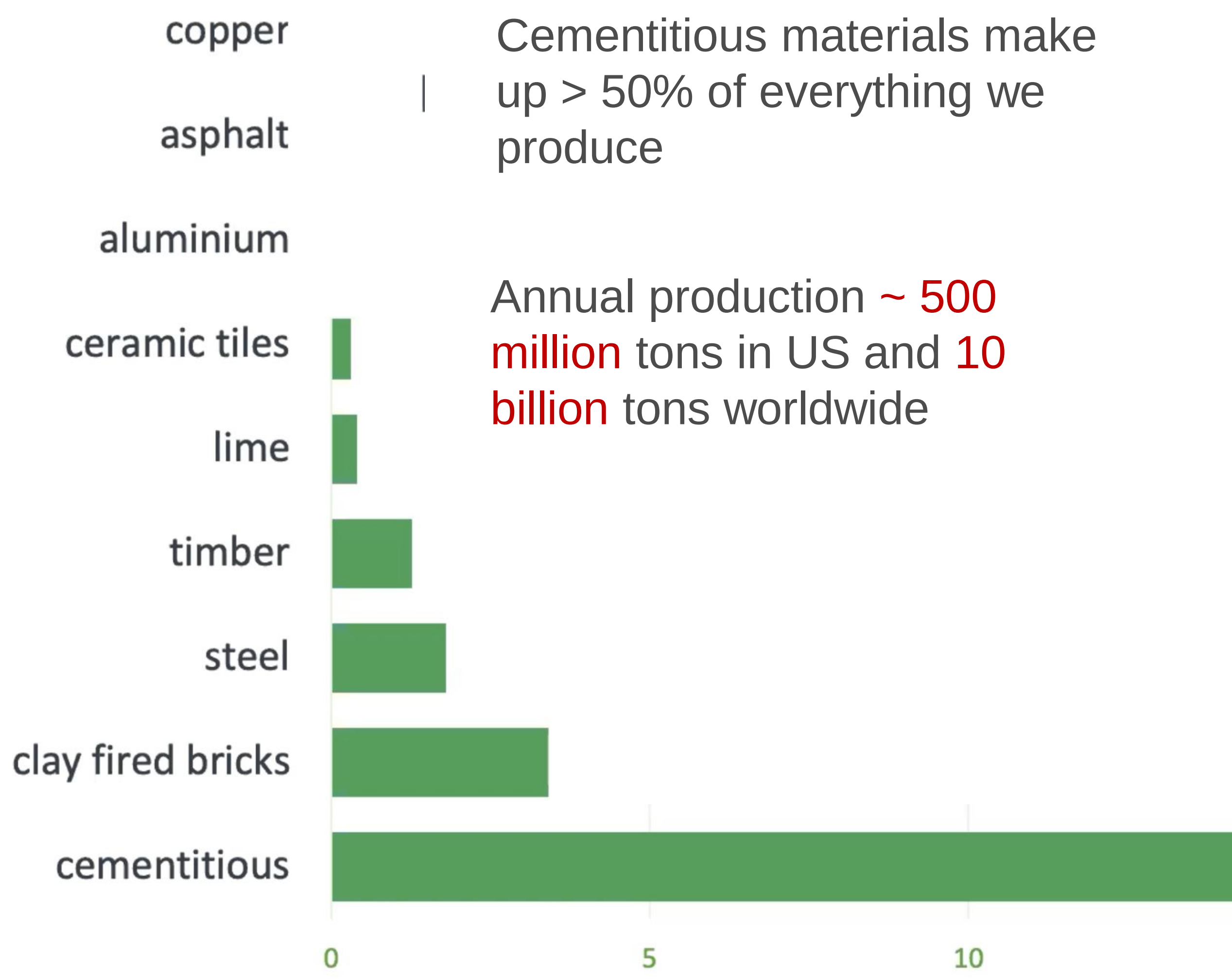


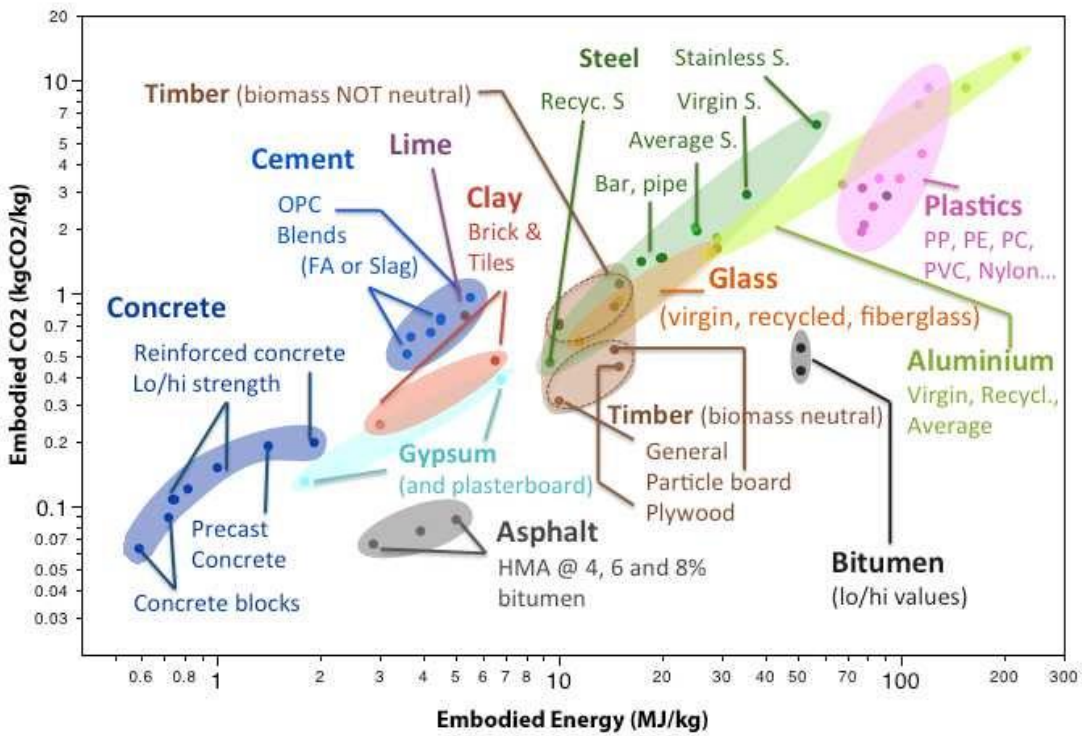
To meet the urbanization needs, **new infrastructure** and **buildings** will be required

Concrete is the most widely used material for infrastructure

Cementitious materials make up > 50% of everything we produce

Annual production ~ 500 million tons in US and 10 billion tons worldwide

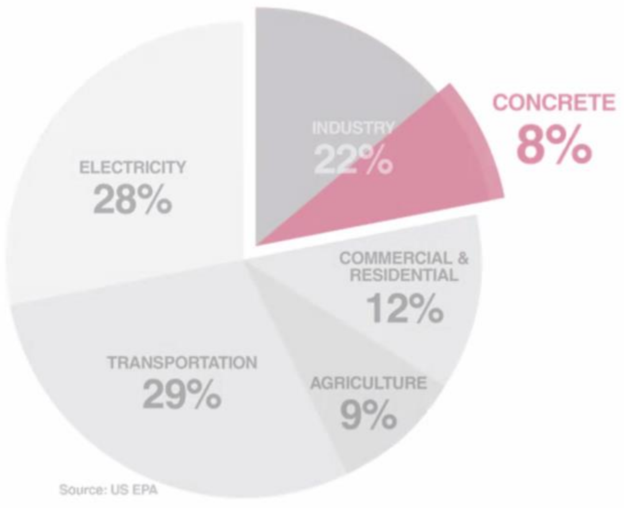




J.Y. Richard, 2019

Does concrete meet social and environmental goals?

Eco-efficient Issues: Cement contributes up to **8%** of global CO_2 emission



CO_2 emissions by business sector

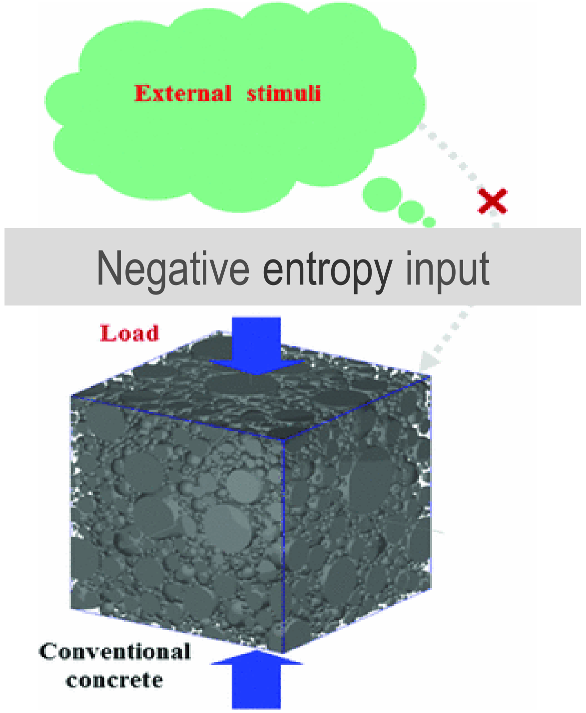
1 ton of cement leads to the emission of 900 kg CO_2 ($CaCO_3$ decomposition and Fuel)

Monteiro, P., Miller, S. & Horvath, A. Nature Mater. 16, 698–699 (2017)

Durability issues: repair of deteriorated infrastructures costs $$$ billions

40% of bridges in US require rehabilitation costing ~ $28 billion annually

Functionality issues: concrete has no negative entropy input through matter or energy with external stimuli



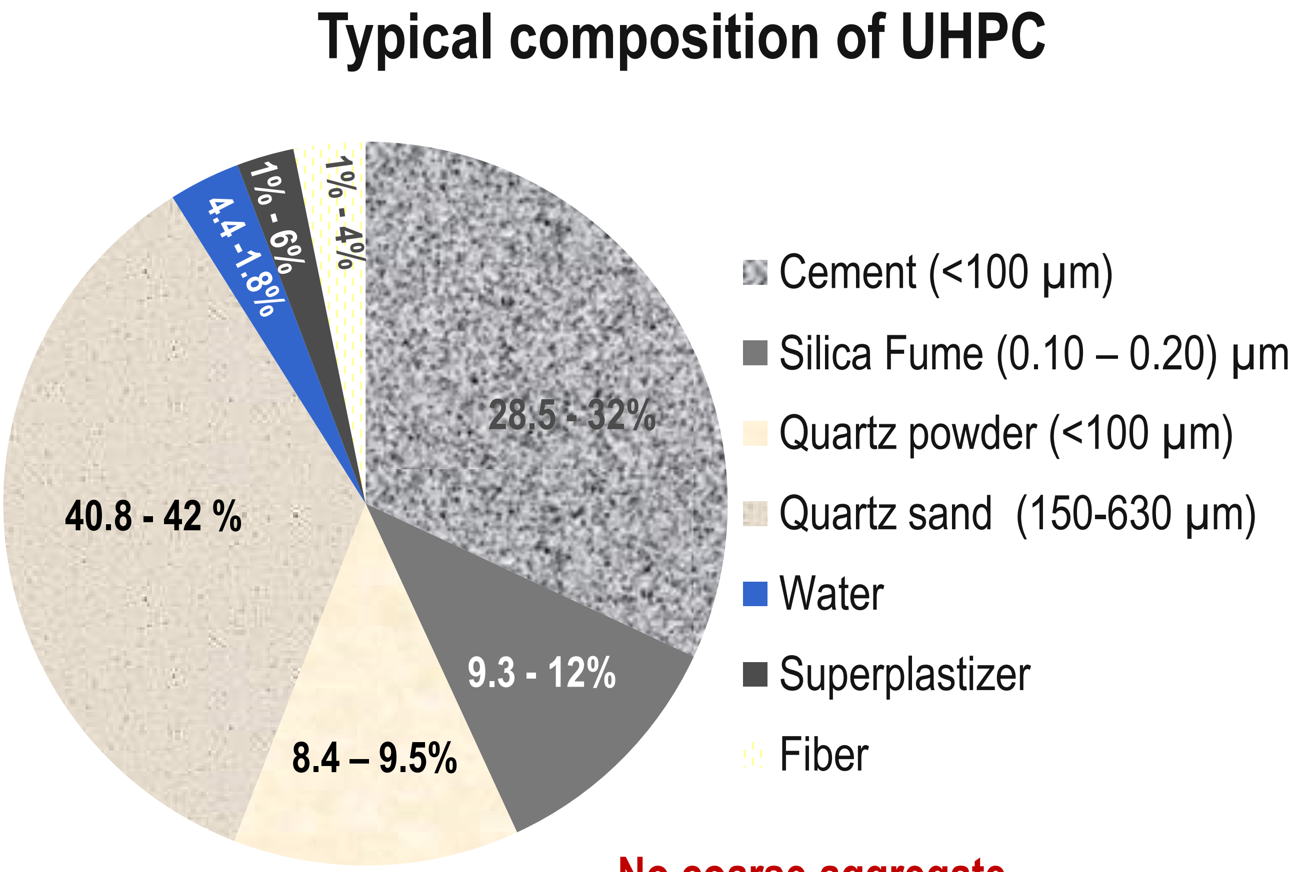
Smart materials are designed with properties that can be changed in a controlled fashion by external stimuli (stress, moisture, electric, chemical compounds

Han et al. 2017

What is ultra-high-performance concrete (UHPC)?

UHPC: is a new type of concrete that provides:

- Ultra-high strength
- High ductility
- Excellent durability



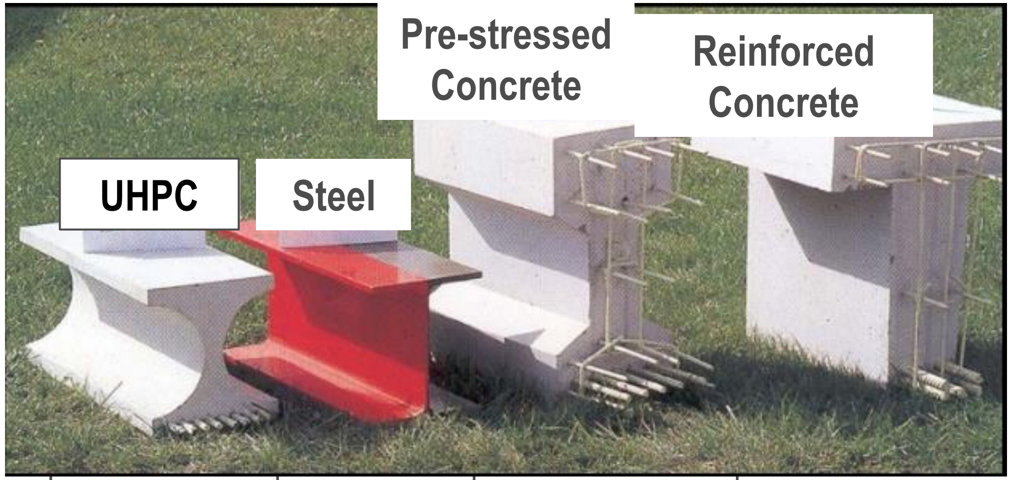
No coarse aggregate

(Richard & Cheyrezy, 1995)

Why UHPC?

- UHPC can be used as conventional HPC without passive reinforcement
- UHPC can lead to longer structure spans with reduced member size and self-weight (< **70 %** NC or HPC)
- UHPC has superior durability properties ➔ longer service life and reduced maintenance cost

Beams with equal moment capacities



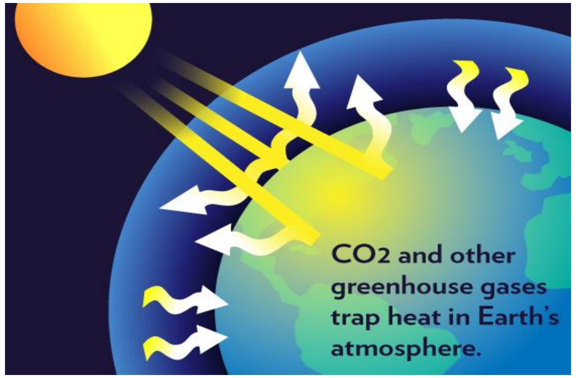
	UHPC	Steel	Pre-stressed Concrete	Reinforced Concrete
Depth (mm)	360	360	700	700
Weight (kg/m³)	141	110	466	528

(Perry, 2006)

Challenges with UHPC

1. Higher cement content (800 -1000 kg/m^3)

   - requires higher energy
   - consumes natural resources
   - high CO_2 (1000 kg cement releases ≈ 864 kg CO_2)
   - GHG and global warming



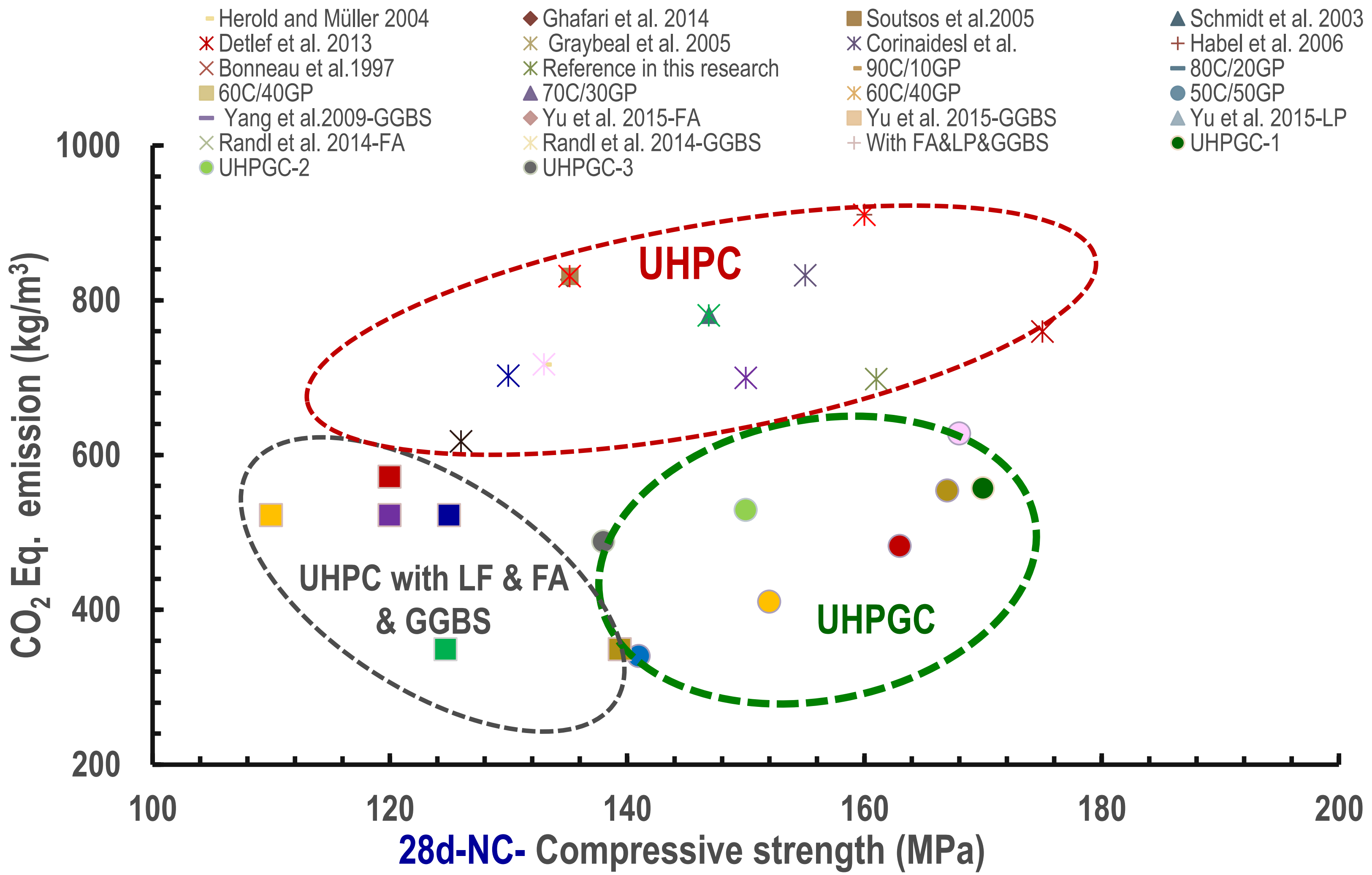
2. High amount of crystallized silica materials

   - high cost
   - consumes natural resources
   - carcinogenic to humans
   - biological diversity

☠ Lung Cancer Risk

Sustainable UHPC through using SCM

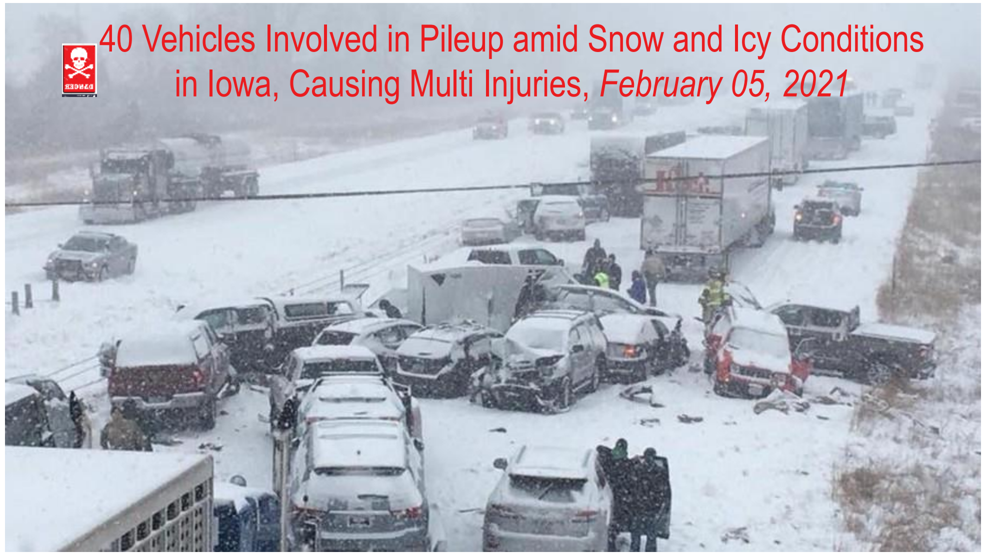
Novel UHPGC has high compressive strength, and low embedded CO_2



N. A. Soliman and A. Tagnit, 2016, Journal of Construction and Building Materials

Motivation

Winter comes with threat of icy roads, which turns highways deadly



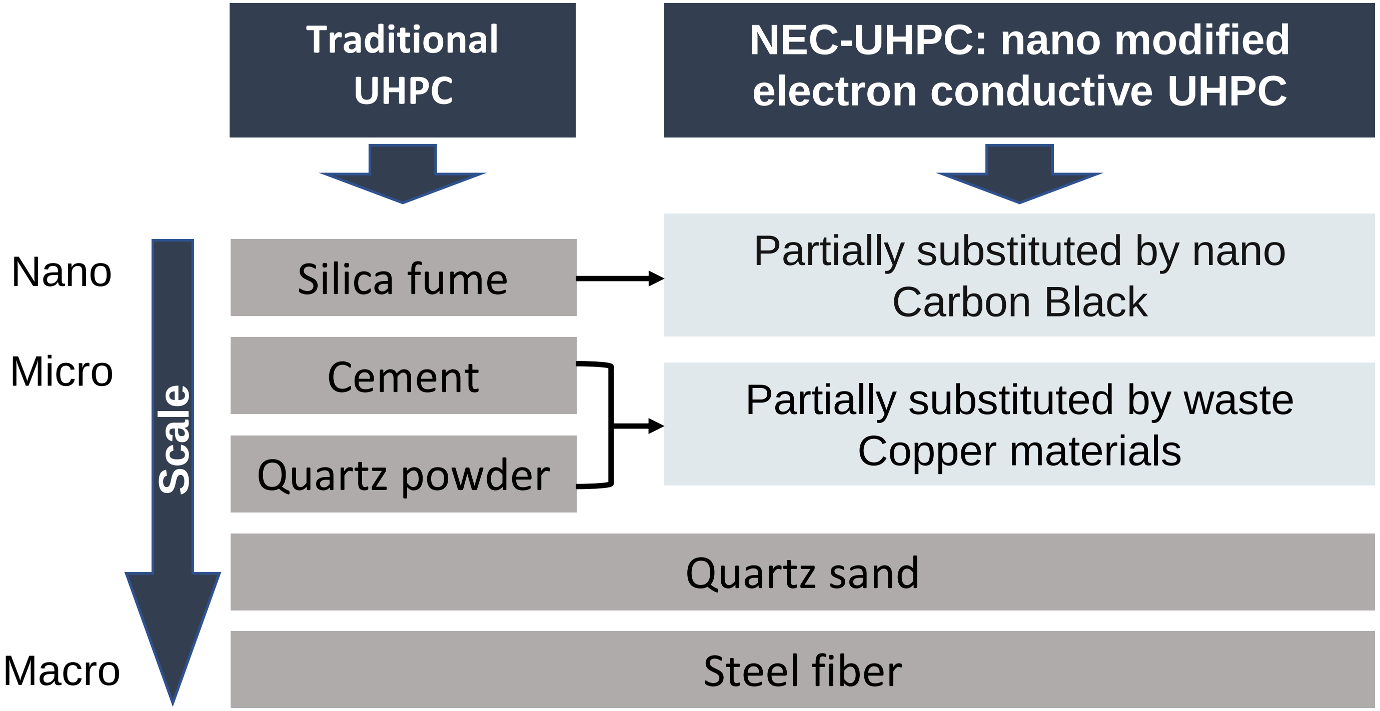
Repair of deteriorated infrastructures costs $ billions

Can UHPC be a sustainable material by adding new functionalities?

Nanomodified Electron Conductive UHPC (NEC-UHPC)

Objective: To construct intricate multi-conductive networks in NEC-UHPC to enhance electrical conductivity via two mechanisms;

- ❖ Quantum tunneling conduction induced by nanomaterials (nCB)
- ❖ Contact conduction facilitated by WC, Steel fiber a micro-scale material



Nano and Micro Materials Integration

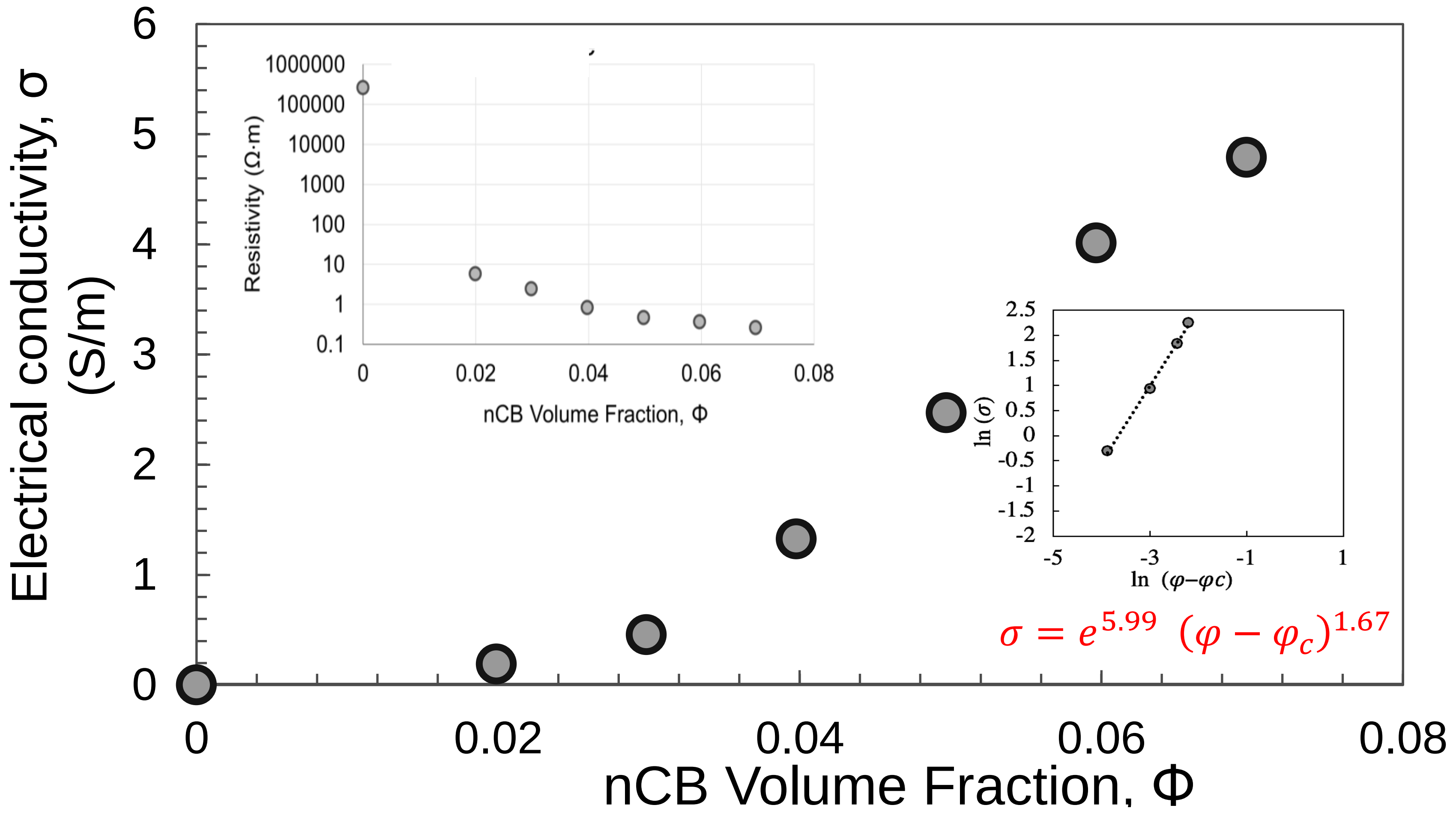
Self-heating & Sensing

Research question?

Dispersion	Scalability	Mechanical
What is the dispersion mechanism of hydrophobic functional materials, nCB particles, in a complex UHPC matrix, and How does it affect the electrical properties and strength capacity of the composite?	How do the different ratios of conductor-insulator composites (e.g., water-to-cement ratio, volume of cement paste, volume of aggregate, and nano/micro functional materials) in NEC-UHPC affect the electrical conductivity, the Joule effect, and their interrelation?	How does the formation of a conductive material network " volumetric wire" in NEC-UHPC affect the micro and macrostructure and associated mechanical properties?

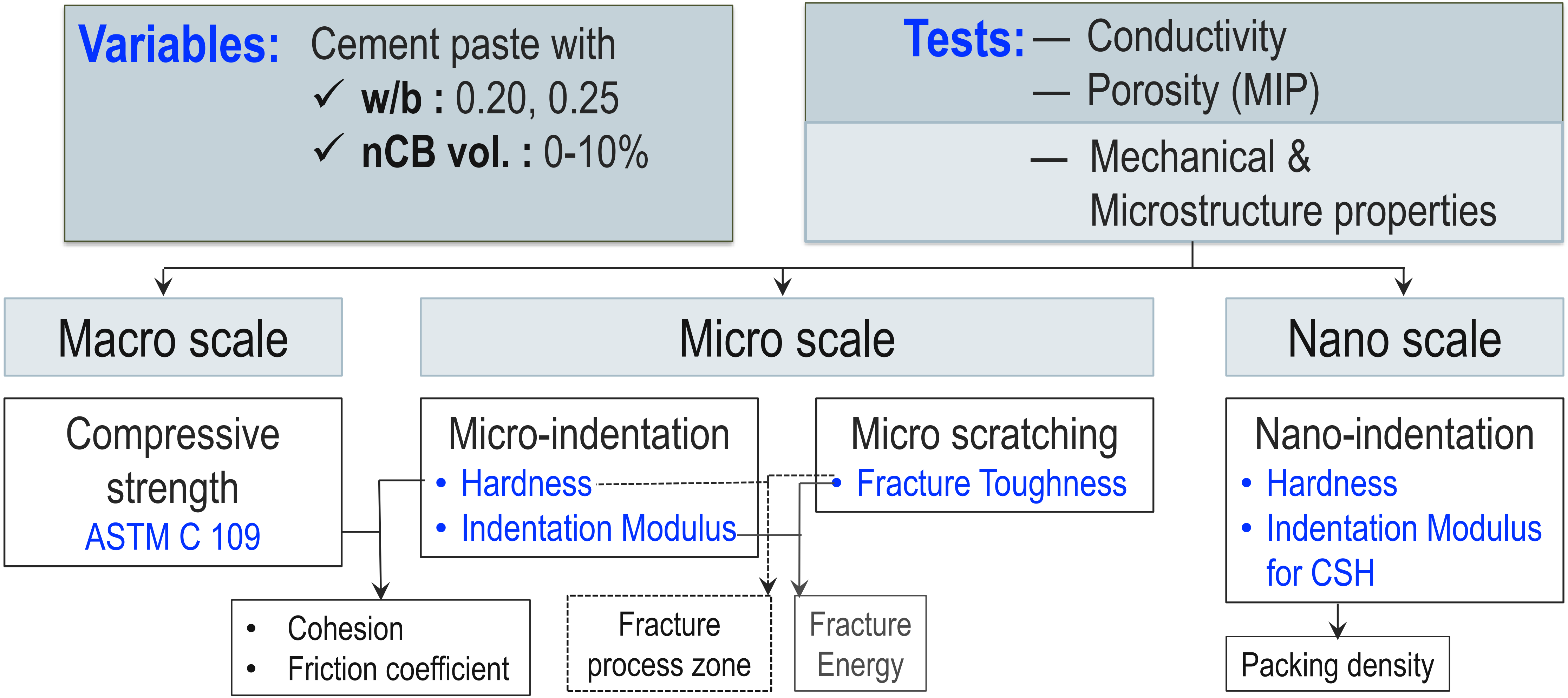
Conductivity of NEC-UHPC

- increases with nCB content
- percolation ≈ 2% nCB
- Exponent (t) of 1.67 in the inset relates to conducting phase geometry. A higher value indicates a more complex nCB network, consistent with amorphous solids physics.

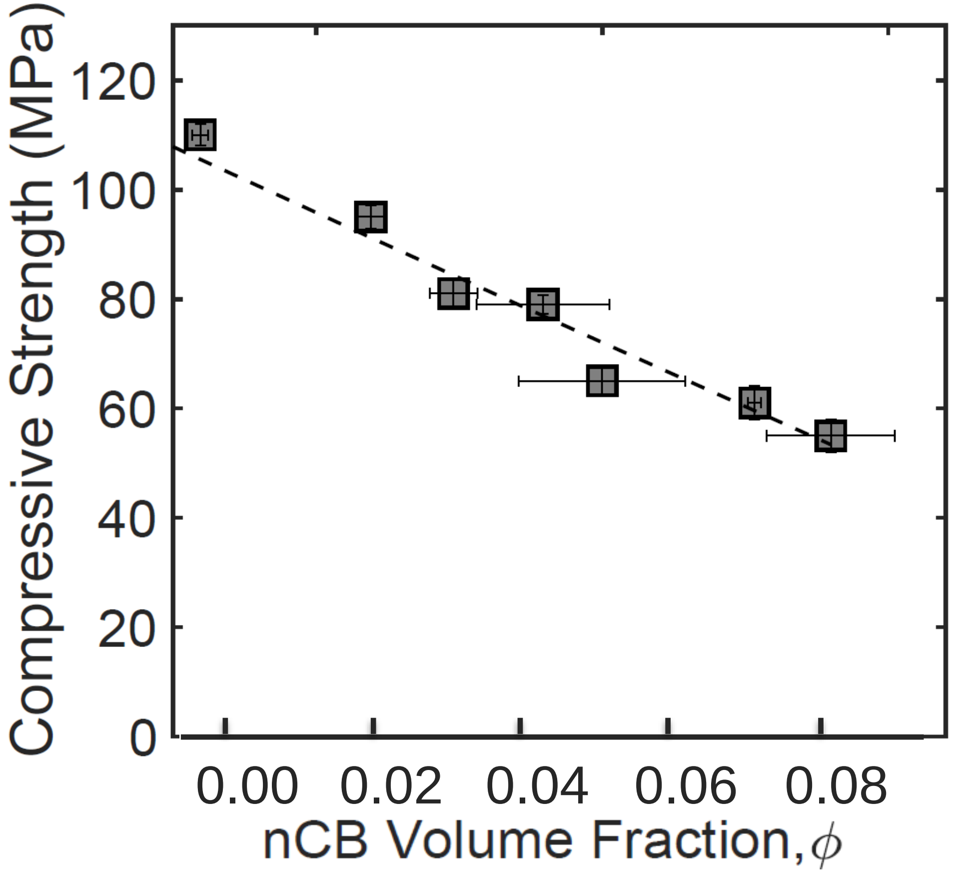


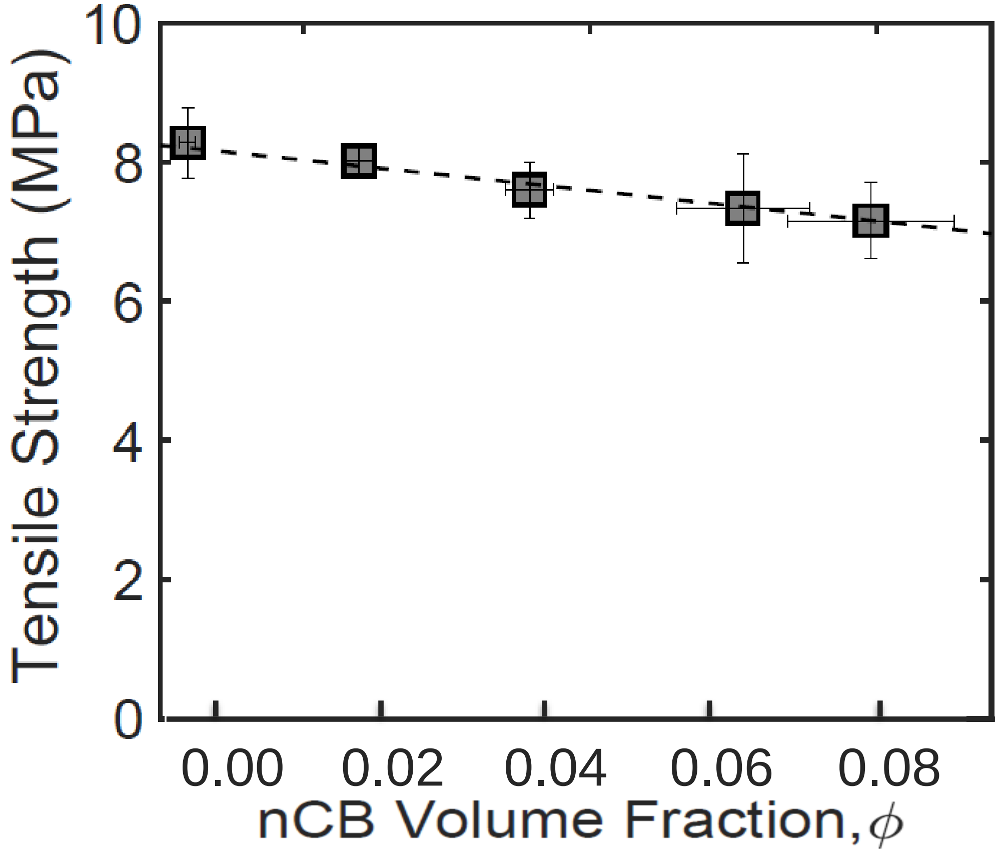
- Percolation: conductivity increases by several orders of magnitude
- Saturation: increasing carbon concentration results in marginal increase in conductivity

Mechanical and microstructural properties: multiscale engineering chemo–mechanical material characterization



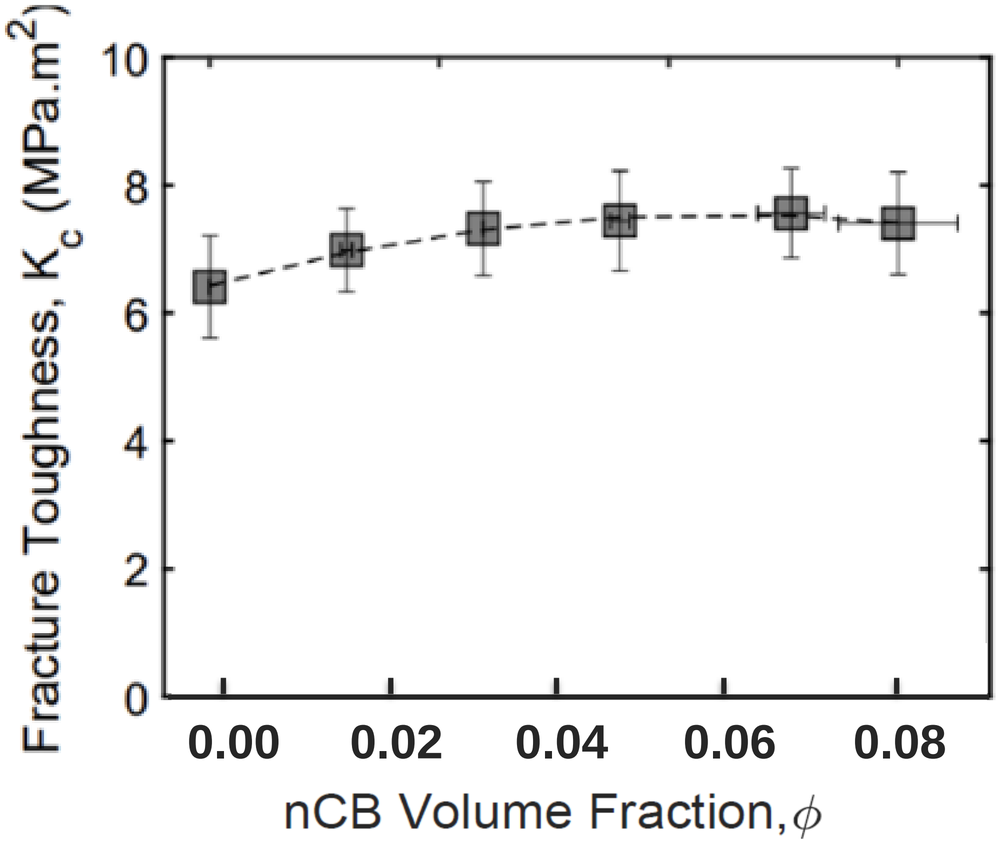
Results: Mechanical properties– macroscale (compressive strength & Tensile strength)

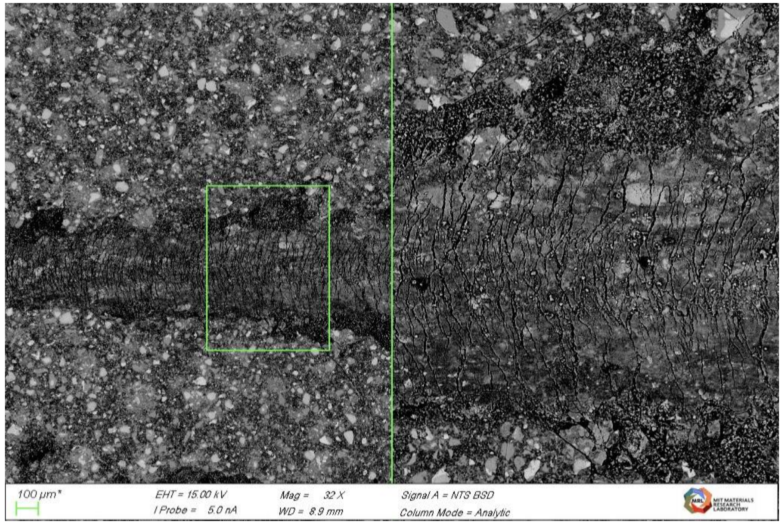


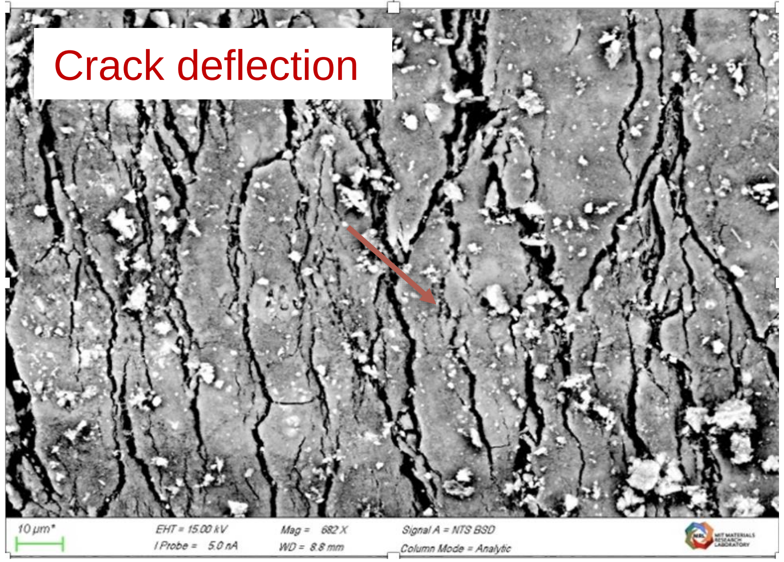


nCB addition ➔ compressive strength reduction
nCB addition ➔ tensile strength reduction
f'_c reduction >> tensile strength

Fracture analysis via scratch test – microscale





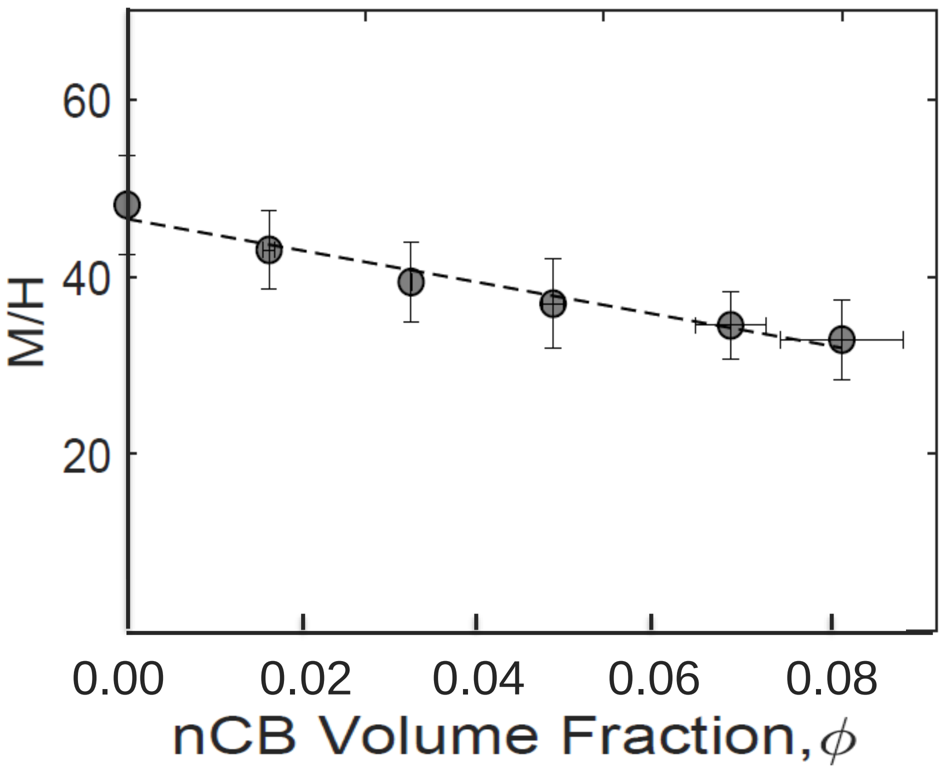


- nCB addition ➔ increases fracture toughness
- Improvement on fracture toughness is originated from the effect of **crack deflection**, which results from the nCB inclusion in the cement matrix
- crack deflection is observed in a magnified SEM image of the scratch groove

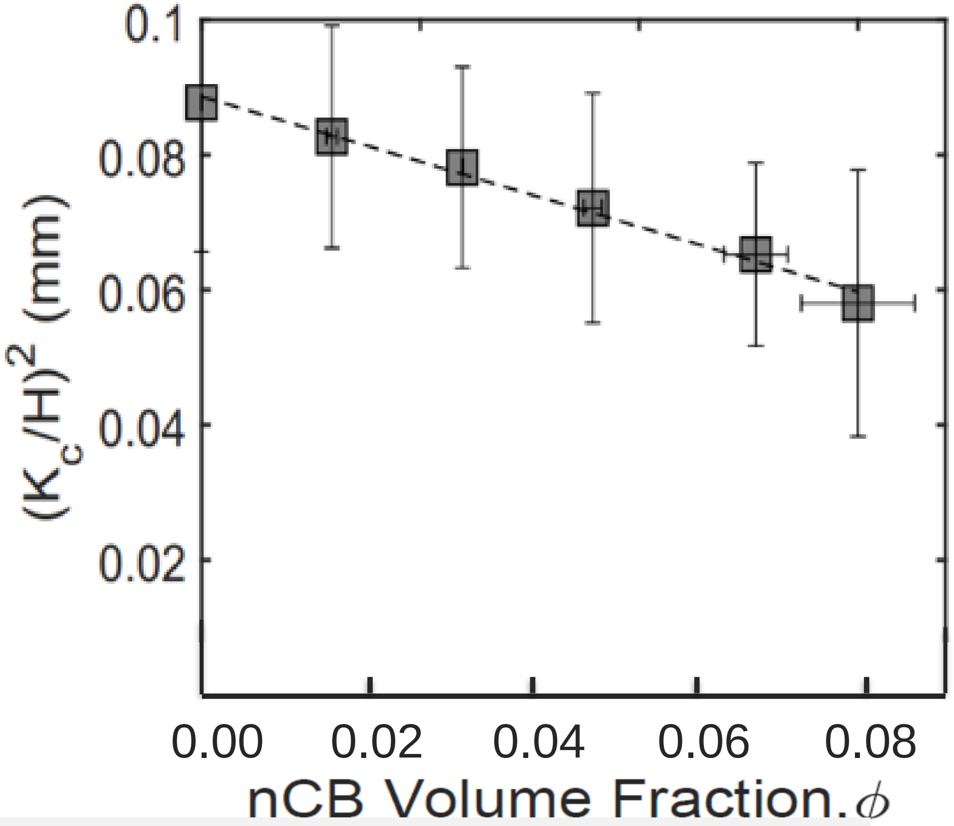
The tortuosity (non-planar geometry) of the crack path was visible along with crack surface.

Results: ductility

Indentation Modulus / Indentation Hardness (M/H): competition of plastic dissipation and elastic energy storage



FPZ: zone of a material at the head of the crack tip where the stress decreases from a maximum value to the far field stress.



- nCB inclusion ➔ reduces ductility (M/H) and fracture process zone
- the plastic dissipation capacity is reduced and hence the FPZ becomes smaller

Discussion questions?

increase fracture toughness?

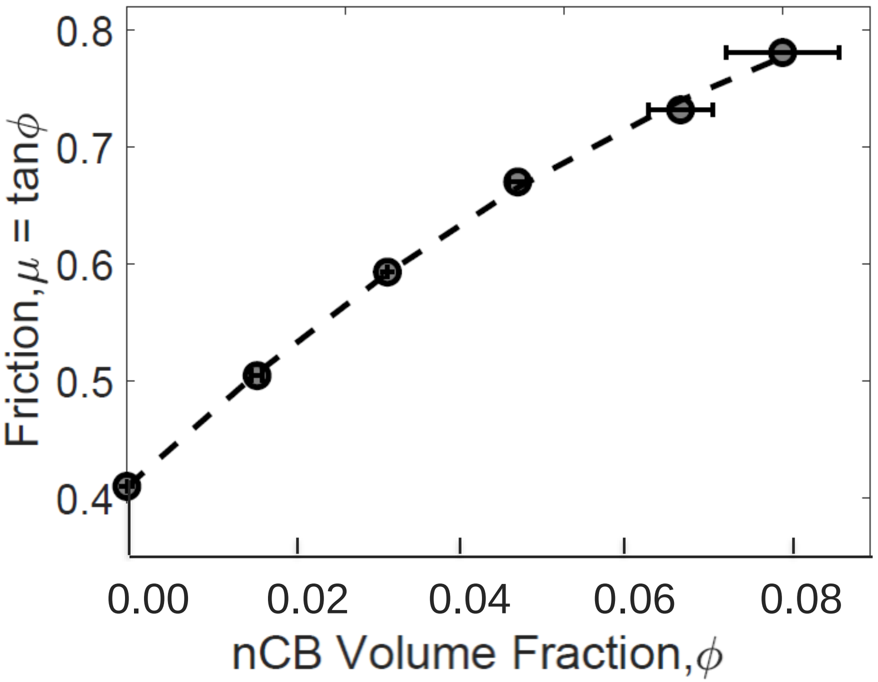
Why does nCB addition...

decrease macro mechanical strength?

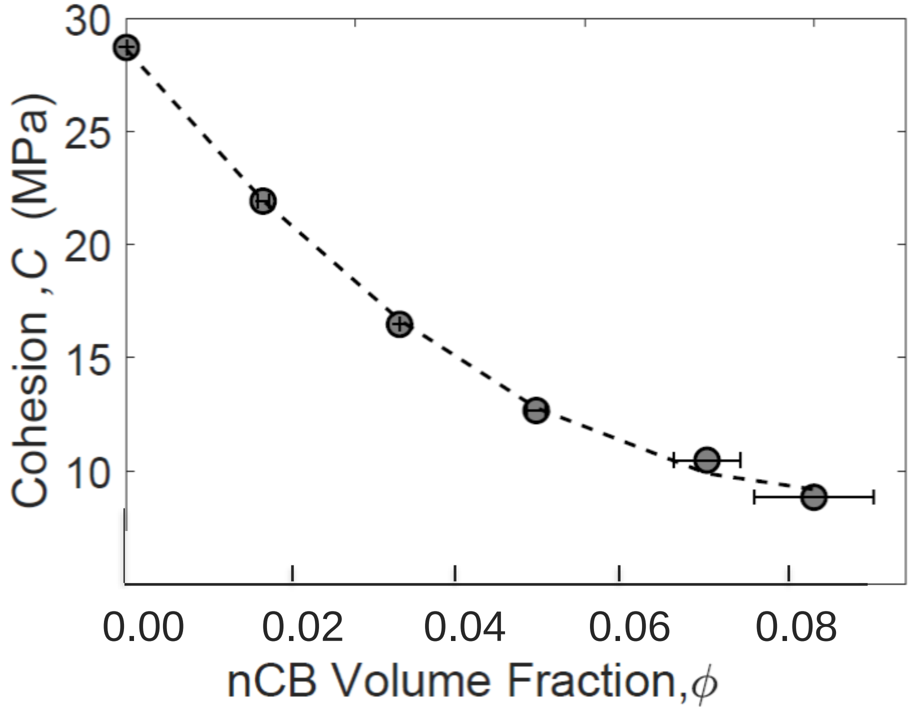
decrease ductility?

Origin of strength reduction (de-cohesion) – microscale

Friction = f (f'$_c$, Hardness)



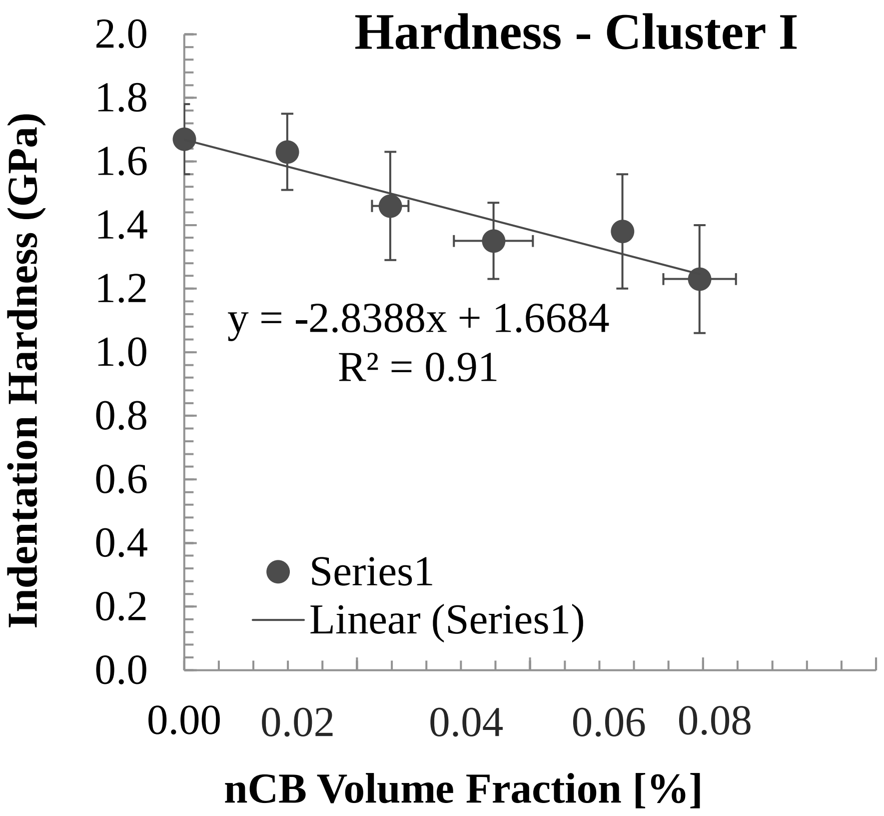
Cohesion = f (f'$_c$, Friction)

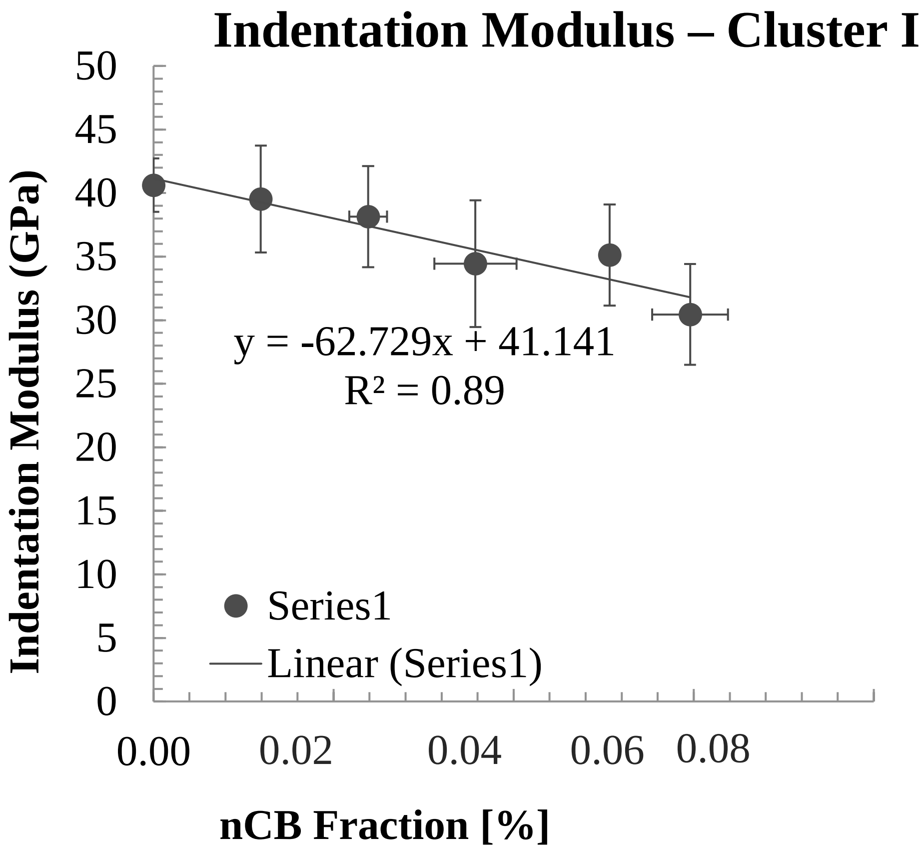


- Friction enhancement at macroscale results from filling the capillary pores with nCB
- Cohesion reduced by the nCB addition ➔ losses in the strength and ductility
  - Friction enhancement is not large enough to compensate for de-cohesion ➔ decohesion becomes dominant

What are the reasons for macroscopic de-cohesion of materials?

Origin of microscopic de-cohesion – reduction of mechanical at nano scale < 1µm





- Addition of nCB decreased indentation modulus and hardness of C-S-H
- Microscopic decohesion results from reduction in hardness and (stiffness) at nano-scale with carbon content

Why does nCB addition reduce the hardness and stiffness at nano scale?

Next Steps

- ✓ Dispersion: using surface functionality, and chemical and physical techniques
- ✓ Unveiling the nano-mechanical signature of NEC-UHPC
- ✓ Investigating the self-sensing and self-heating characterization of NEC-UHPC

Conclusion

✓ Addition of nCB leads to:

- Enhance electrical conductivity
- Friction enhancement at the micro-scale due to the presence of nCB in large pores
- De-cohesion results from a reduction in C-S-H packing density at the nanoscale

Thank you