Overview of ORNL activities on developing low-CO_2 emission building materials

NIST workshop: Fostering a circular economy and carbon sequestration for construction materials

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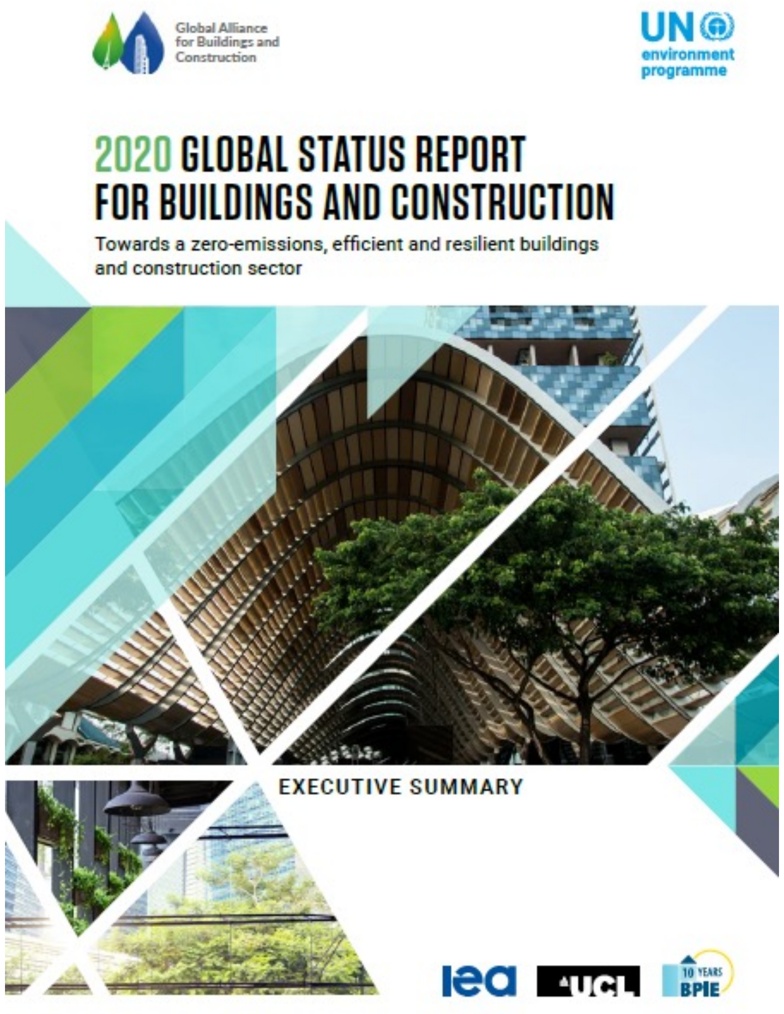
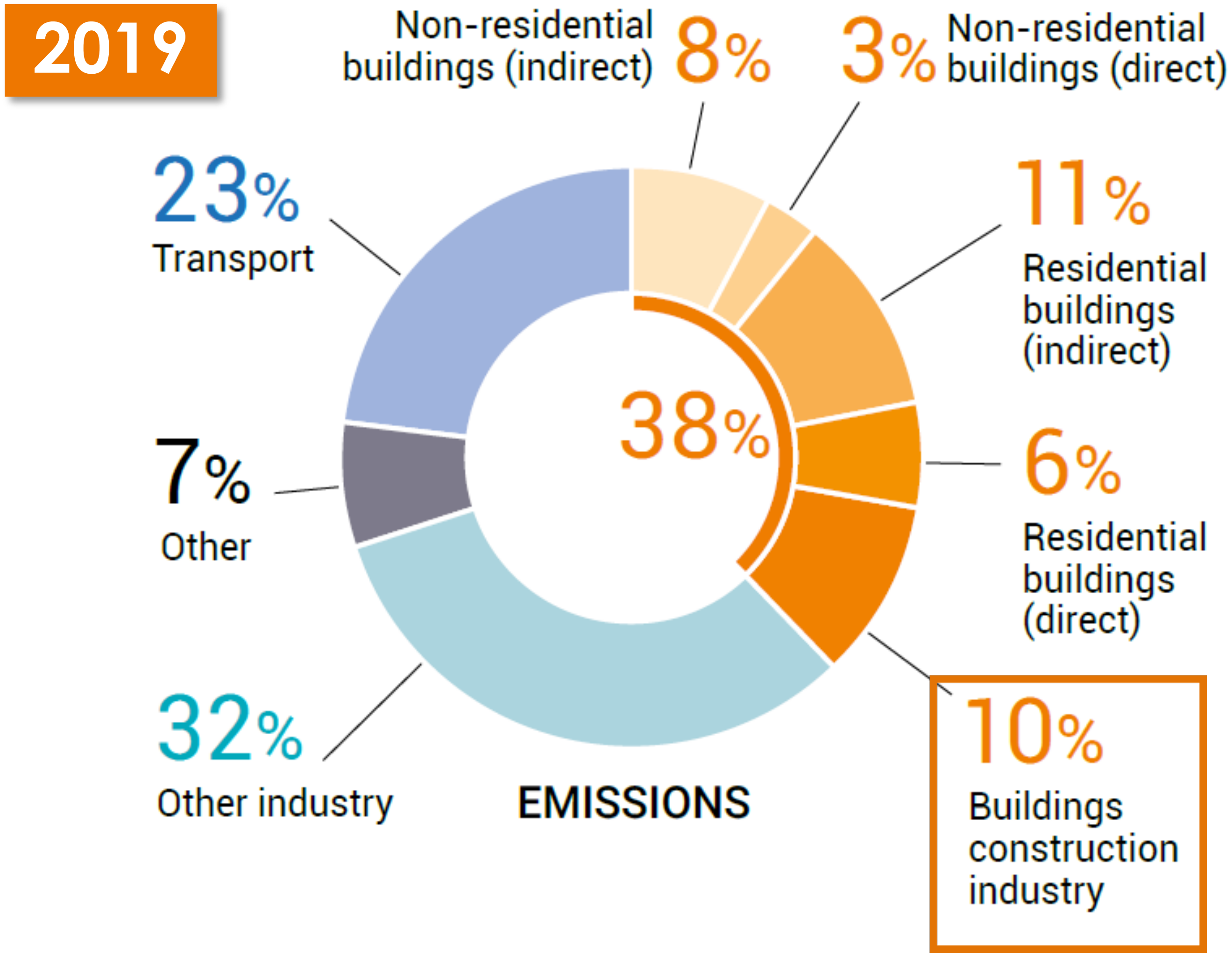
Carbon Emissions



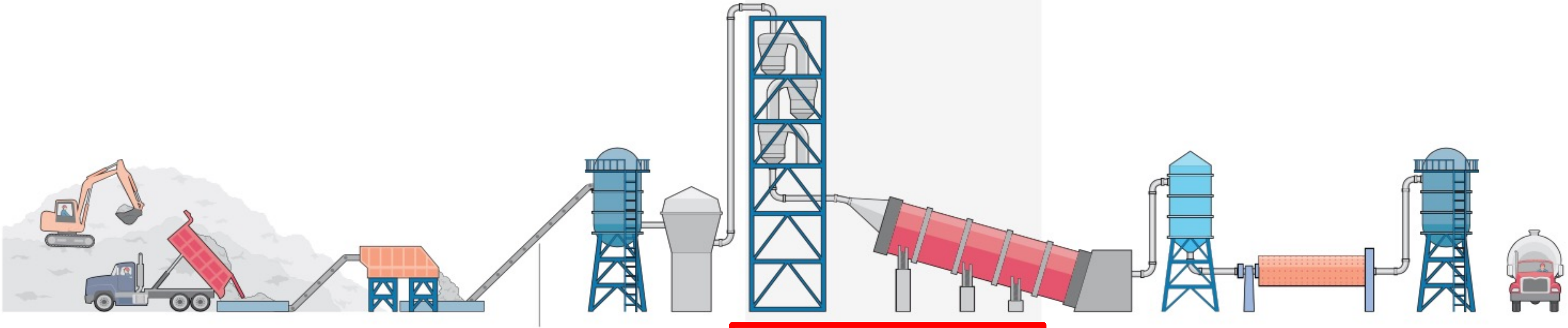


Embodied carbon:
extraction, manufacturing, transportation, construction, and end-of-life of building materials and assemblies

Oak Ridge National Laboratory   Slide courtesy of Dr. Denise A. Silva

Sources of CO_2 Emissions

2017



	Raw materials, energy, and resources				Clinker and cement manufacturing					
	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]		Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150		160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process	319 Fossil fuels	28	49	22	925

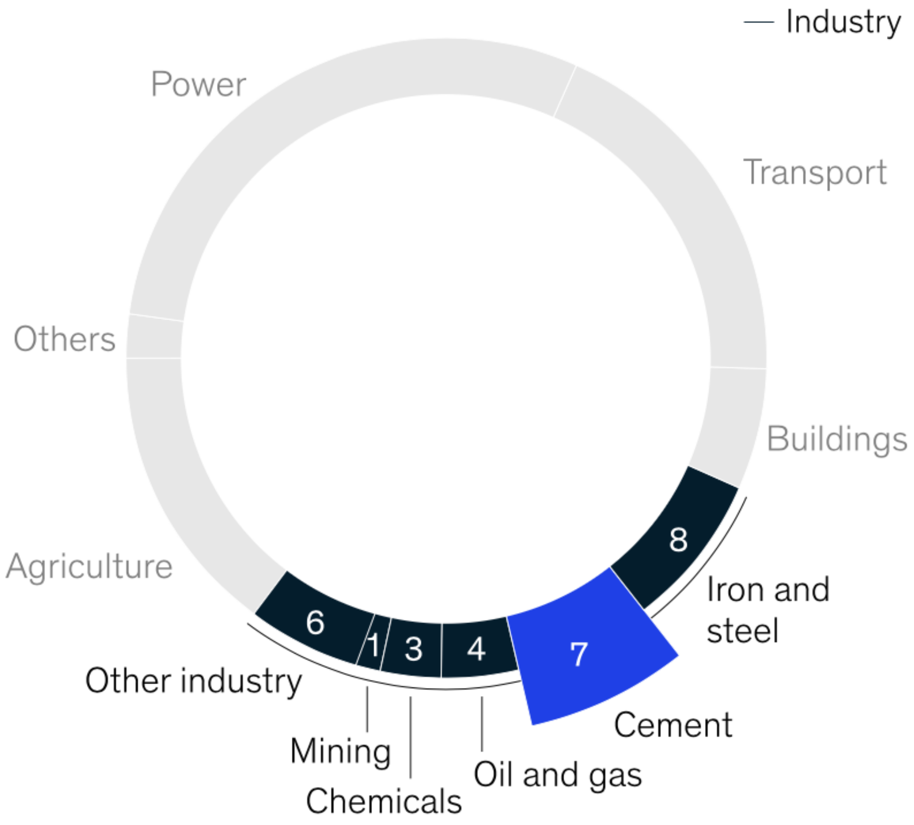
[1] Assumed with 1kWh/t/100m.
[2] Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3] Assumed reciprocating grate cooler with 5kWh/t clinker.
[4] Assumed lorry transportation for average 200km.

Sources: https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement
https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change

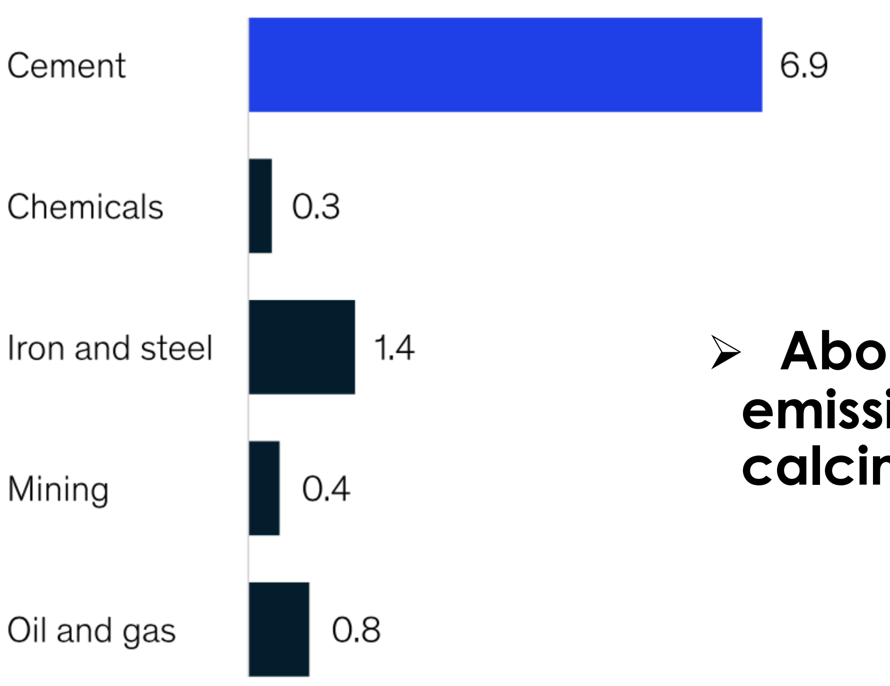
Impact of Cement Production on CO_2 Emission

Cement production is a major source of global CO_2 emissions and also generates the most emissions per revenue dollar.

Share of global CO_2 emissions, % in 2017



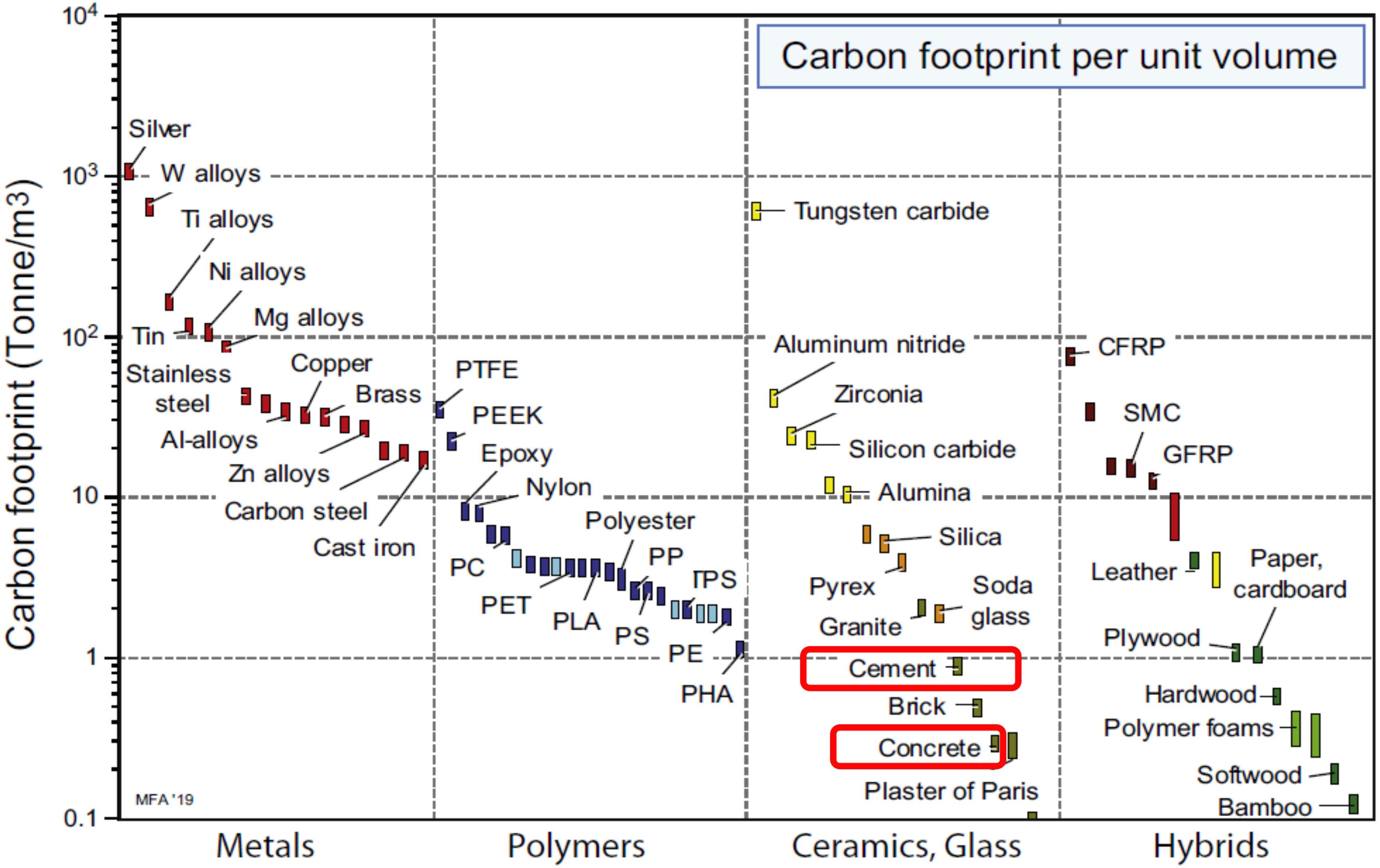
kg of CO_2 per $



- ➢ **About 2/3 of those total emissions result from calcination in the kiln**

Source: https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

Carbon Emissions from Materials (per Volume)



** Biogenic (stored) carbon in natural materials such as wood is not accounted for.*

Source: Ashby, M.F. (2021) Materials and the Environment – Eco-Informed Material Choice. Elsevier/ Butterworth-Heinemann, 3rd edition

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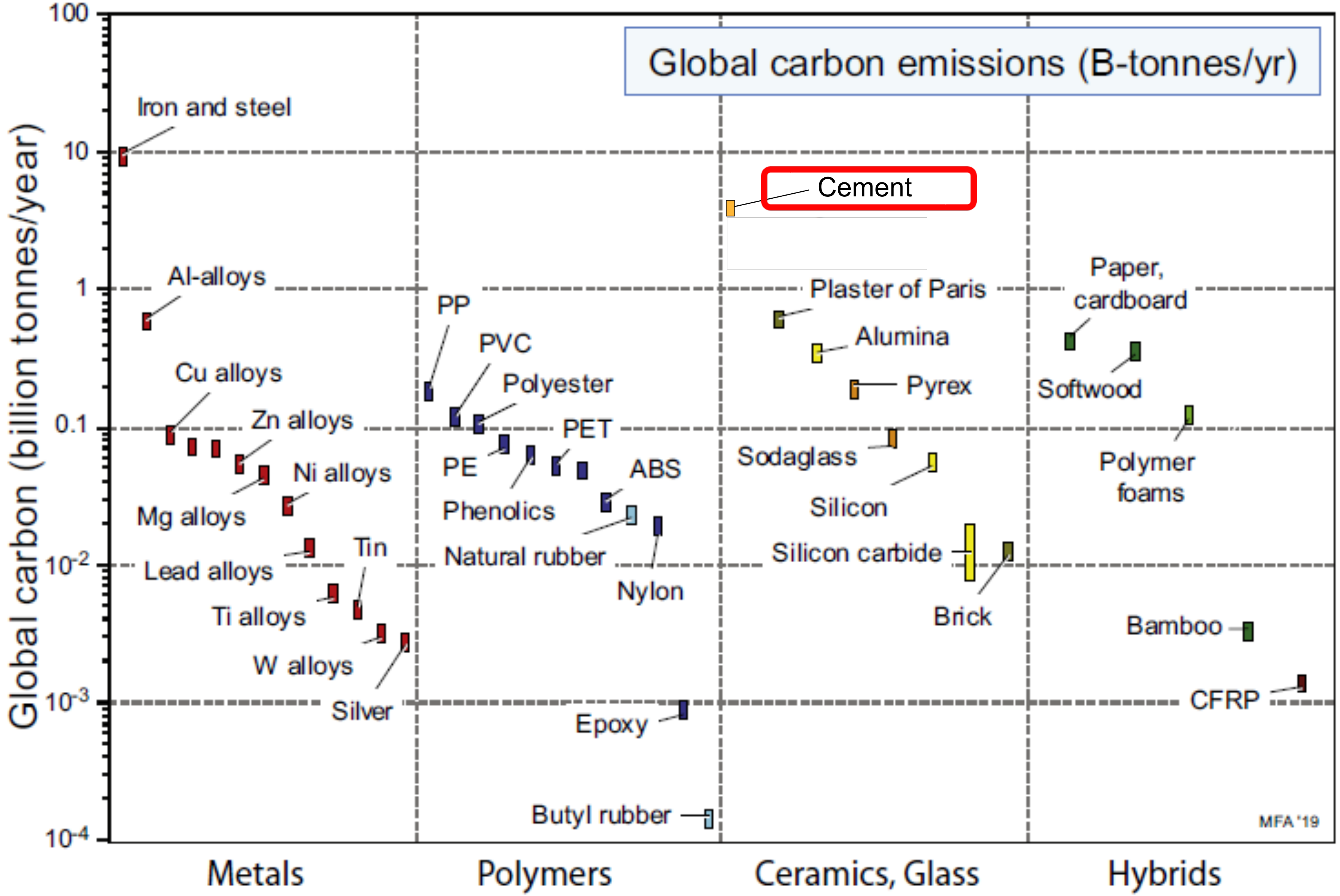
Carbon Emissions from Materials (per Year)



Global Cement Production

4.3 Gt

Global Concrete Production

10-30 Gt

Source: Ashby, M.F. (2021) Materials and the Environment – Eco-Informed Material Choice. Elsevier/ Butterworth-Heinemann, 3rd edition (modified)

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Building Materials Decarbonization Efforts at ORNL

Building Technologies Research and Integration Center

BUILDINGS-TO-GRID

- Low-cost wireless sensor technologies
- Transactive controls
- Power electronics
- Building energy models

HVAC&R AND APPLIANCES

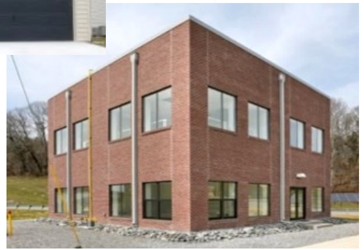
- Develop affordable component and system technologies
- HVAC
- Water heating
- Refrigeration
- Appliances
- Thermal energy storage

ENVELOPES

- Develop affordable techniques and technologies to address heat, air, and moisture flow
- Dynamic insulation
- Thermal energy storage
- Walls, roofs, attics, foundations, sheathings, membranes, coatings, and materials

INTEGRATION

- Performance characterization at the materials, component, system and whole-building levels
- Evaluate prototypes under realistic conditions
- Evaluate impacts of retrofit technologies

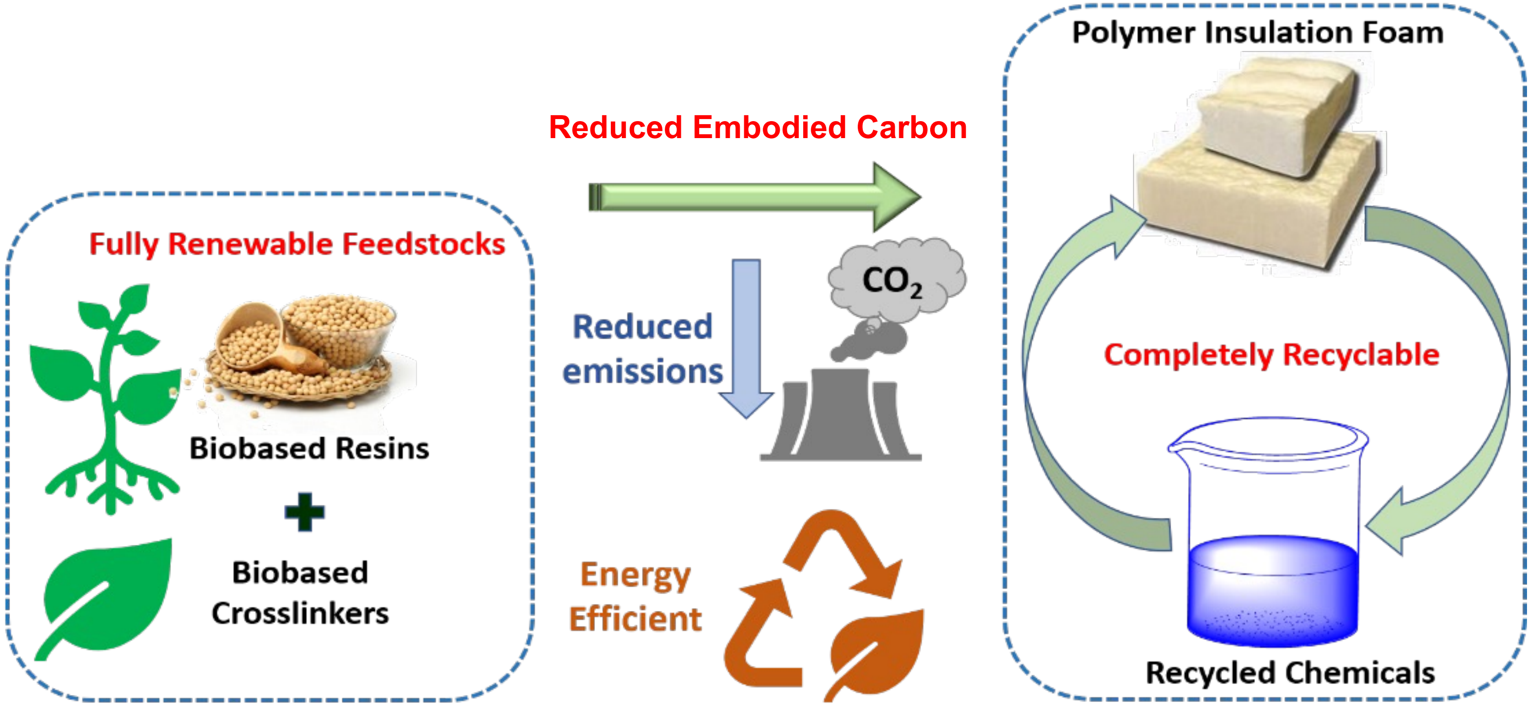


- **Mission:** Deliver scientific discoveries and technical breakthroughs to accelerate building energy efficient solutions
- Established in 1993
- DOE's only designated user facility focused on building technologies
- Over 60,000 ft^2 research space
- 70+ staff members
- ~120 active projects

Slide courtesy of Dr. Denise A. Silva

Low-Carbon, Recyclable, Biobased Foam Insulation

- Polymer-based thermoset foams are mostly petroleum-based and non-recyclable
- **Goal:** Reduce embodied carbon of foam insulation
  - R-value ≥5/inch and meet common performance metrics
  - 20% to 30% lower embodied carbon
    - Partial replacement of petroleum-based polymers with biobased building blocks
    - Conduct LCAs thru project
    - Recyclable through low-energy thermal and/or chemical processes



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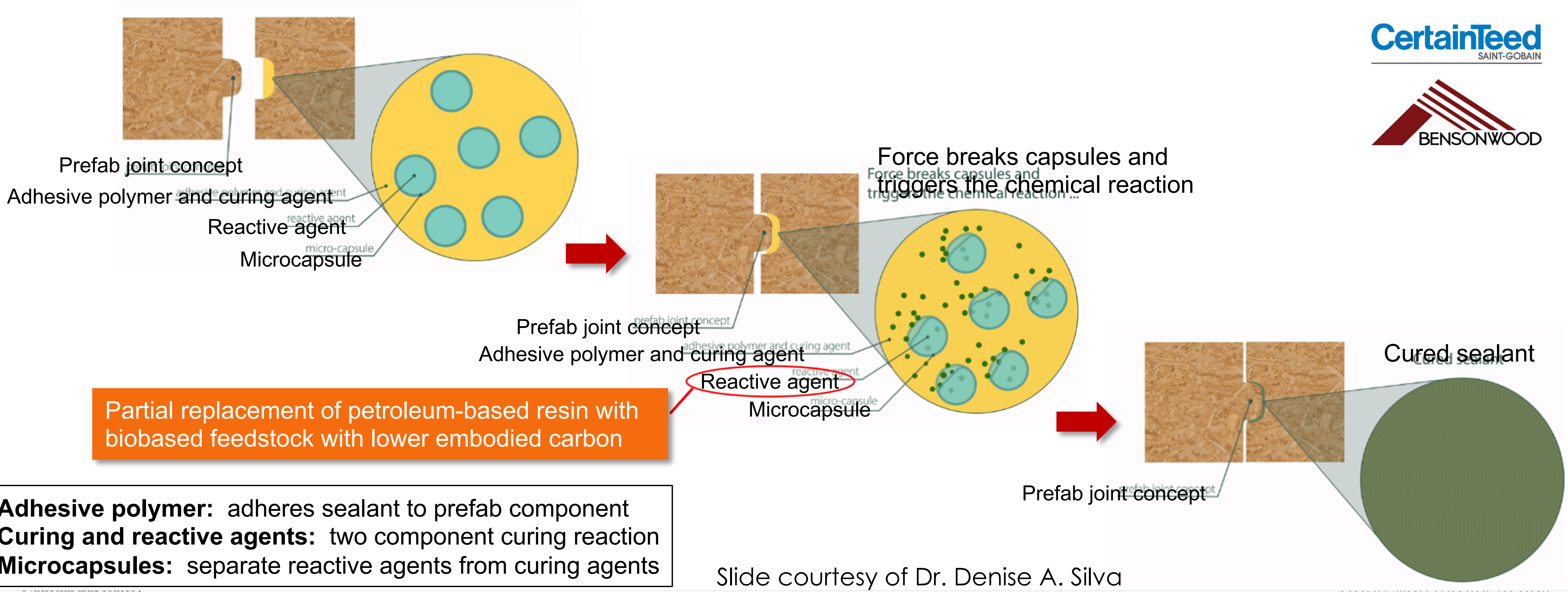
Preinstalled Sealant for Prefab Components

- Prefab construction lacks time-efficient method to air/water seal joints at the jobsite
- **Goal:** Develop a low-carbon sealant that is installed at the prefab plant and is pressure activated at the jobsite

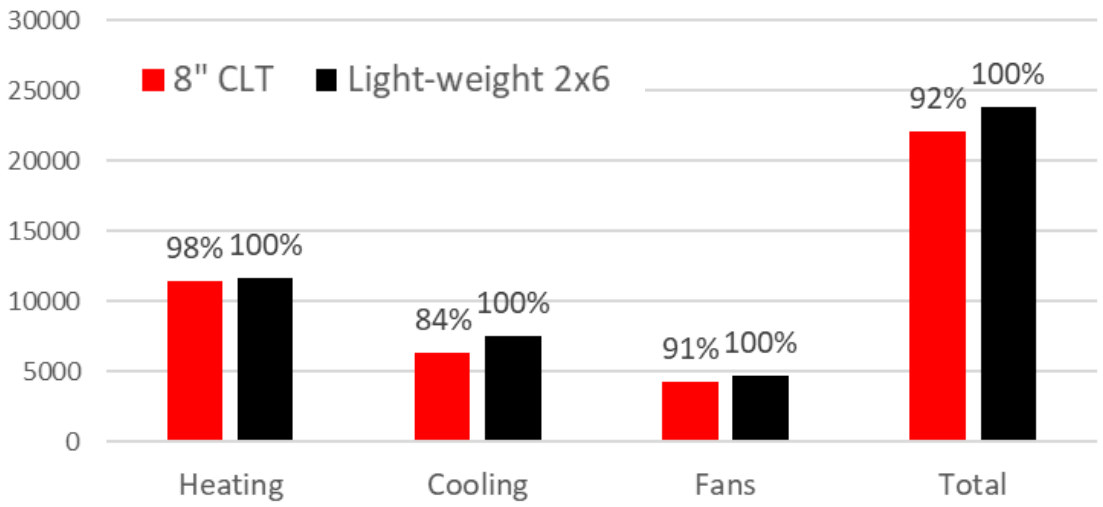


Adhesive polymer: adheres sealant to prefab component
Curing and reactive agents: two component curing reaction
Microcapsules: separate reactive agents from curing agents

Slide courtesy of Dr. Denise A. Silva

Cross Laminated Timber (CLT)

- CLT benefits on energy use and peak demand have been minimally studied
- **Goal:** Quantify effects of CLTs
  - Moderation of indoor temperatures
  - Increased comfort
  - Operational energy
  - Peak demand



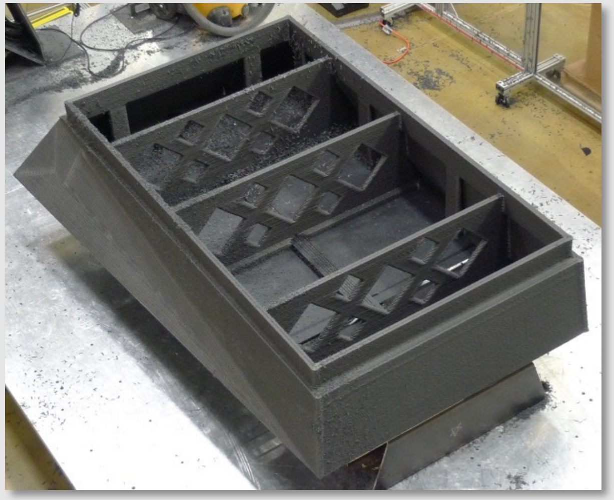
ORNL's large-scale environmental chamber

CLT hotel in Columbus, SC

Slide courtesy of Dr. Denise A. Silva

Biobased 3D Printed Molds

ABS w/ 20% carbon fiber



PLA w/ wood flour

- Renewable feedstock
- Biodegradable
- ~50% cheaper than ABS/CF

Slide courtesy of Dr. Denise A. Silva

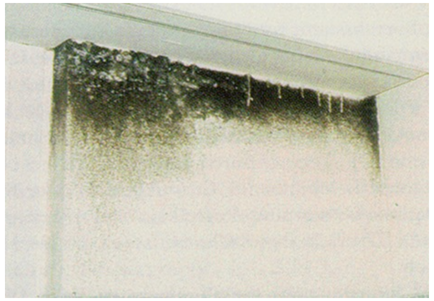
PCI Precast/Prestressed Concrete Institute

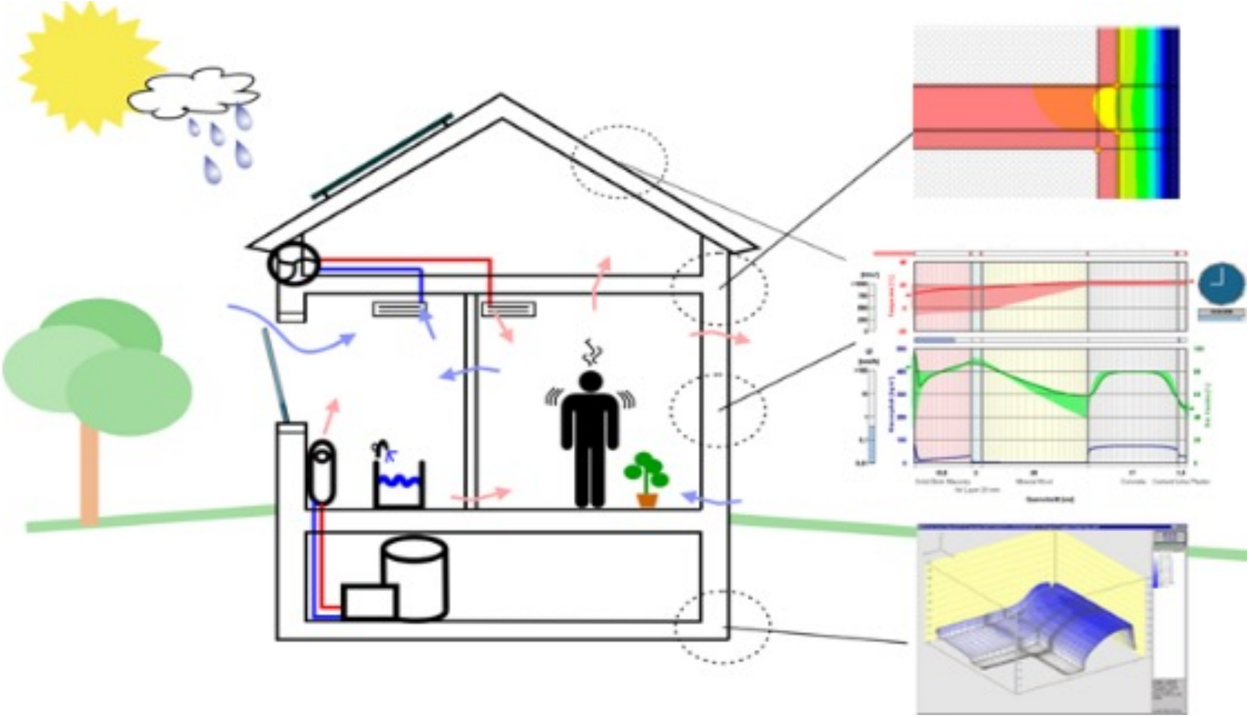
GATE Precast Company

Database of Biobased Materials for Building Envelopes

- Widespread acceptance of biobased materials for building envelopes is hindered by minimal availability of hygrothermal properties needed to run simulations that prevent moisture durability problems

- **Goal:** Generate key material properties of biobased materials
  - Heat capacity
  - Thermal conductivity as a function of temperature and moisture content
  - Moisture dependent permeance
  - Sorption isotherm
  - Liquid uptake
  - Porosity
  - Airtightness





https://wufi.de/en/software/wufi-plus/

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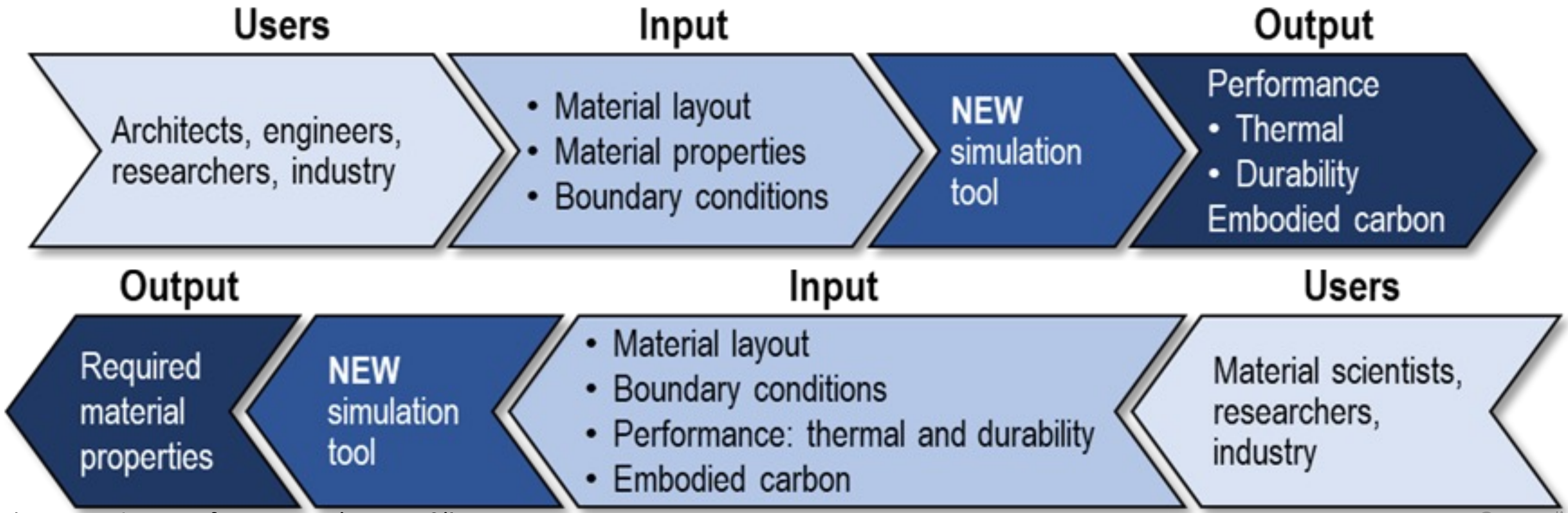
PHIUS Passive House Institute US

Machine-Learning (ML) Assisted Low-Carbon Building Material Development and Integration Tool

- Traditional approaches used by the construction industry to develop and integrate new building materials are slow, complex, and expensive.
- **Goal:** Develop a ML-assisted simulation tool
  - Material scientists determine, at an early stage, the required properties to optimize development time and cost.
  - Architects/designers have a simple, yet powerful, tool to integrate new low-carbon materials into energy efficient and moisture durable walls, roofs, and foundations.
  - No need to run complex hygrothermal simulations.



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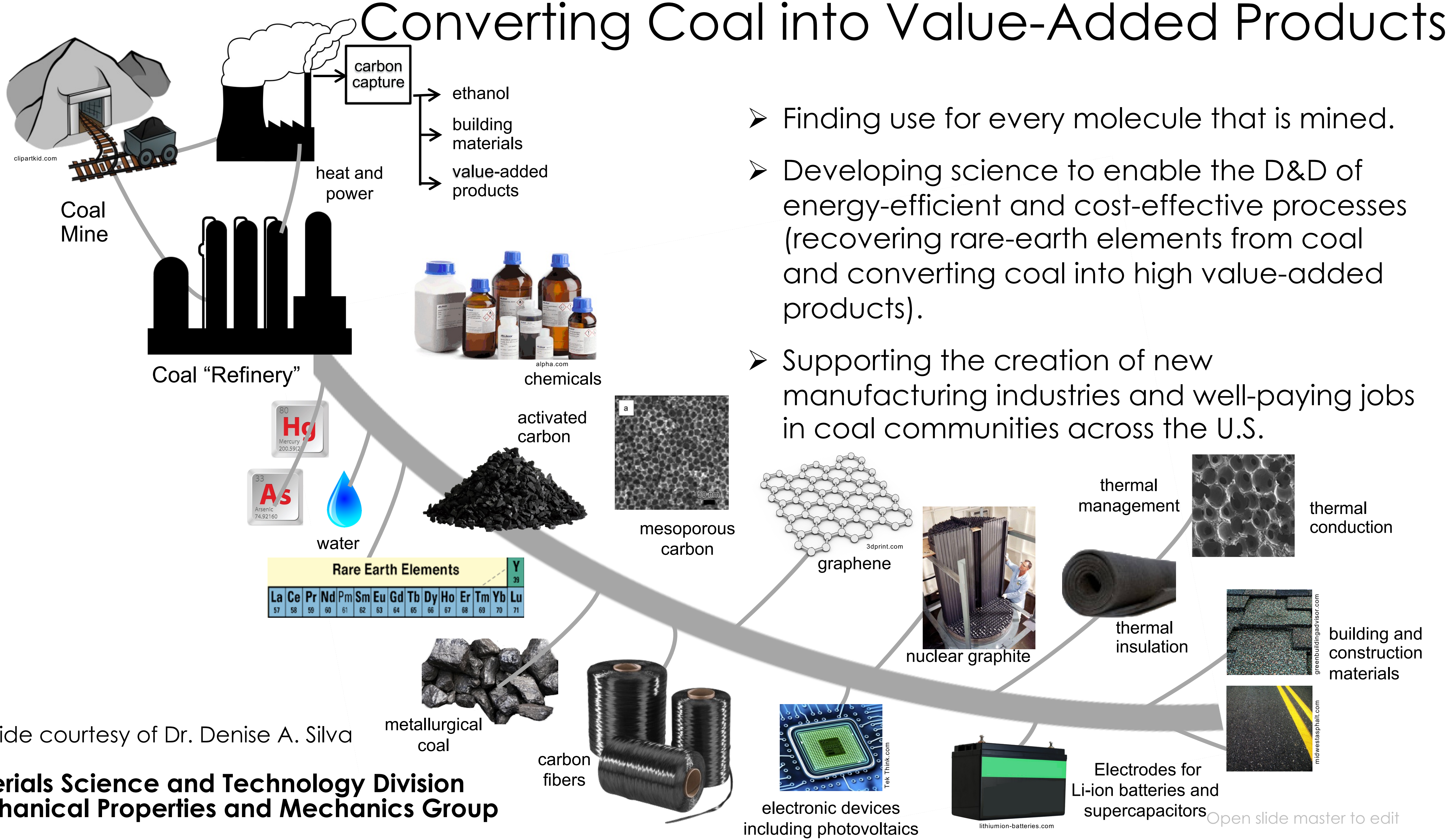
Converting Coal into Value-Added Products

- Finding use for every molecule that is mined.
- Developing science to enable the D&D of energy-efficient and cost-effective processes (recovering rare-earth elements from coal and converting coal into high value-added products).
- Supporting the creation of new manufacturing industries and well-paying jobs in coal communities across the U.S.



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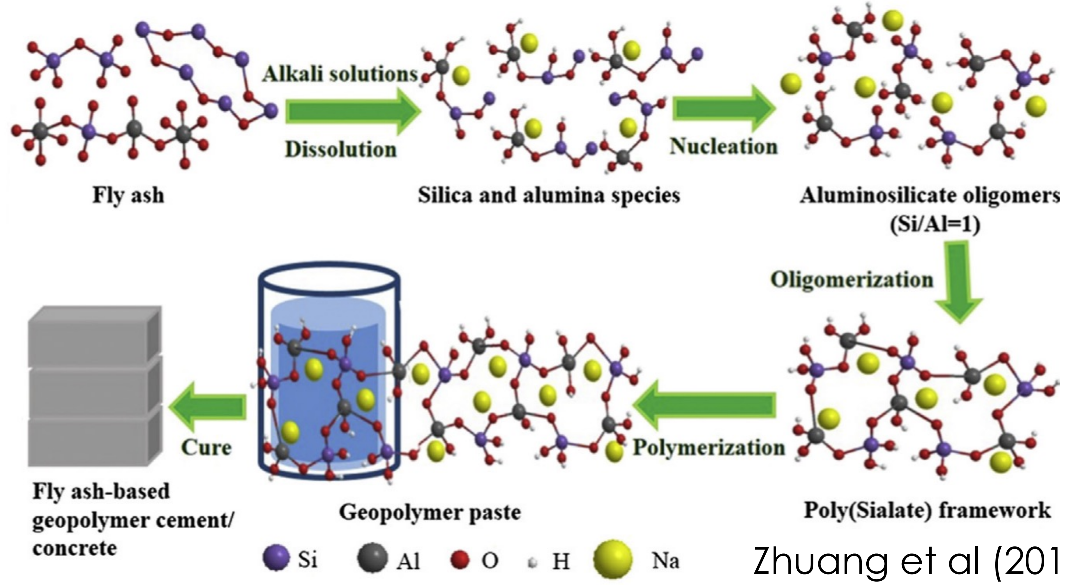
Materials Science and Technology Division
Mechanical Properties and Mechanics Group

Alkali-Activated Harvested Coal Ash Binder

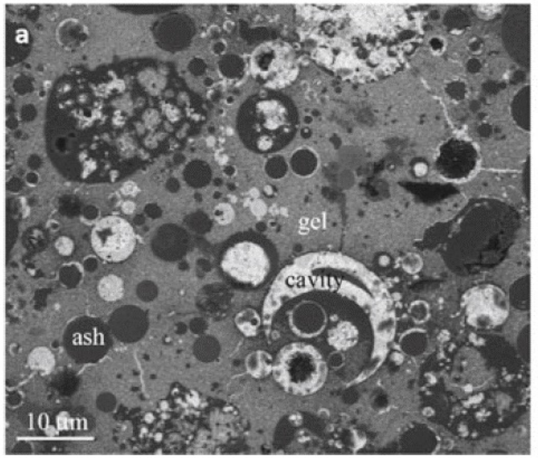
- Alternative binder to Portland cement in structural and non-structural applications.

- **Goal:** demonstrate feasibility of using ponded coal ashes to produce alkali-activated binders (AABs)
  - Reduce embodied carbon of cement-based material.
  - Reduce environmental risks of coal ash ponds (> 1 billion tons of reserves)
  - Immobilization of trace metals in AABs

https://insideclimatenews.org/news/04122018/toxic-coal-ash-spill-illness-verdict-kingston-tennessee-cleanup-workers-compensation/



Zhuang et al (2016)



Provis and Bernal (2014)

Lower carbon footprint and less environmental risk

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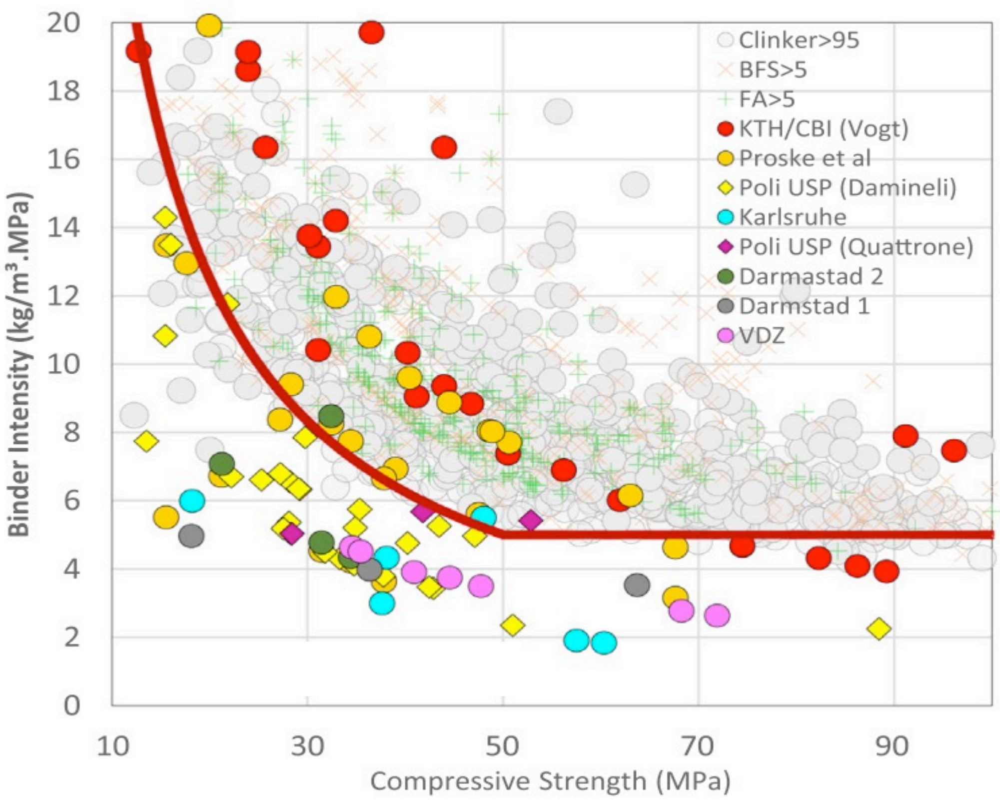
High Filler, Low Water Concrete Design Approach

- High binder intensity in most concrete designs → high CO_2 emissions by cement industry (8% of all man-made emissions)
- **Goal:** reduce cement consumption by >35%
  - Superior mechanical performance → elements with smaller dimensions that use less concrete.
  - Superior concrete durability.
  - Comparable or lower cost.
  - Minimal adjustments to current concrete production practices.
  - Minimal capital investment by concrete producers.



Better performance and lower embodied carbon

PCI Precast/Prestressed Concrete Institute · The University of Tennessee · Universidade de São Paulo Escola Politécnica

Oak Ridge National Laboratory
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High-Performance Concrete for Precast Insulated Panels

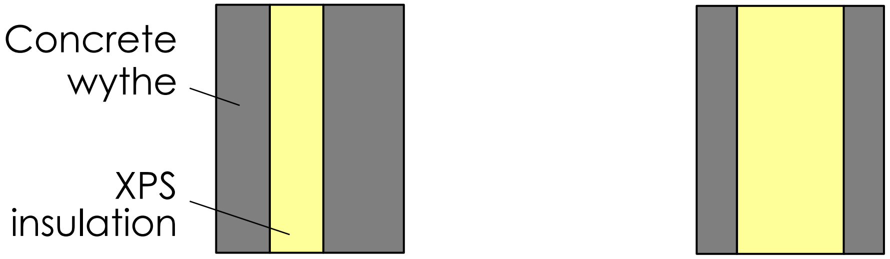
- Concrete is a relatively heavy construction material (~150 pcf)
  - Precast insulated panel ~62.5 psf
  - Increases required design capacity and cost of other components
  - Increases transportation and erection cost
- **Goal:** Decrease panel weight to 25 psf
  - Decrease concrete wythe thickness to 1.5 in
  - Decrease concrete density to 100 pcf
  - Meet required mechanical properties
  - Self-consolidating
  - ~$300/yd^3 → max cost set by industry partner

PCI Precast/Prestressed Concrete Institute

THE UNIVERSITY OF TENNESSEE CHATTANOOGA

Baseline | **New design**

2 : 2 : 3 in | 1.5 : 3 : 1.5 in



150 pcf concrete density
62.5 psf panel weight

100 pcf concrete density
25 psf panel weight

Large-scale trial

~40% less concrete and embodied carbon

Slide courtesy of Dr. Denise A. Silva

High-Early-Strength, Self-Compacting Concrete

- Precast concrete beds used once per day
- **Goal:** Double plant production
  - Concrete mix that gains required mechanical properties in ½ time
  - No capital investment in plant expansion
  - Uses typical mixing procedures and commercially available materials
- 15% lower embodied carbon
  - Replaced Type I cement with Type III cement, ground-granulated blast-furnace slag, calcium sulfo-aluminate cement
  - ≤$350/yd^3 → max cost set by industry partner

PCI Precast/Prestressed Concrete Institute

The University of Tennessee

Large-scale trial

Higher throughput and lower embodied carbon

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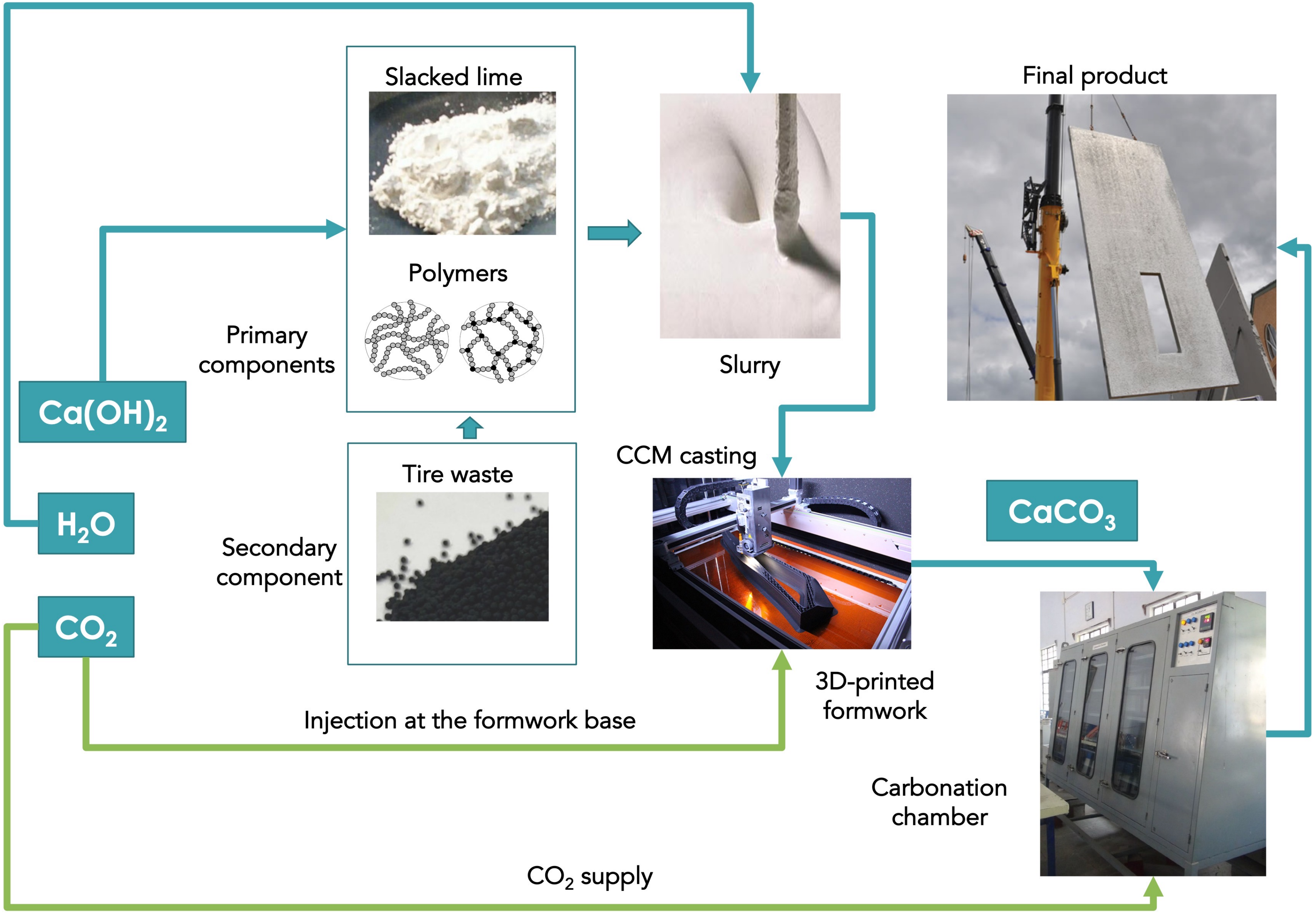


Nuclear Structures and Construction Group
Nuclear Energy and Fuel Cycle Division

Carbon Mineralization for Concrete Alternatives

Goal

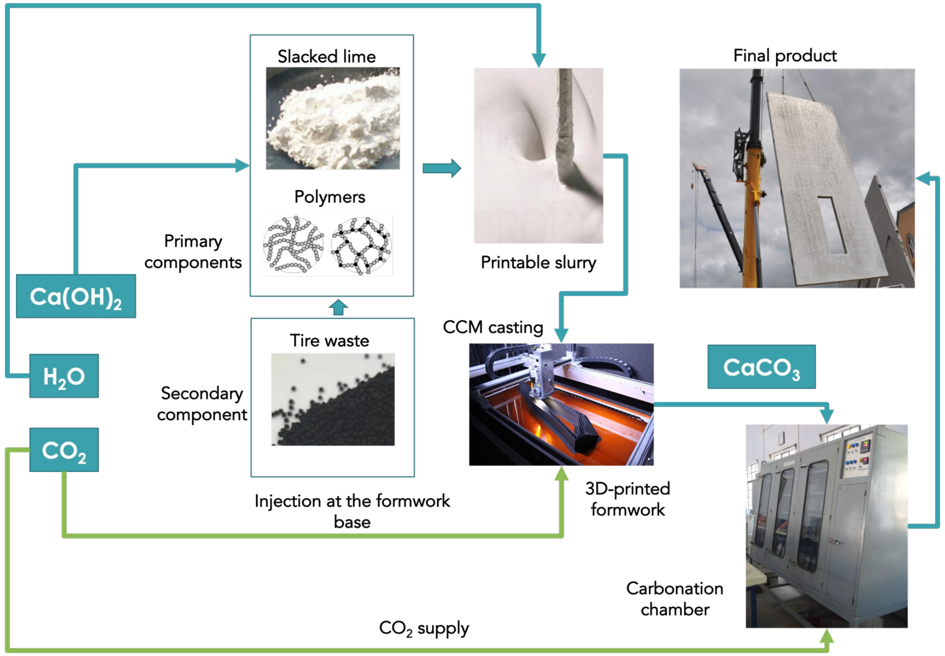
- Develop an **alternative concrete** that captures CO_2 for its strength gain

Objectives

- Complete characterization of material
- Improve carbonation degree to at least 70%
- Fabricate a CO_2-injecting-formwork for precast panels
- Upscale material development
- Complete fabrication of a thin precast wall panel

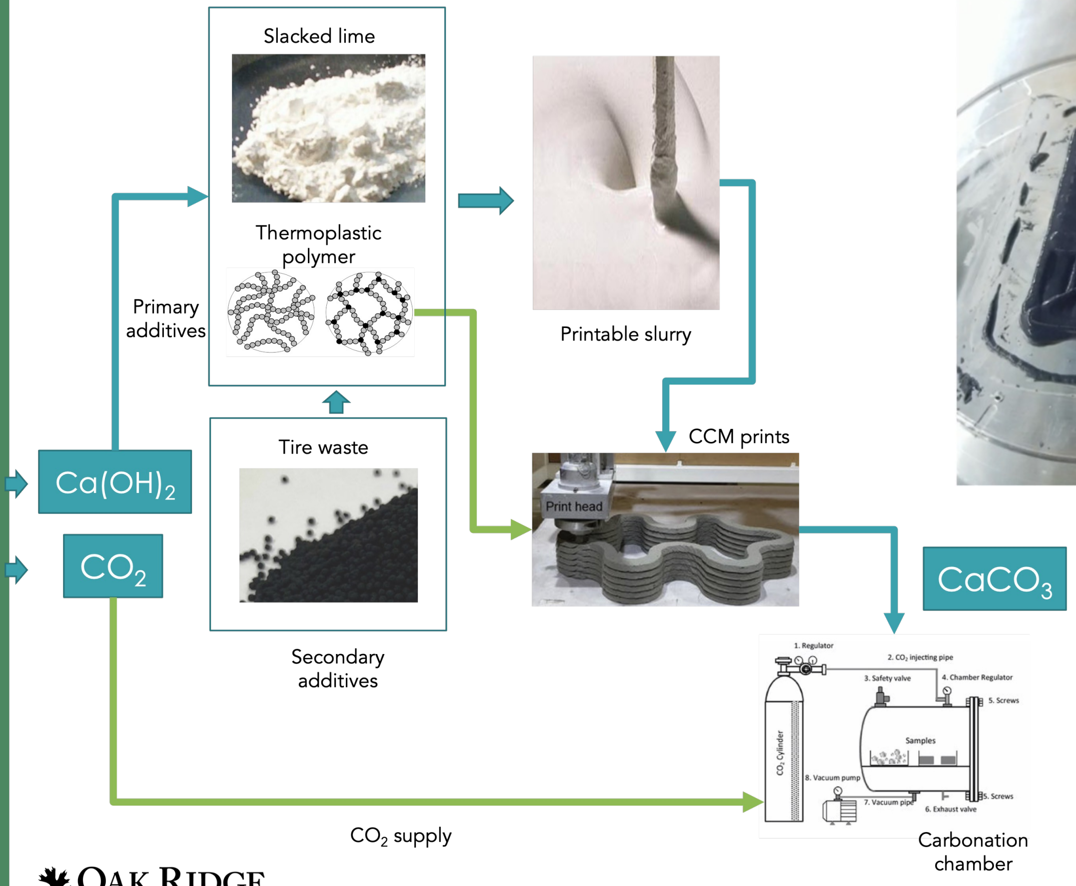
Impacts

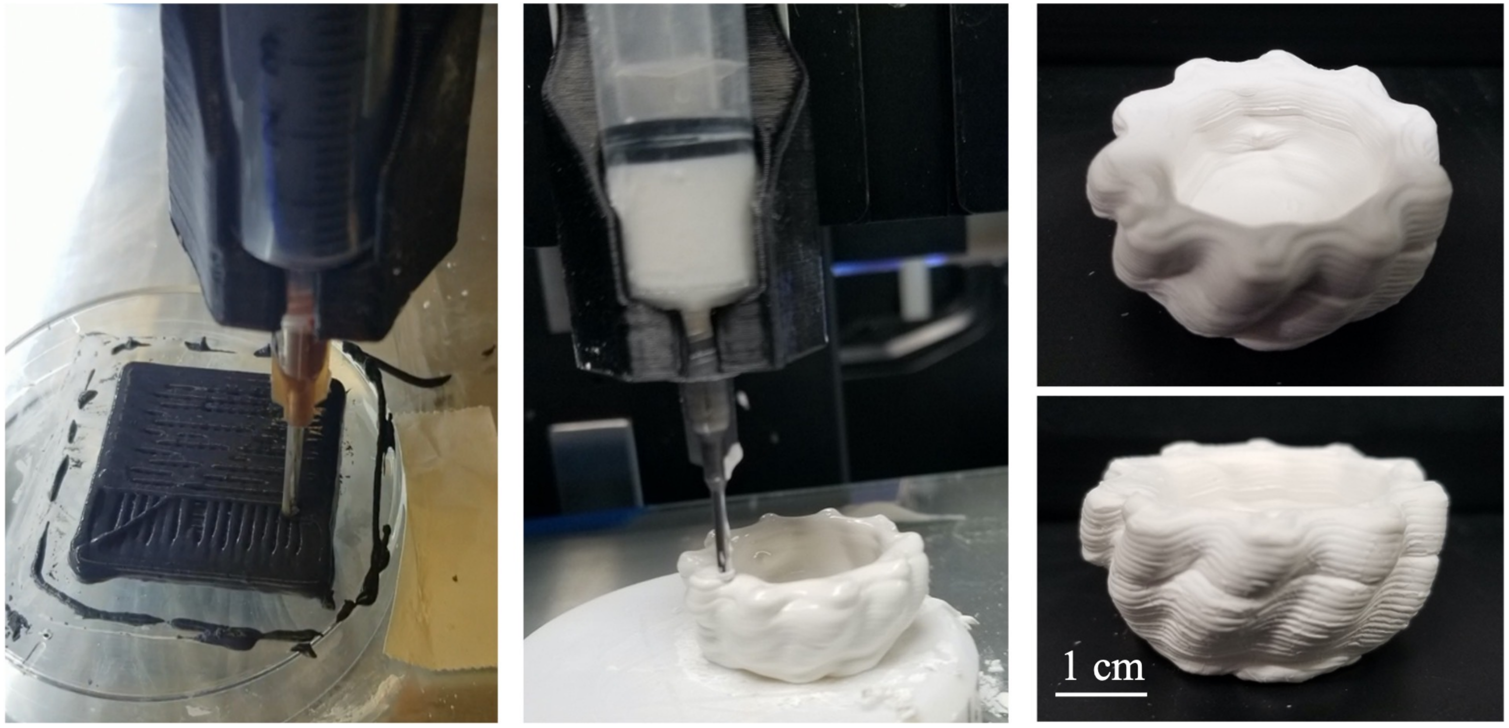
- The potential **change the cement industry** by replacing a significant share of the Portland cement production
  - → ~800 kg CO_2/ton of cement vs ~460 kg CO_2/ton of quicklime
- Proof of concept already achieved a degree of carbonation of ~57%



- Parent project: 6-month, internally funded project from discussion with Prof. Sant from UCLA.
- MoU ORNL/UCLA

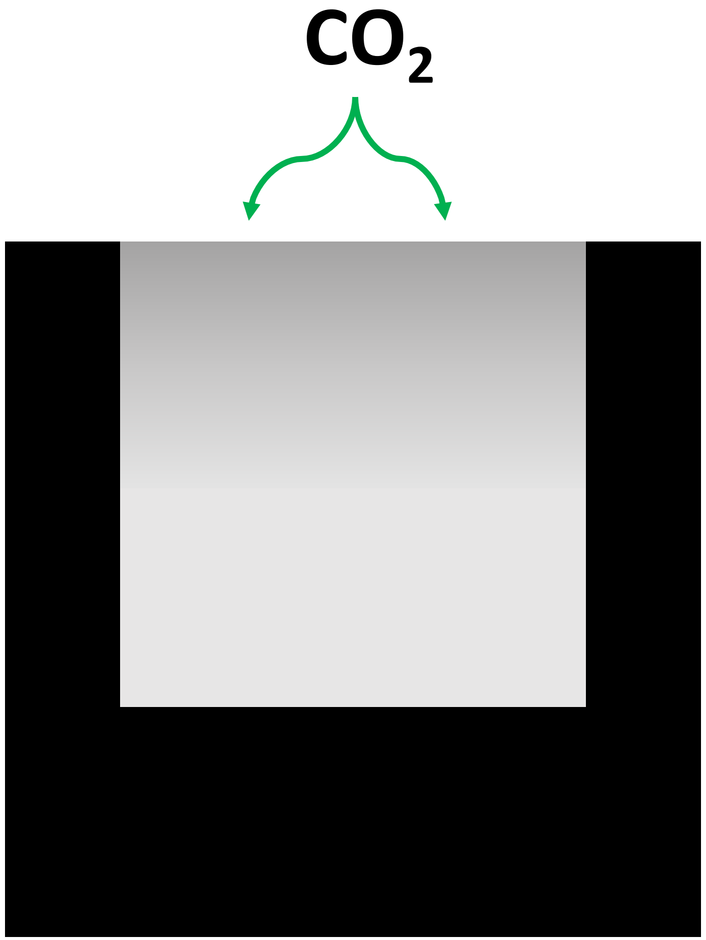
Additive manufacturing of carbonated lime





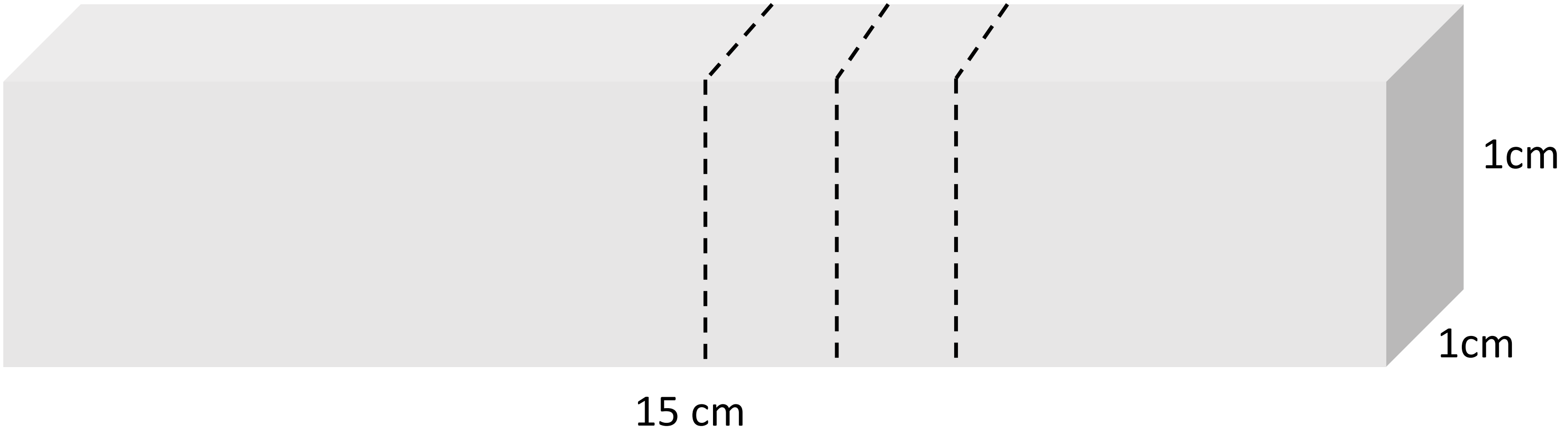
→ Small scale extrusion was achieved

Characterization: Initial results



Mold

Sample dimensions



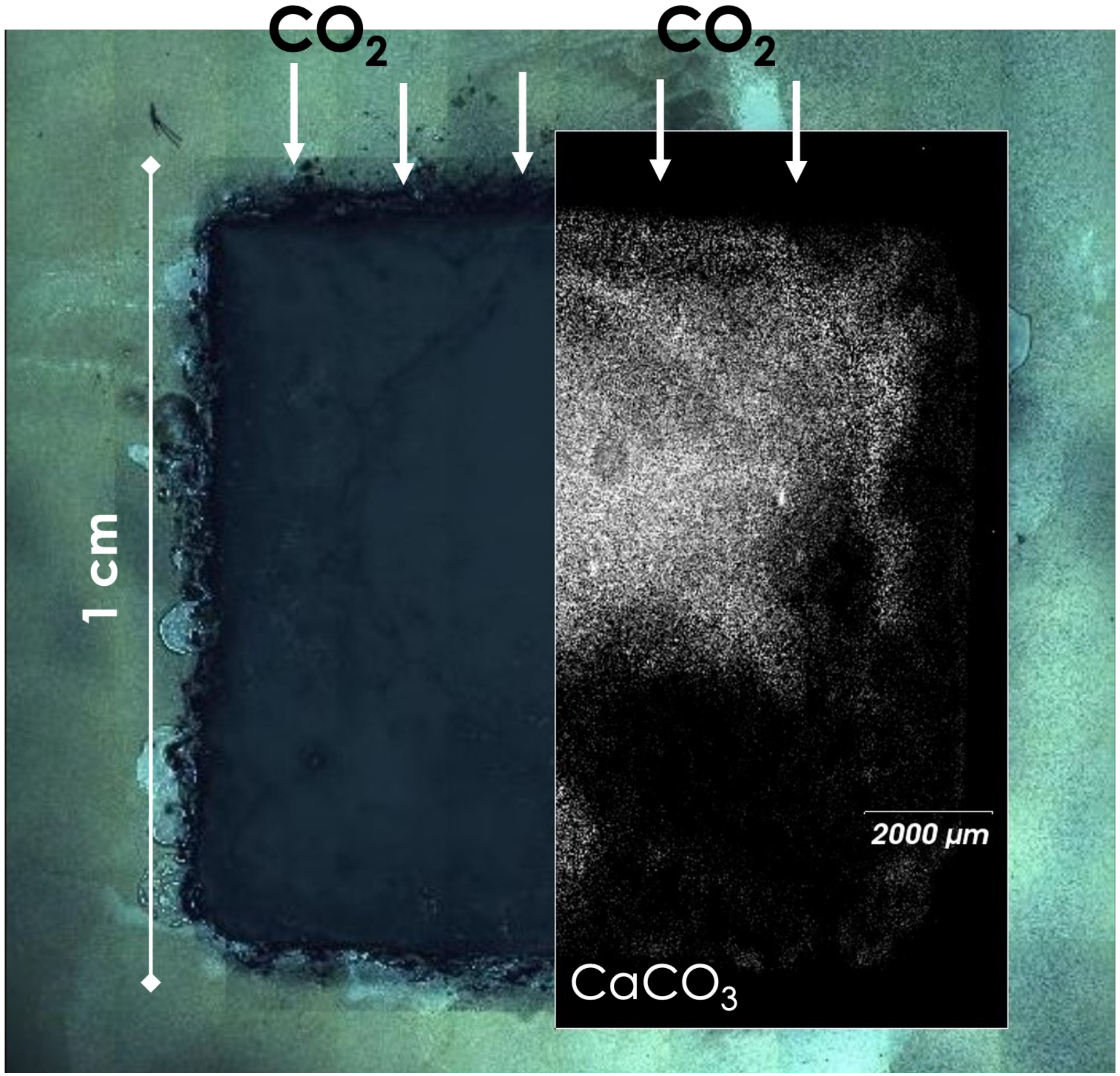
Characterization: Initial results

- XRD at difference ages
- More carbonation with PEI than with PVA after a week
  - Barely no change in carbonation from 1 day to 1 week with PVA
- After 1 week not only calcite forms in the presence of PEI, but also aragonite

Sample	Calcium hydroxide (weight %)	Calcite (weight %)	Aragonite (weight %)	Vaterite (weight %)	Total Carbonate (weight %)
PEI_4.5%_8h	97.8 ± 0.01	2.23 ± 0.02			2.23
PEI_4.5%_1d	92.0 ± 0.01	6.14 ± 0.03	1.84 ± 0.03		7.98
PEI_4.5%_1w	6.92 ± 0.04	66.4 ± 0.02	11.10 ± 0.09	15.6 ± 0.01	93.1

Characterization: Initial results

- Sample with 4.5 % PVA
- Raman map of $CaCO_3$ after 1 day of carbonation
- CO_2 from top down
  - Carbon has penetrated about 50% of the sample
  - Still, lots of unreacted $Ca(OH)_2$



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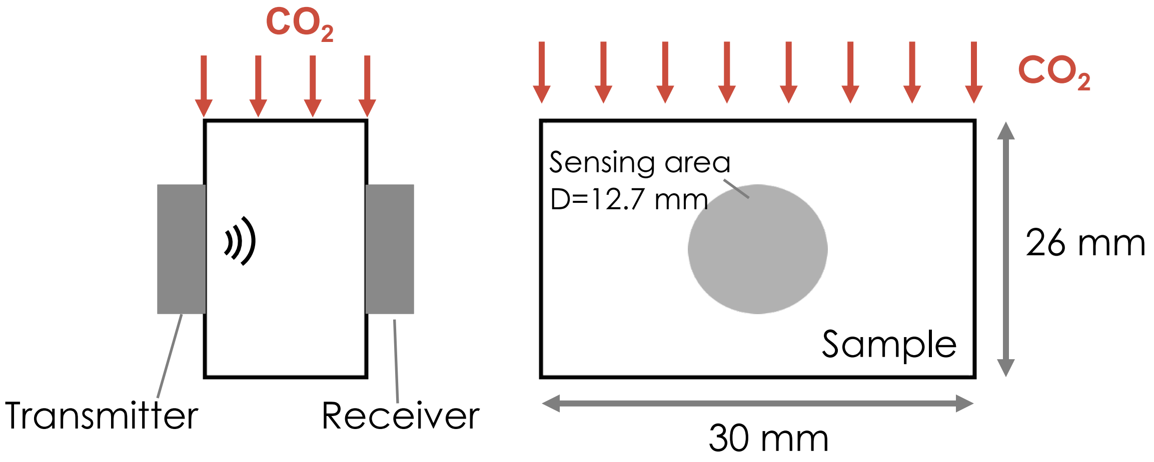
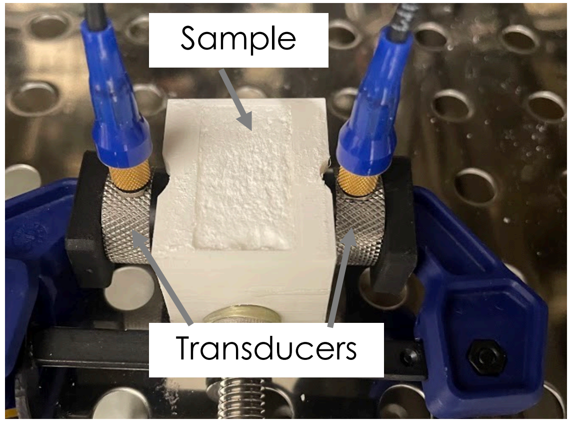
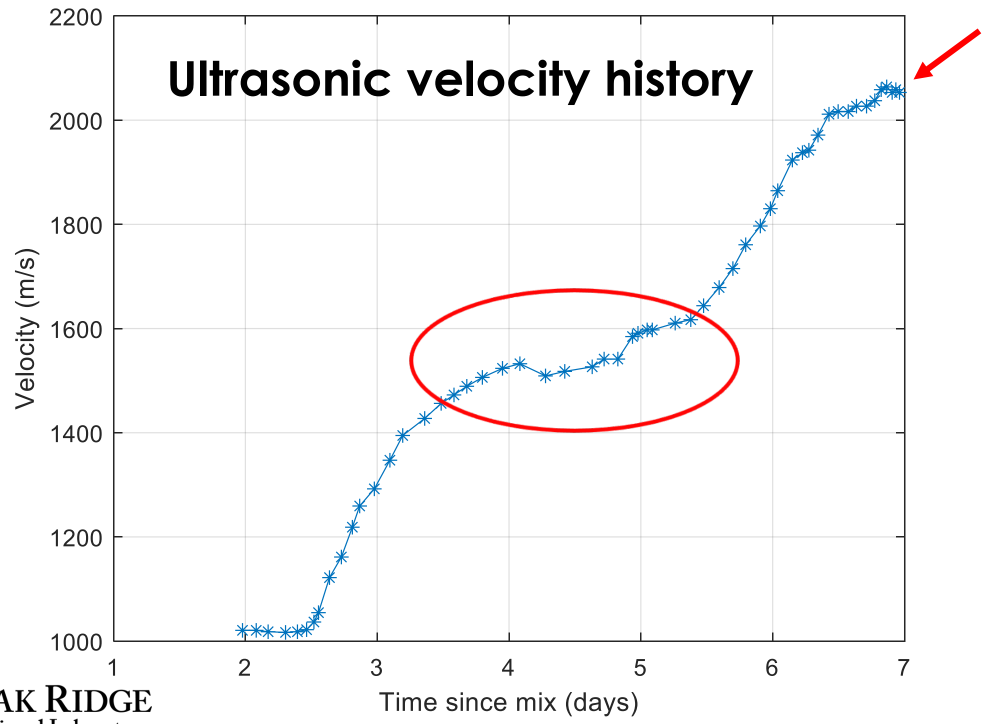
Ultrasonic monitoring of $Ca(OH)_2$ with 4.5% PVA



- Temp: 30 ℃
- CO_2: 20%
- RH: 40%





E=10.33 GPa

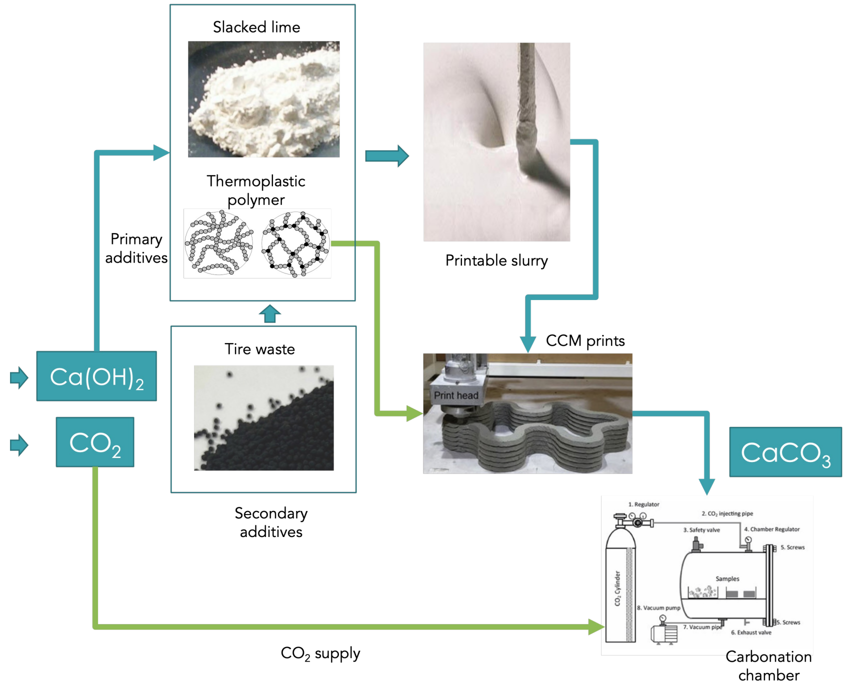
G=4.21 GPa

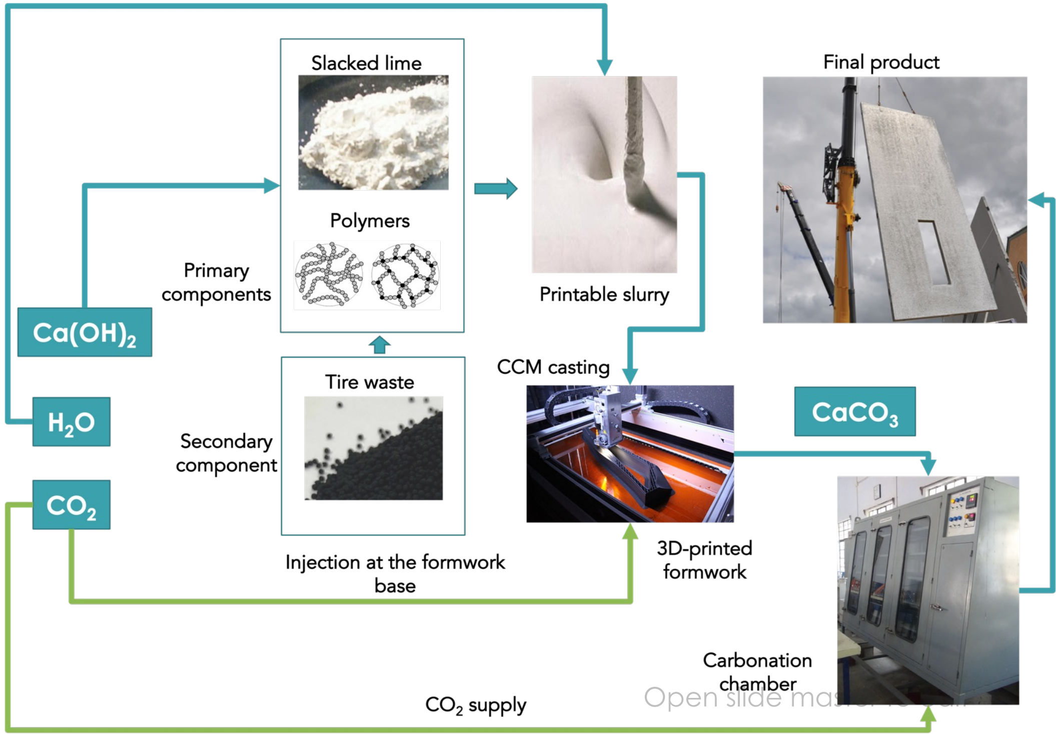
ν=0.228

- Not straightforward
- Multiphysics phenomenon
  - Water evaporation
  - CO_2 transport
    - Dissolution
    - Diffusion
    - Mineralization

Summary and Outlook

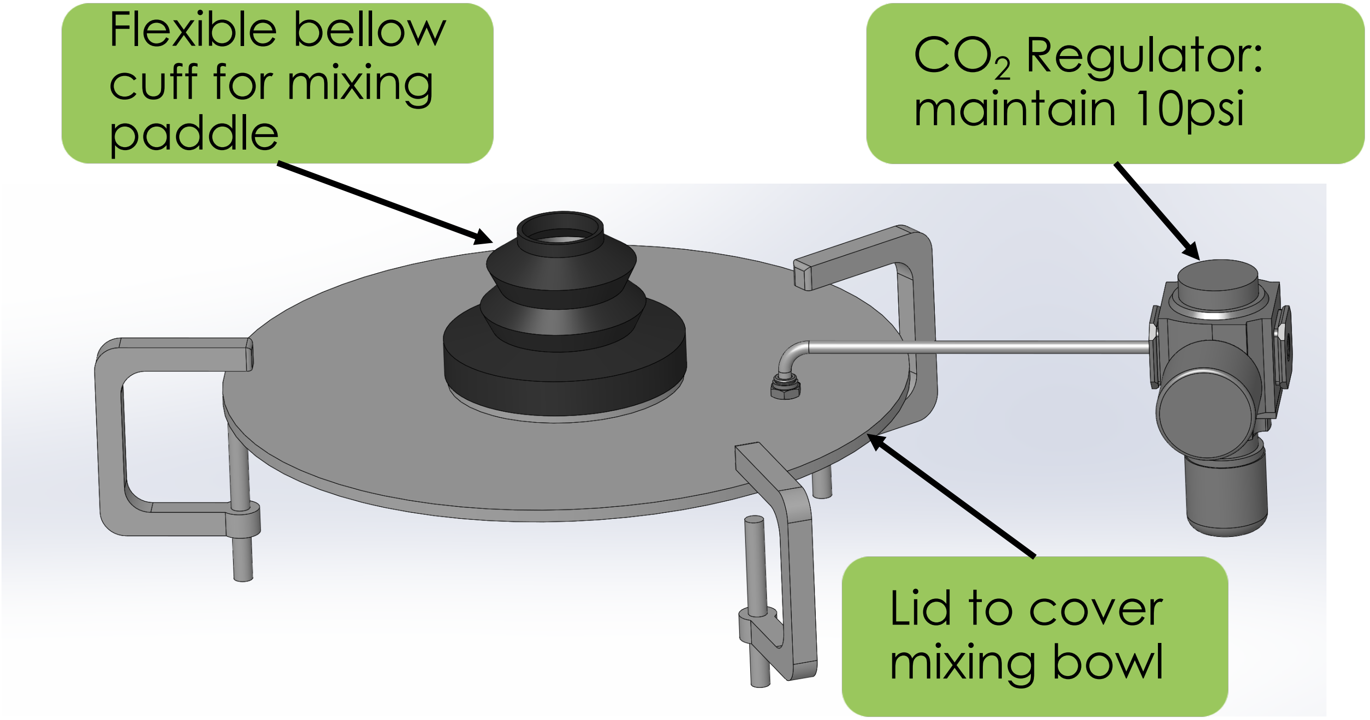
- Successfully demonstrated the printability and the carbonization potential of polymer-enhanced $Ca(OH)_2$ slurries using a lab-scale printer
- Larger scale needs to be tested
- Different polymers and slurry formulations are being investigated
- CO_2 injection during mixing will be tested



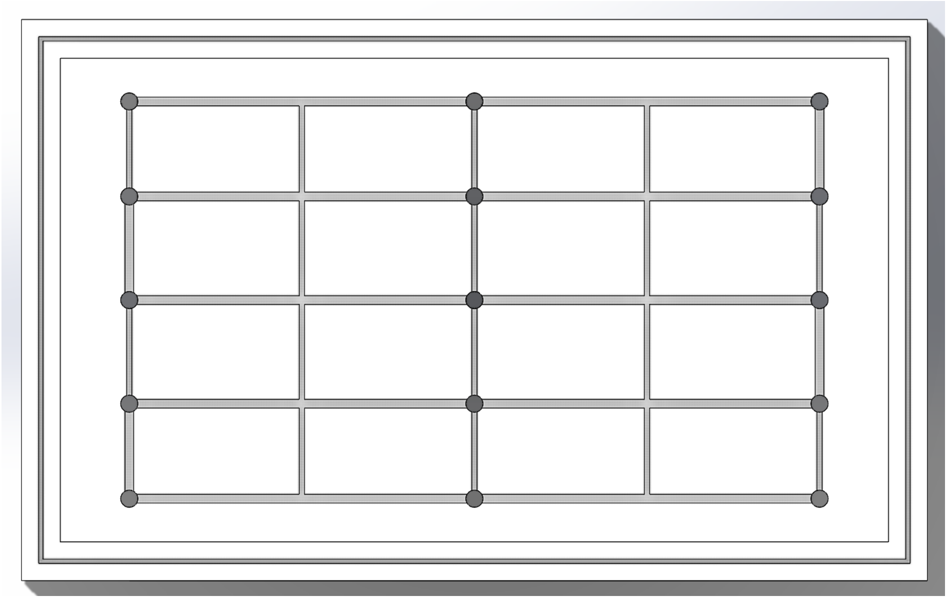


CO_2 injection during mixing

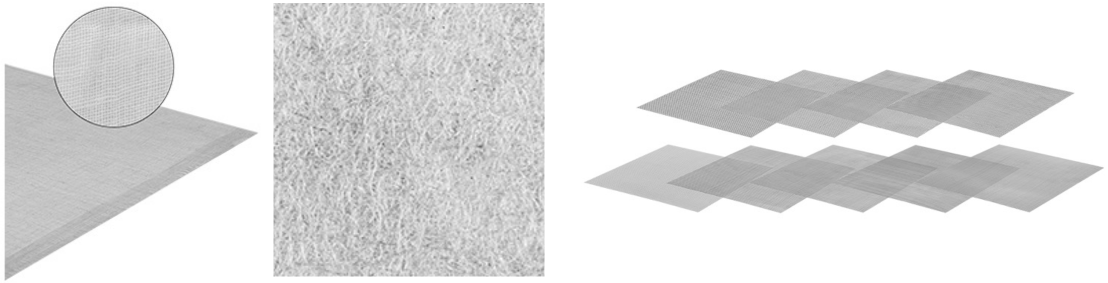
Test initial design: Hobart mixer → Expand and iterate → Confirm result and investigate other mixers



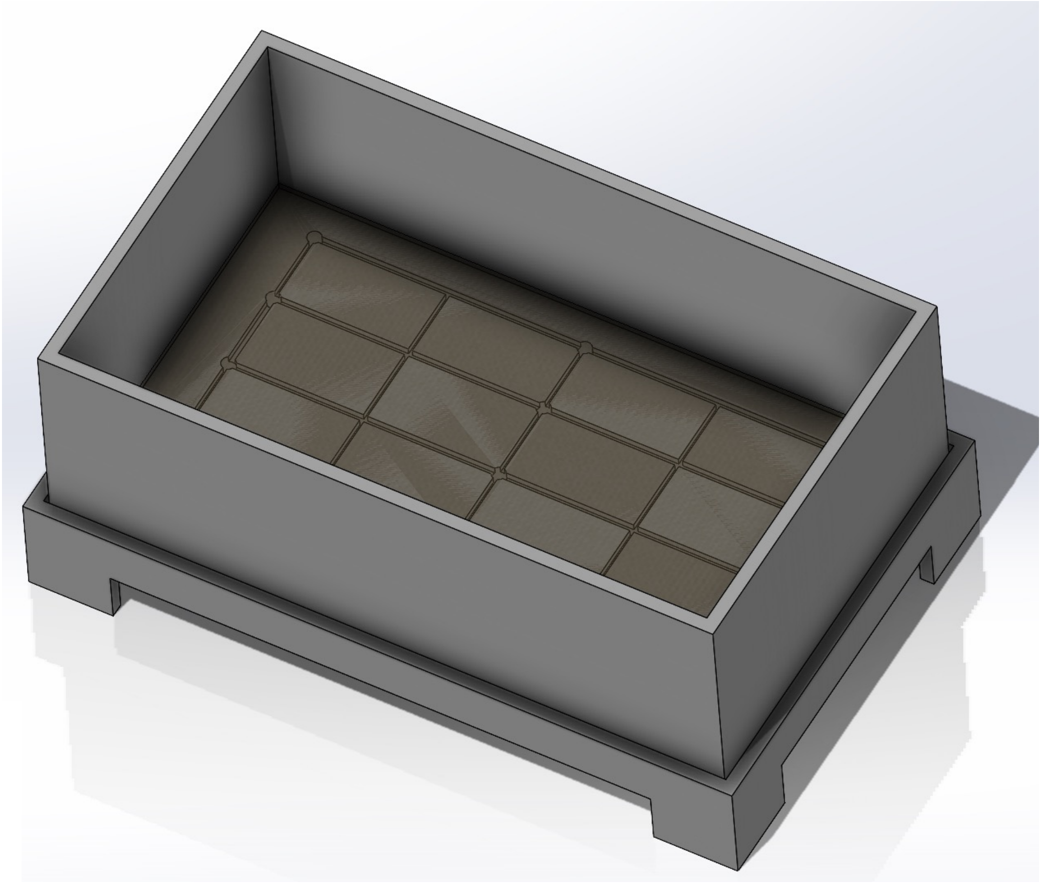
CO_2 Distribution Mold



Distribution grid linking holes



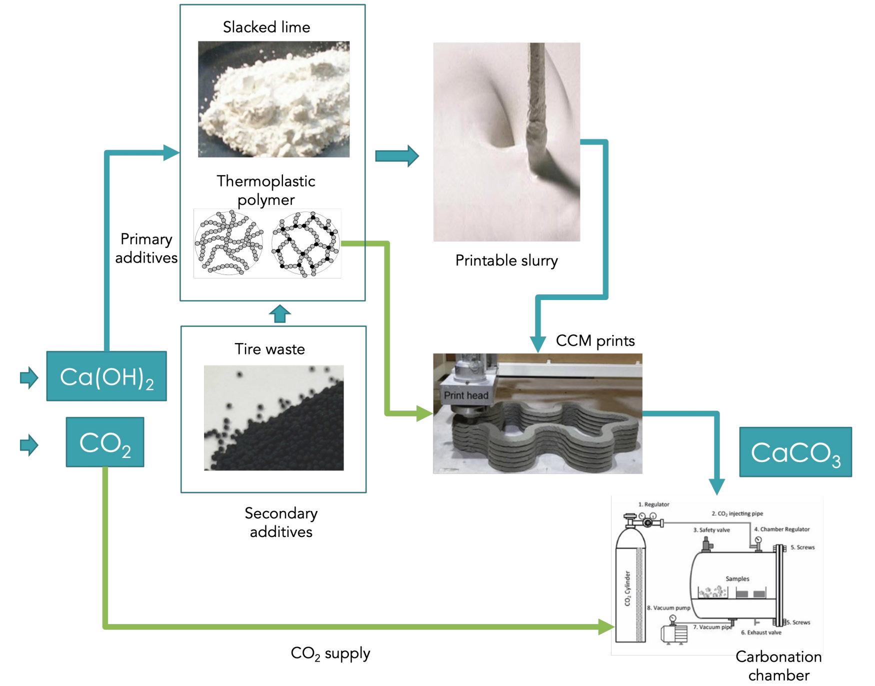
Several types to be tested

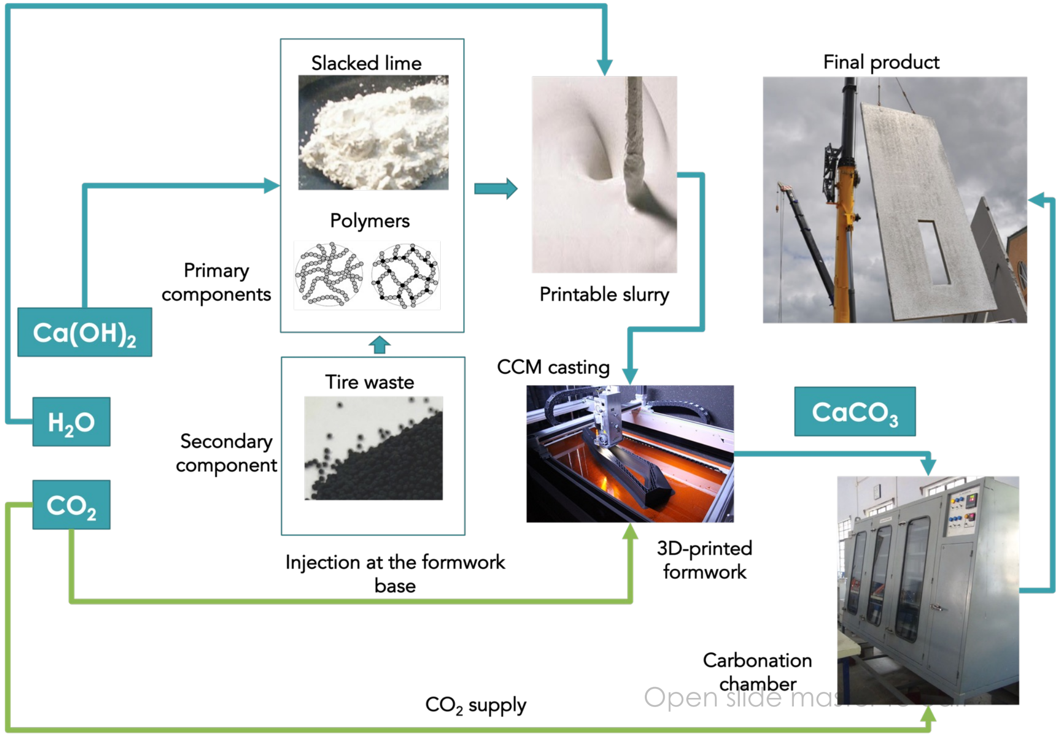


Fabric or mesh over the distribution grid

Summary and Outlook

- Successfully demonstrated the printability and the carbonization potential of polymer-enhanced $Ca(OH)_2$ slurries using a lab-scale printer
- Larger scale needs to be tested
- Different polymers and slurry formulations are being investigated
- CO_2 injection during mixing will be tested
- How does the polymer affect the mineralization of CO_2?
- How does the formed calcite interact with the tire waste?





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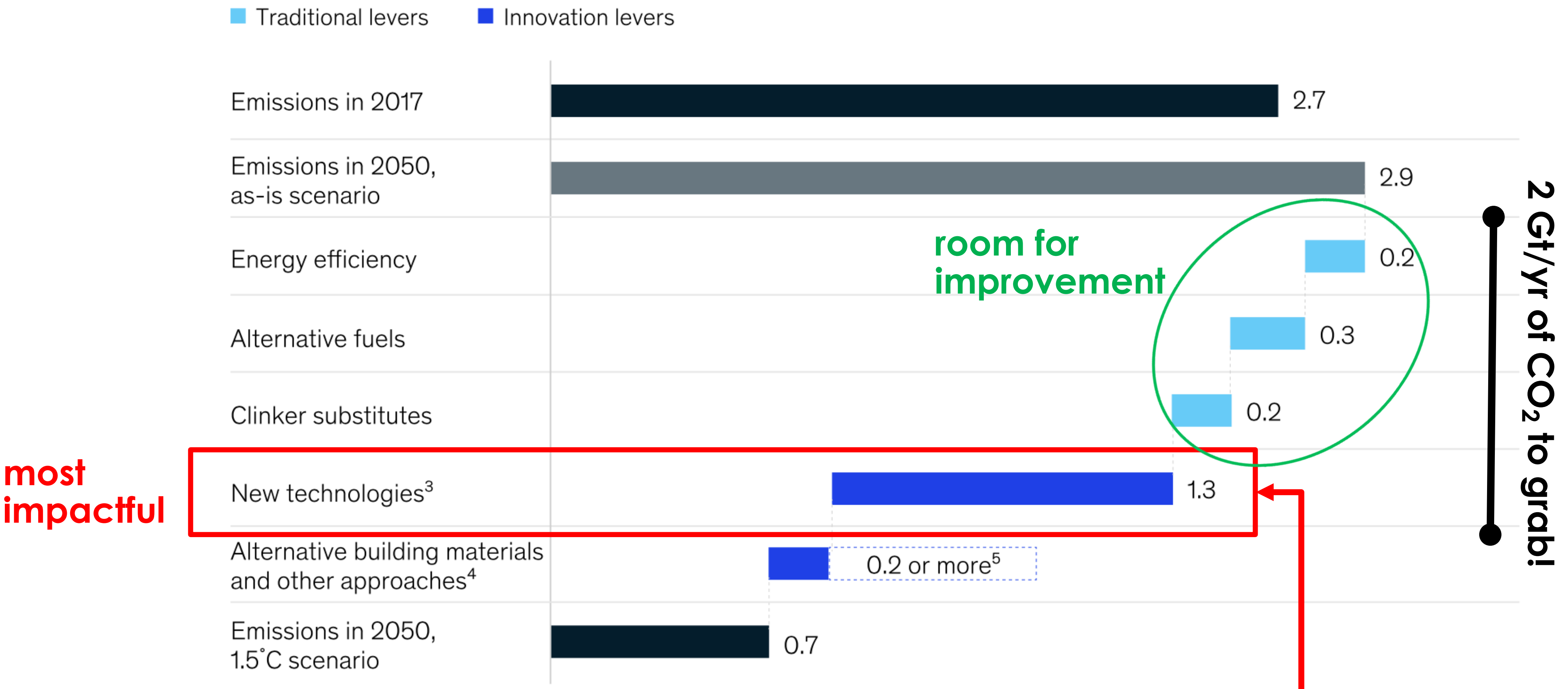
Final observations

The cement industry could cut three-quarters of its CO_2 emissions by 2050.[1]

Potential CO_2 emissions and reductions,[2] $GtCO_2$ anually



[1] Figures are global estimates for emissions potential, taking all potential levers into consideration.
[2] Effect might be smaller or larger depending on speed of shift.
[3] For example, carbon capture, use, and storage; carbon-cured concrete; 3-D printing.
[4] For example, cross-laminated timber, lean design, prefabricated/modular construction, building information modeling.
[5] Alternative building materials and other approaches will likely play an important role in decarbonizing the cement industry, but a great deal of uncertainty remains as to how much they will reduce emissions.

Source: "Getting the numbers right," Global Cement and Concrete Association, 2017, gccassociation.org; *Global Cement*, fifth edition, Freedonia Group, May 2019, freedoniagroup.com; *The Global Cement Report*, 13th edition, CemNet, cemnet.com; Umweltbundesamt (German Environment Agency); McKinsey 1.5-degree-pathway model; McKinsey Cement Demand Forecast Model

Source: https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

r to edit

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Thank you for your attention!

Co-investigators and Contributors: Yann Le Pape, Qiyi Chen, Craig Bridges, Michael Lance, Xiao-Guang Sun, Celeste Atkins, Hongbin Sun, Adam Brooks, Elena Tajuelo Rodriguez, Parans Paranthaman, Rigoberto Advincula