The Role of Advanced Technologies in Structural Engineering for Resilient Communities

National Academy of Sciences

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Designing for Resilience from Atoms to Structures

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We define resiliency as Durability + Sustainability

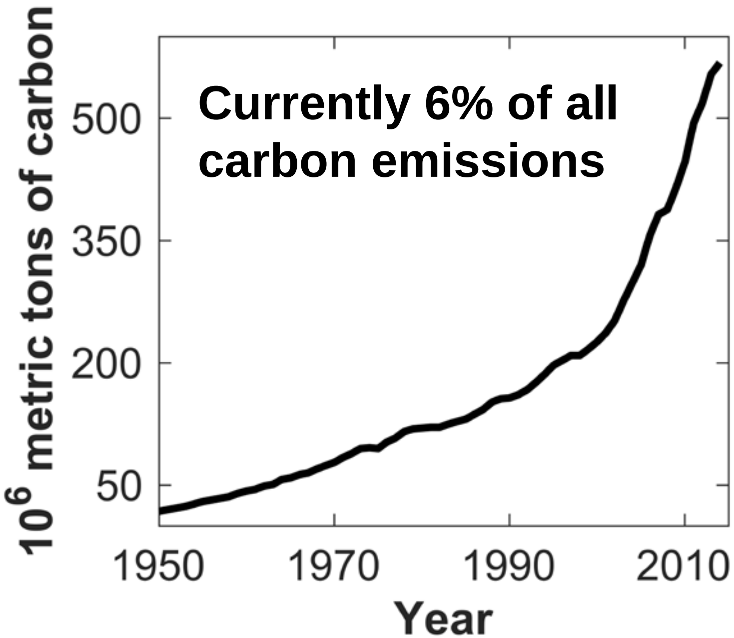
Structural failure is often attributed to material response to degradation or extreme loading events

Sustainability

Concrete is most-used material on earth (3.8 metric ton / person / year)

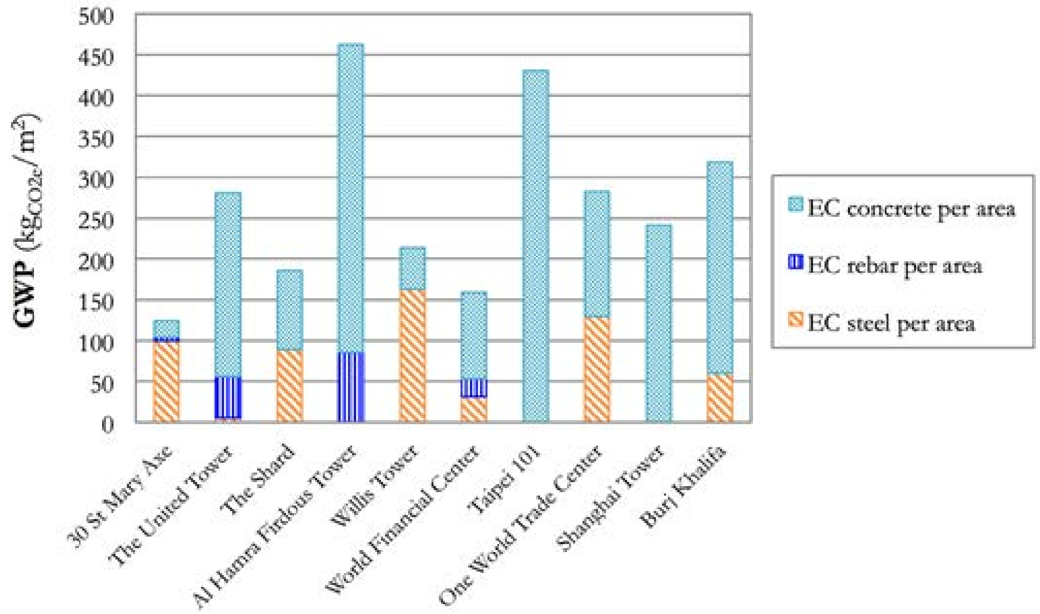
The Cement sustainability Initiative, 2009

Carbon emissions from global Portland cement production



Boden et al., doi 10.3334/CDIAC/00001_V2017

Global Warming Potential (GWP) of landmark structures



C. De Wolf, MIT thesis, 2014.

Achieving Resiliency

1. Design for resiliency through material science
2. Ensure resiliency through structural and material sensing

Example: Al Hamra tower in Kuwait City, Kuwait

Al-Hamra Tower

Lobby Structure

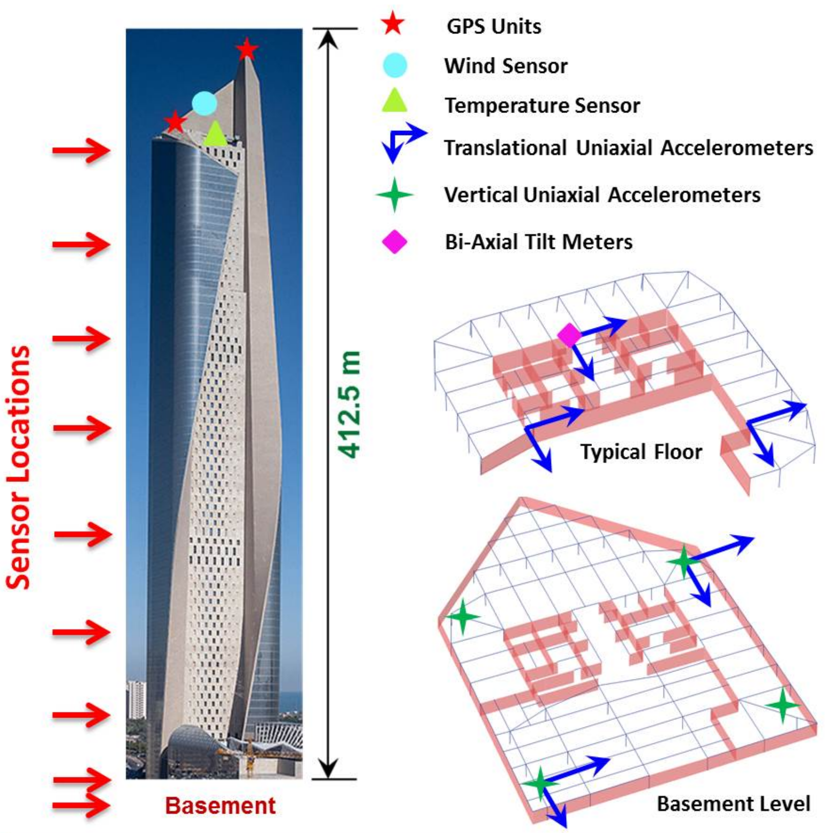
Tower under Construction

414 m tall (80 stories), 4400 m^2 footprint, **490,000 metric tons of concrete**

Total embodied carbon ~150,000 metric ton CO_2 equivalent (C. De Wolf et al. 2017)

Sensing Monitors and Ensures Performance

Advanced modeling techniques allows quantification of structural responses to external influences



Instrumentation of the Al-Hamra Tower in Kuwait

H. Sun, J. Al-Qazweeni, J. Parol, H. Kamal and O. Buyukozturk. Engineering Structures (in submission)

Computer Vision

- Visualize and quantify effects of severe events
- Portsmouth, NH bridge over Piscatagua River with vertical-lift to allow marine traffic to pass under, with a clearance of 39.6 m (130 ft)
- Measurement was made on 10/8/2015 from 80 m (260 feet) away on the NH shore

Field Measurement with Camera System

J.G. Chen, N. Wadhwa, Y.J. Cha, F. Durand, W.T. Freeman, O. Buyukozturk, J. of Sound and Vibration, 2015.

Motion magnification of torsional mode

Resiliency Begins with Materials

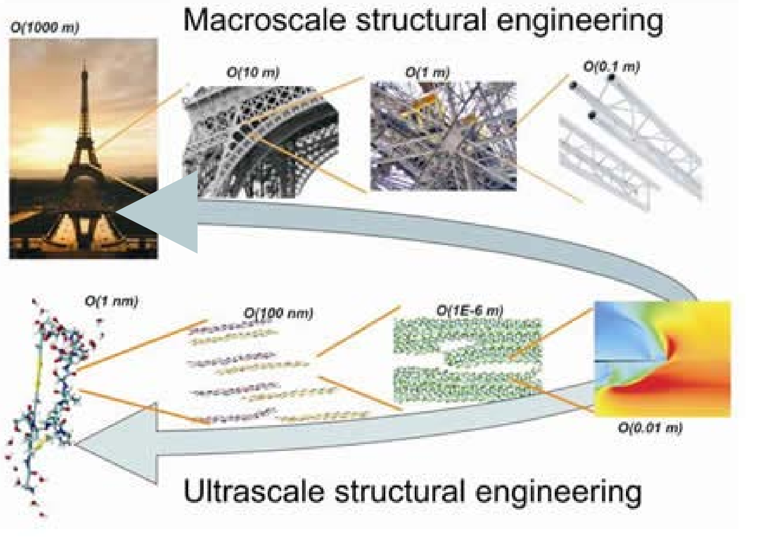
Challenges towards designing for resiliency

- Strength and ductility
- Resistance to degradation (durability)
- Sustainability (reduction of carbon emissions, local materials)

Traditional = Trial and Error

Roman building materials
(Archeological Museum of Priverno, Italy, 2016)

Future = From atoms to structures

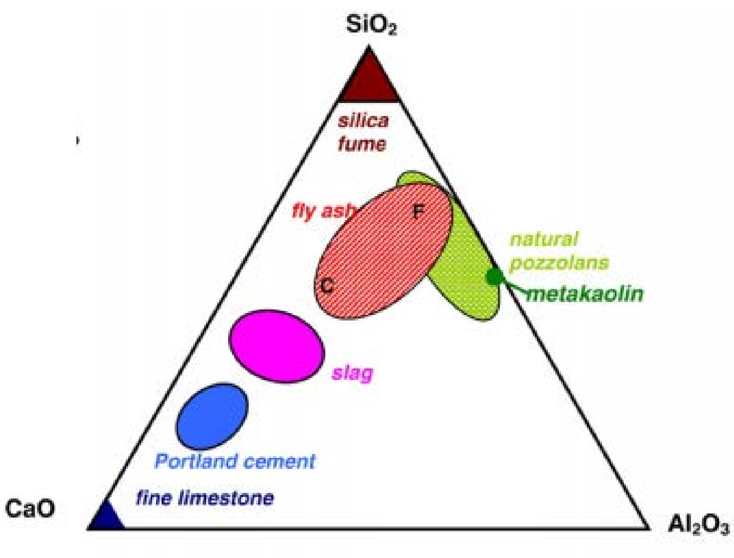


Multiscale design paradigm (http://lamm.mit.edu)

Why Start with Atoms?

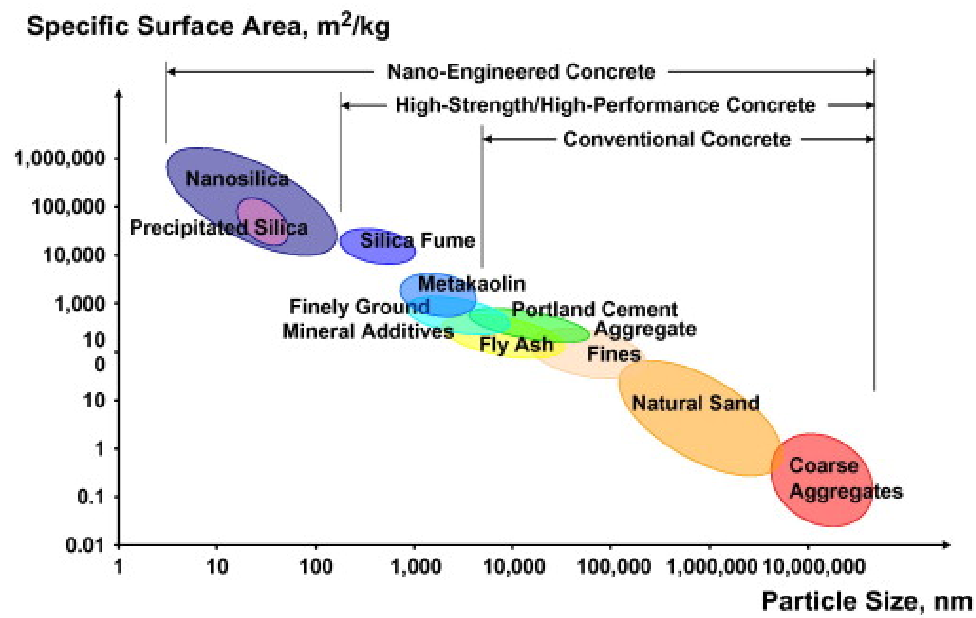
- Sustainable concrete requires additives to partially replace Portland cement
- Design through trial-and-error is due to complexity of the material and sensitivity to ingredient chemistry, environments, and time evolution

Additives are Chemically Diverse



B. Lothenbach, K. Scrivener and R.D. Hooton, "Supplementary cementitious materials," *Cement and Concrete Research*, 2011.

Additives require multiscale analysis



K. Sobolev, M.F. Gutierrez. 2005. How nanotechnology can change the concrete worlds. J. Am. Ceram. Soc.

Bioinspiration

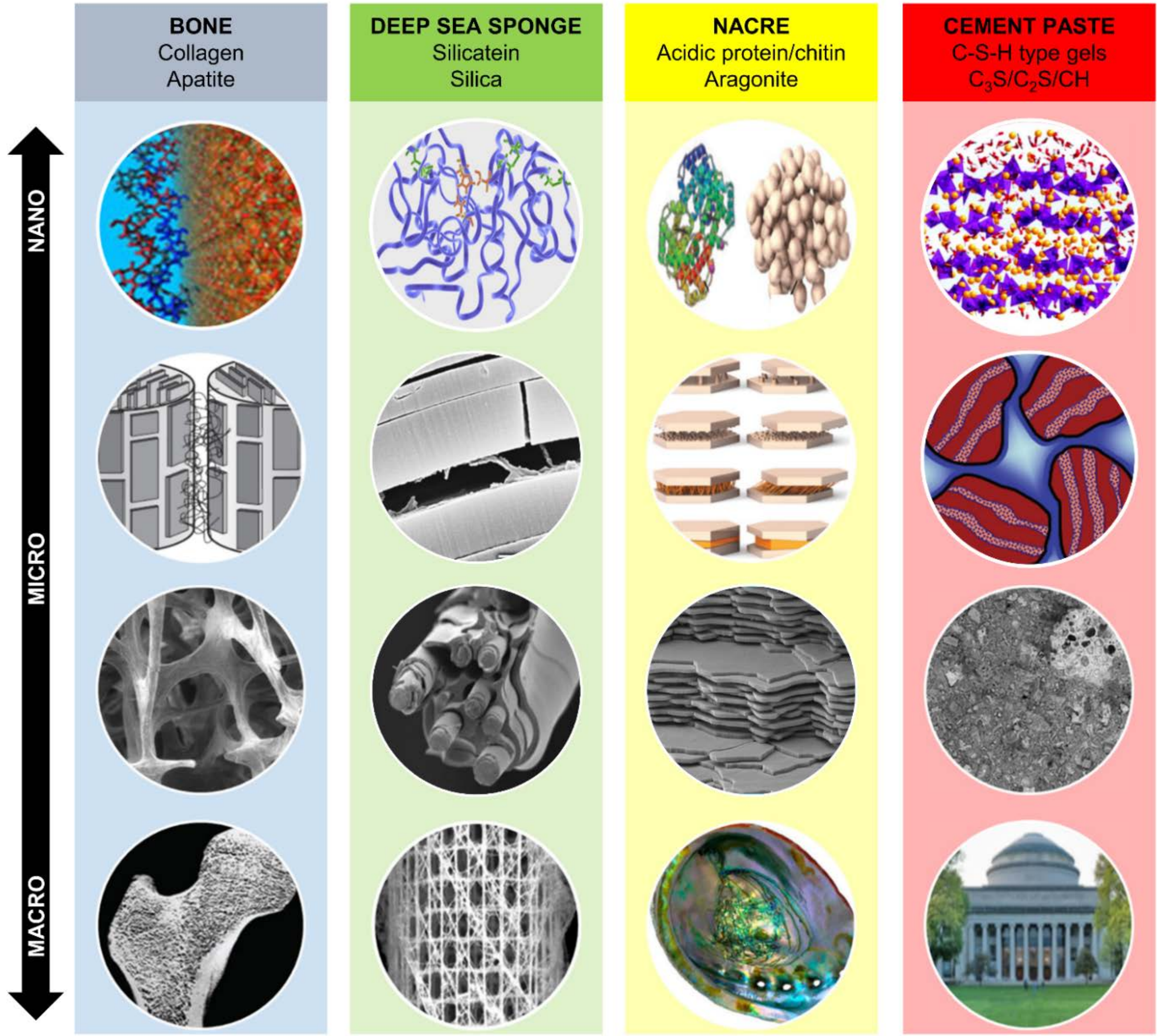
Nature

Fundamental building blocks form hierarchical structures

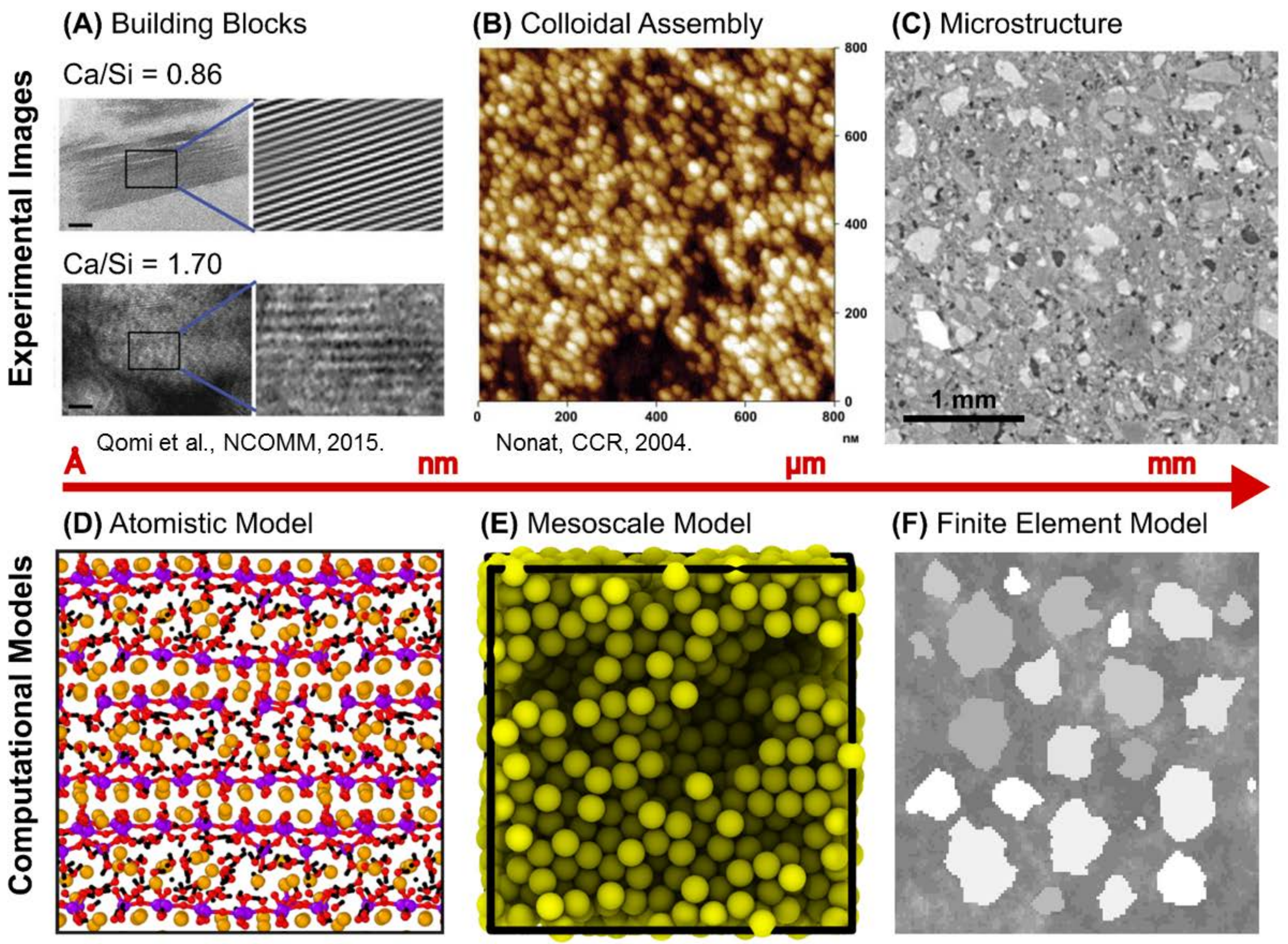
Infrastructure

Can we identify building blocks for construction materials and additives to design new materials?

Palkovic, S.D., Brommer, D.B., Kupwade-Patil, K., Masic, A., Buehler, M.J., Büyüköztürk, O., Construction and Building Materials 2016.

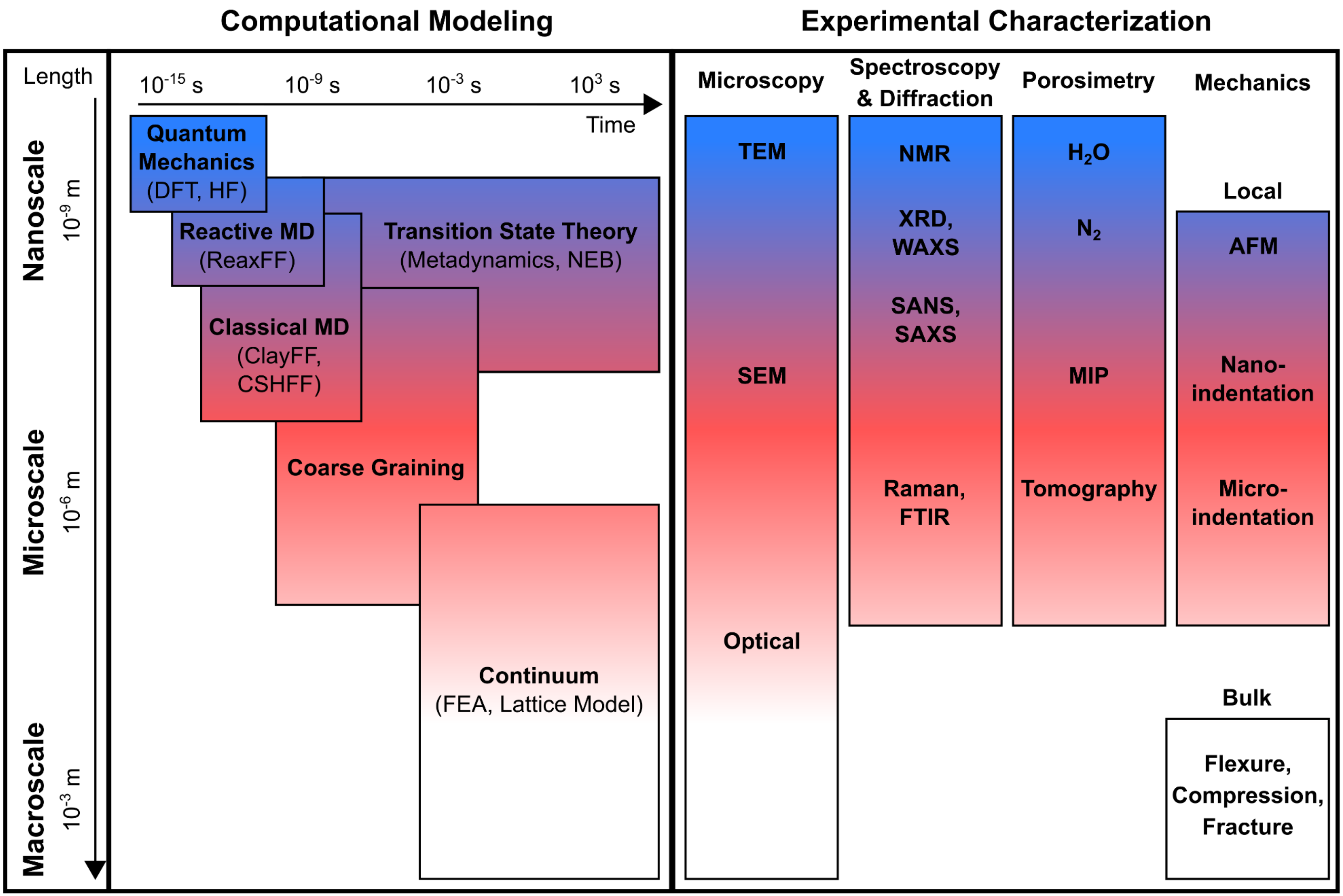


Complexity of the Material



Büyüköztürk, O. and Palkovic, S.D., “Multiscale Modelling for Sustainable and Durable Concrete,“ COMS 2017, April 2017.

Techniques for Multiscale Characterization

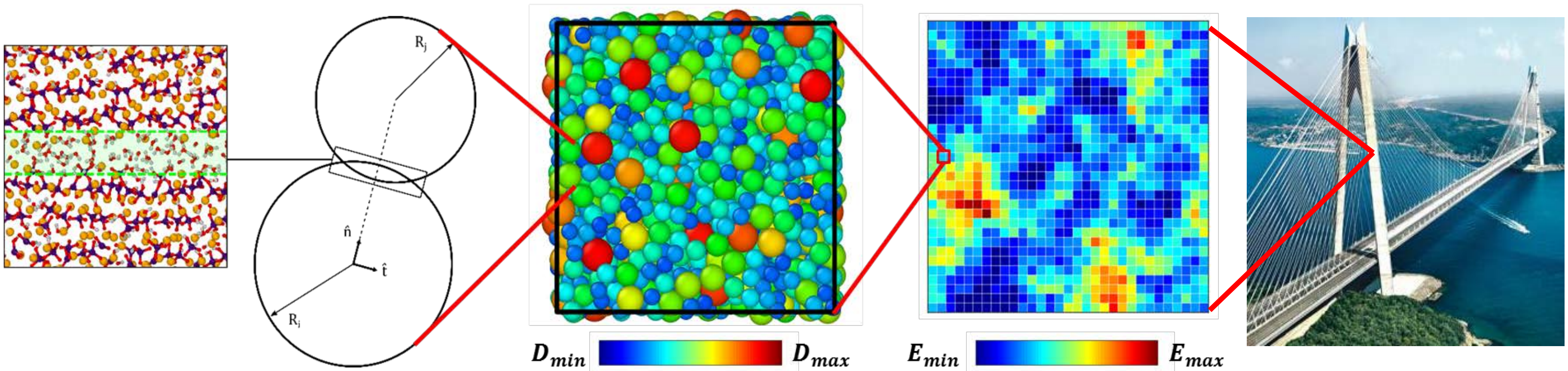


Palkovic, S.D., Brommer, D.B., Kupwade-Patil, K., Masic, A., Buehler, M.J., Büyüköztürk, O., 2016. Roadmap across the mesoscale for durable and sustainable cement paste – A bioinspired approach. Construction and Building Materials 115, 13-31.

Breakthrough Advancement

Multiscale framework for translating atomistic behavior to engineering scales

Building Block	Effective Interactions	Colloidal Packing	Composite Microstructure	Structural Scale



10^{-10} m — 10^{-9} m — 10^{-6} m — 10^{-3} m — 10^{0} m

Reactive MD → **MD + DEM** → **FEM** → **Building Codes**

10^3 atoms
~1 week / simulation

10^4 colloid particles
10^8 atoms
~1 day / simulation

10^4 finite elements
10^{13} colloid particles
10^{17} atoms
~4 hour / simulation

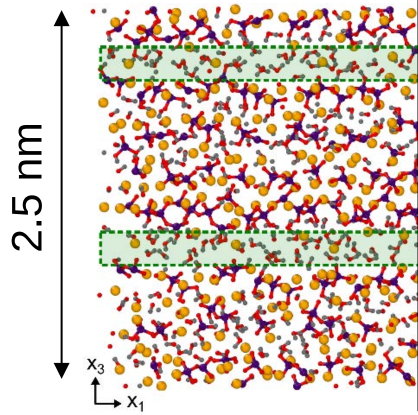
Massachusetts Institute of Technology

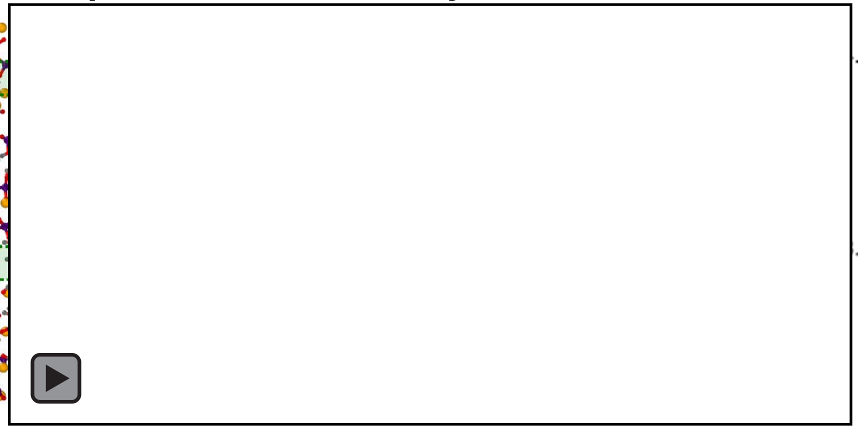
LISS

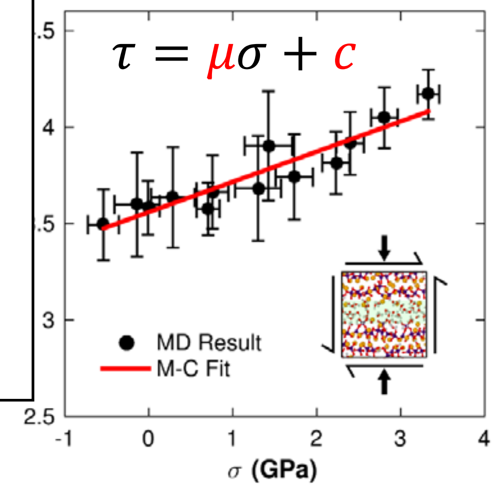
Molecular Modeling of Layered Structure

Water-filled interface controls deformation behavior

Atomistic model (4000 atoms) **Atoms colored by shear strain** **Cohesive-Frictional Strength**



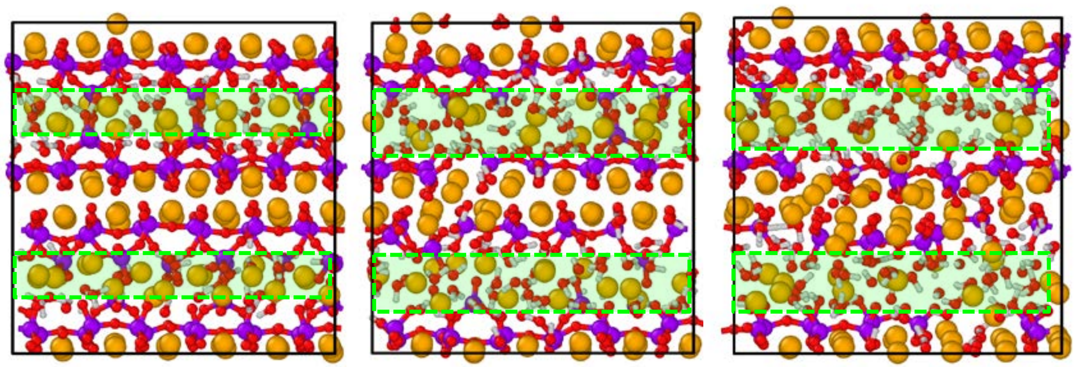


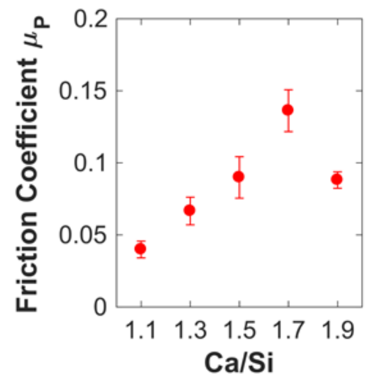


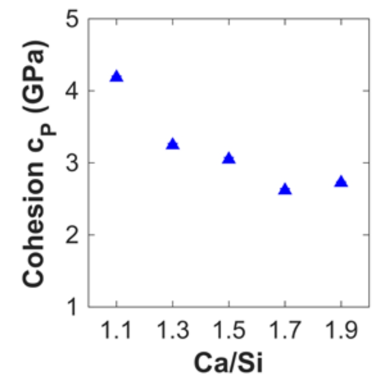
Palkovic, S.D., Yip, S., and Buyukozturk, O., *J. of Amer. Cer. Soc.*, 2016.

Changes with chemical composition

Ca/Si = 1.1 **Ca/Si = 1.5** **Ca/Si = 1.9**







Atom Types: **Red** = H, **Grey** = O, **Orange** = Ca, **Purple** = Si

Massachusetts Institute of Technology

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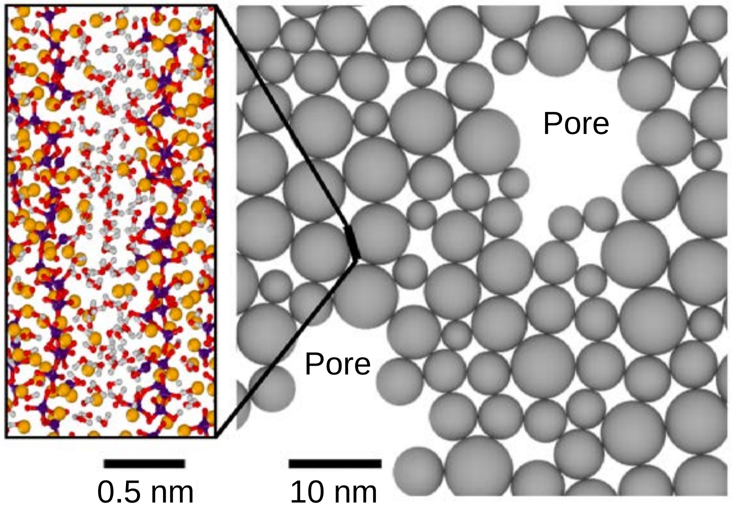
Colloidal Behavior from Atomistic Interface

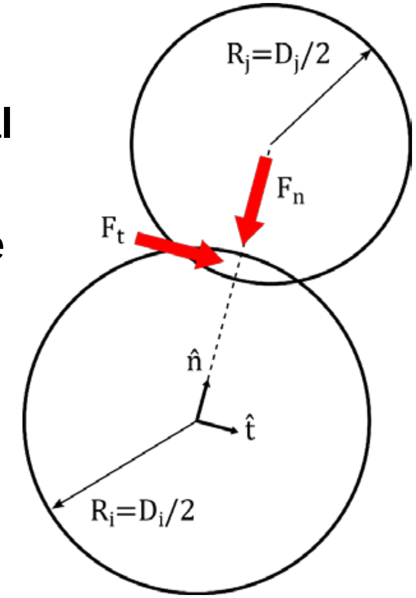
Cohesive-Frictional Force Field (CFFF)



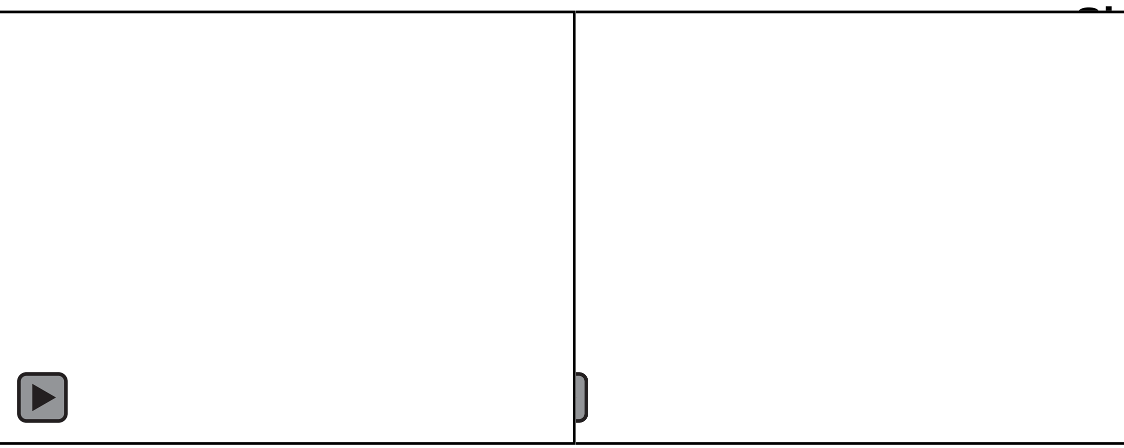
Palkovic, S.D., Yip, S., and Buyukozturk, O., *J. of Mech. Phys. of Solids*, (In Press).

Fundamental Interactions

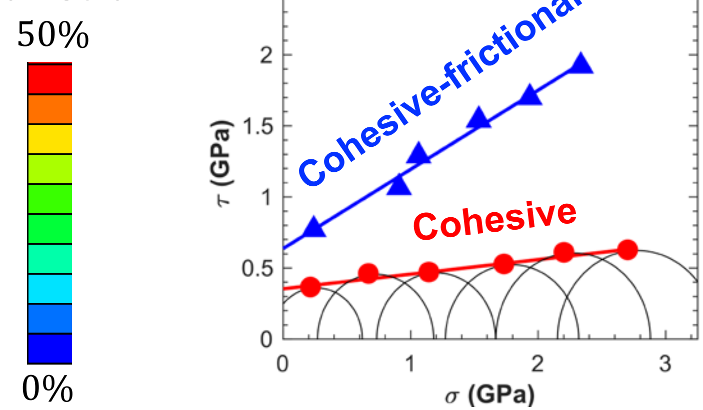
F_n = cohesive
F_t = frictional



Mechanics with Cohesive-Frictional Interactions (10,000 particles)



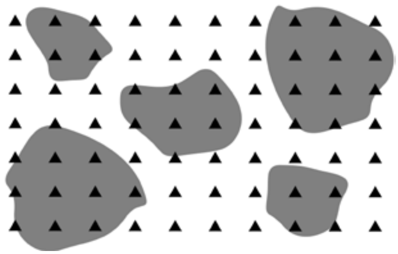
Shear strain



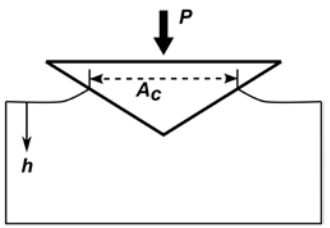
Microstructure Models

Develop Models from Experiments and Random Fields

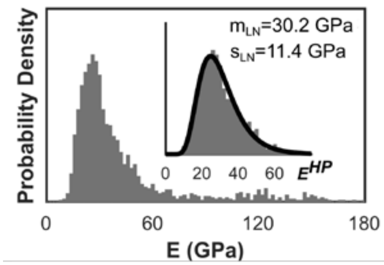
Grid Indentation

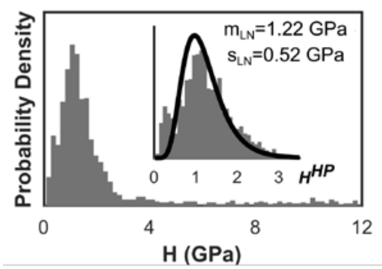


20x20 grids (400x400 μm)

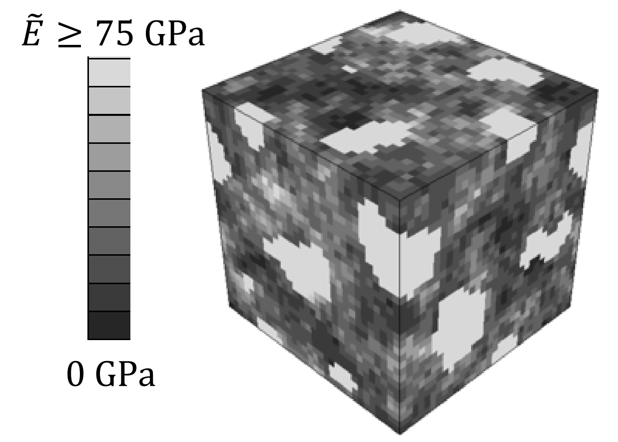


Mechanical Distribution



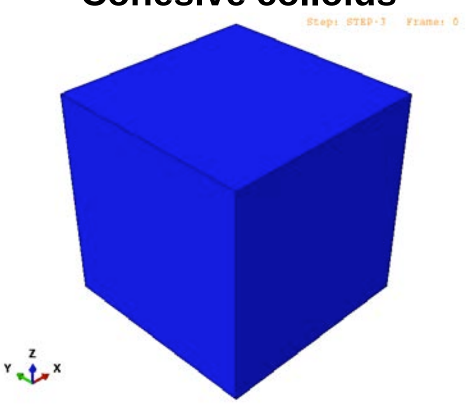


Random Field Model Young's Modulus Distribution

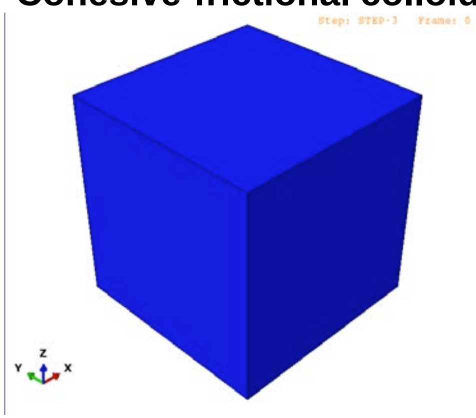


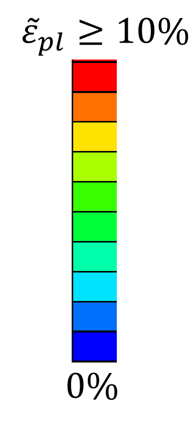
Strain Localization under Compression (64 μm cube)

Cohesive colloids



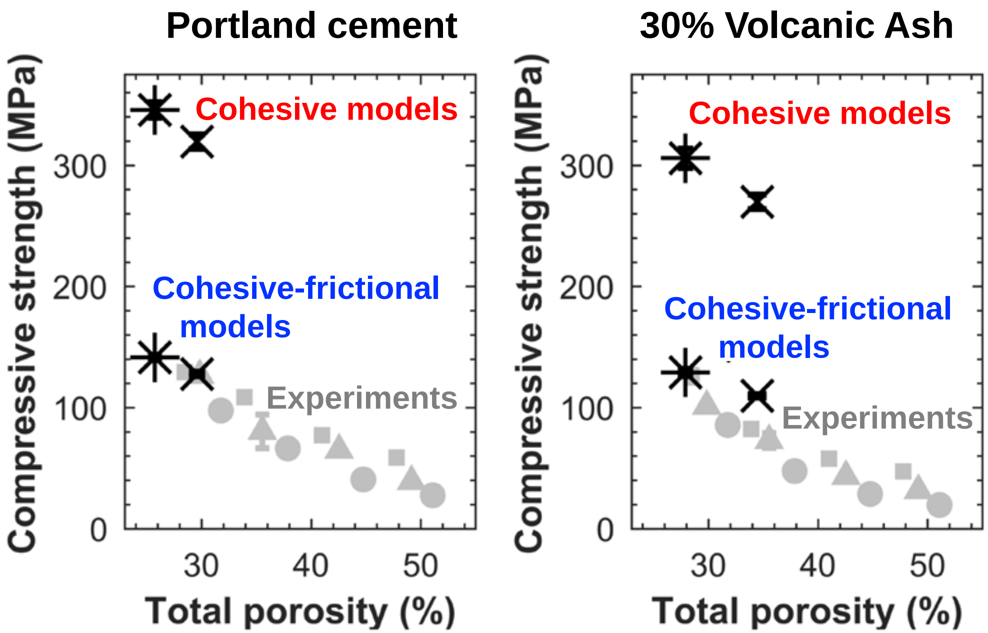
Cohesive-frictional colloids





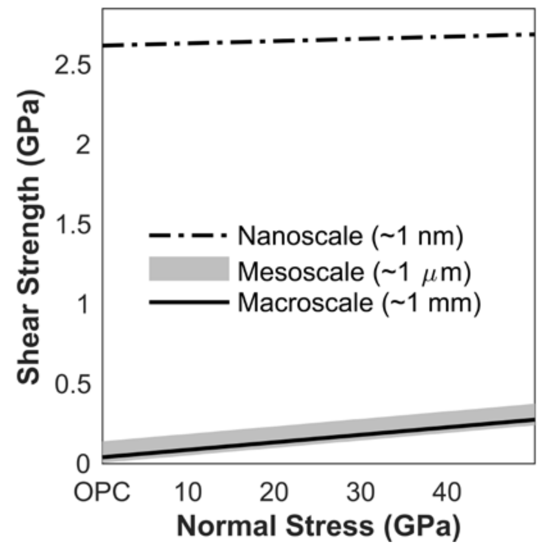
Framework Validation with Macroscale Experiments

Cohesive models do not capture behavior of macroscale compression experiments



Experiments on 2 cm cement paste cubes

Multiscale strength envelope for cohesive-frictional models



Scale	Friction Coefficient	Cohesion (GPa)
Nano (~ 1 nm)	0.15	2.8
Meso (~ 1 μm)	~0.50	0.005 to 0.14
Macro (~ 1 mm)	~0.50	0.04

Quantifying Sustainability

Future Directions = community and neighborhood scales

Materials

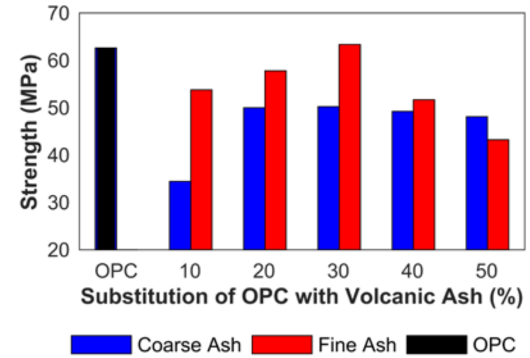
Volcano

Volcanic Rocks

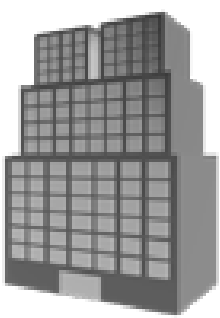
Energ

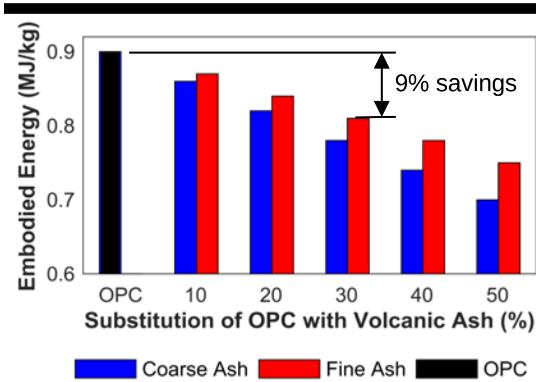
Ball Milling

Volcanic Ash



Buildings





~15,000 metric ton embodied carbon saved with 30% VA for Al Hamra

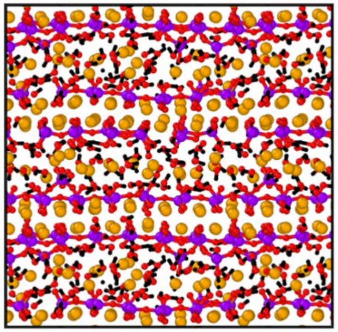
Neighborhood

Reinhart *et al.* 2013

K. Kupwade-Patil, C. De Wolf, S. Chin, J. Ochsendorf, A.E. Hajiah, A Al-Mumin, O Buyukozturk, Journal of Cleaner Production (Under review)

Future Exploration

Molecular Structure (~ 1 nm)

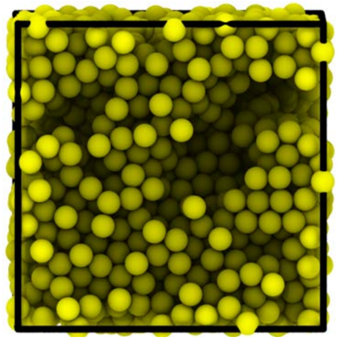


Additional hydrated phases (Al, Mg, K)

Degradation and reactivity with harmful elements

Long-term response using metadynamics

Colloid Structure (~ 100 nm)



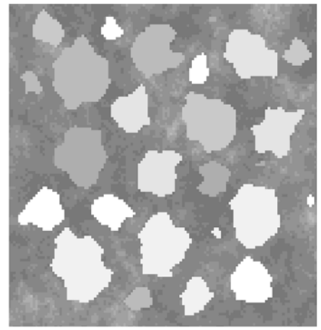
Precipitation, aggregation and early-age setting (fluid-to-solid, residual stresses)

Mixtures of colloid chemistries

Saturated pore structures

Tension and fracture behavior

Microstructure (~ 100 μm)

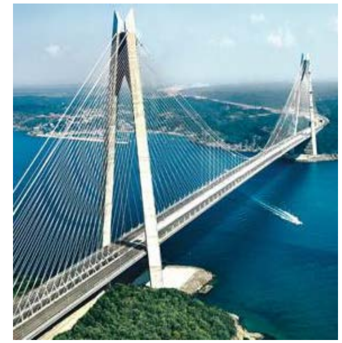


Nanoindentation studies with varying age, w/c, other additives

Role of interfaces for sand and aggregate

Spatial mechanical and chemical distributions

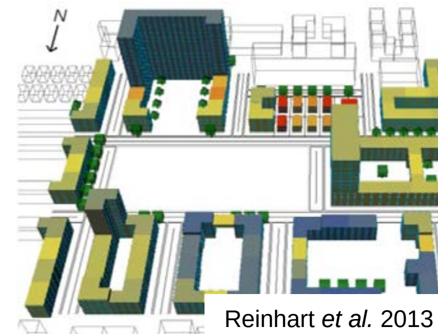
Structural (~ 1 m)



Database connecting additive inputs with engineering properties

Design for resiliency considering strength, durability and low embodied energy

Neighborhood / City (~ 1 km)



Reinhart *et al.* 2013

Extrapolate material impact to neighborhood and city scales

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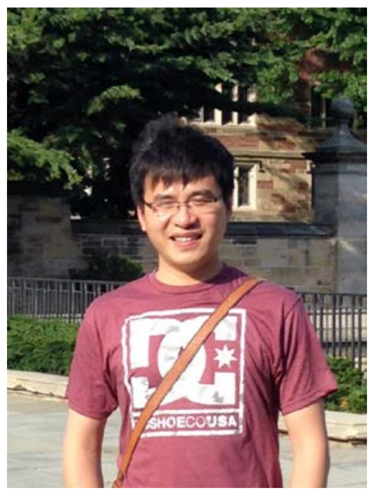

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