A Scalable Process for Upcycling Carbon Dioxide (CO_2) and Coal Combustion Residues into Construction Products

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Agreement Number: FE0031718
https://netl.doe.gov/project-information?p=FE0031718

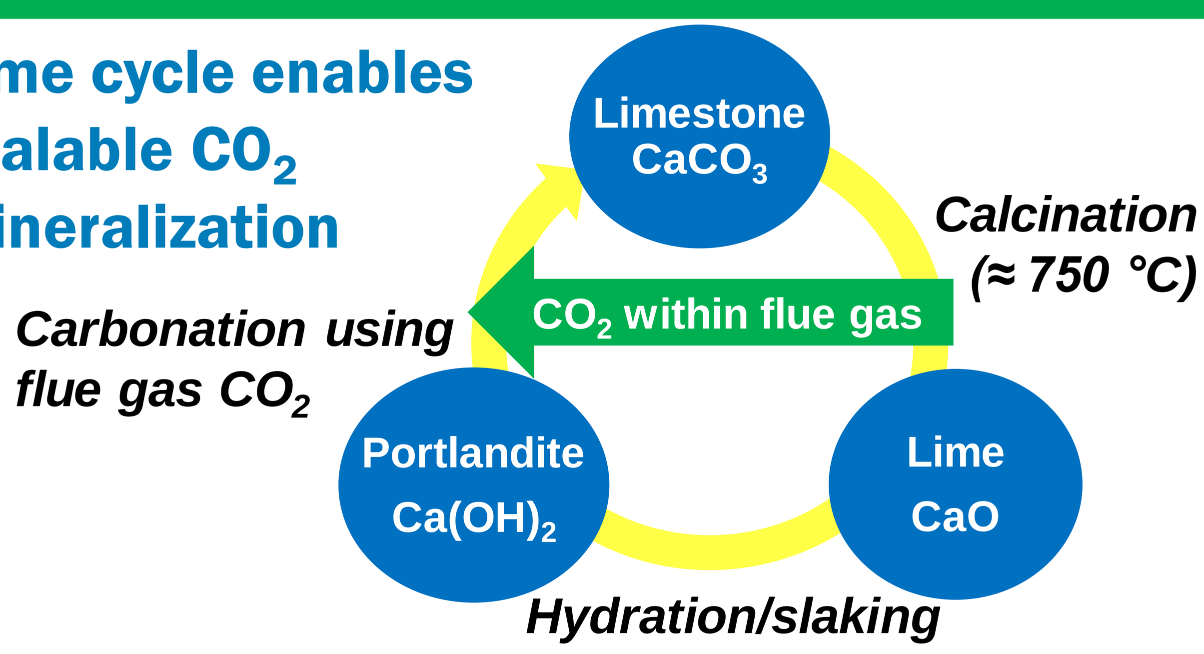
Motivation and project objectives

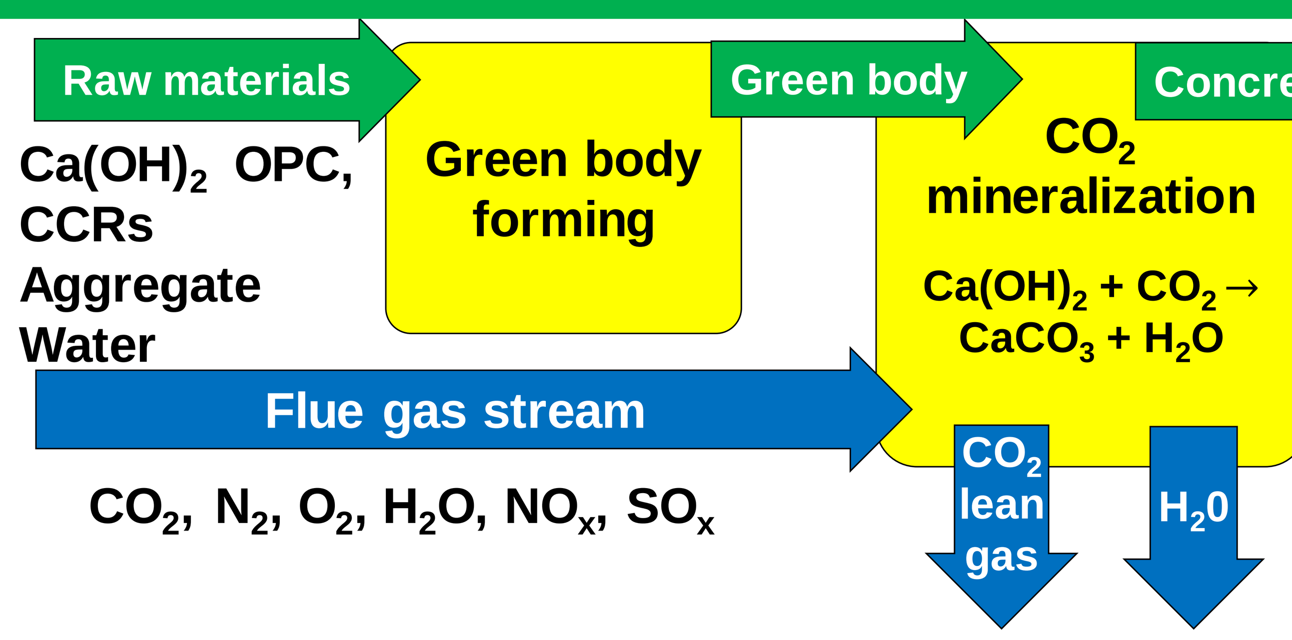
The problem at hand – CO_2 emissions from cement/concrete: Concrete, a mixture of portland cement, aggregate, and water is indispensable in construction (> 30 billion tons produced / year). But nearly 1 ton of CO_2 is emitted for each ton of portland cement produced (> 4 billion tons / year). As the vast concrete market provides an impactful sink for CO_2 emissions, the CO_2 mineralization process can enable scalable and cost-effective decarbonization in construction.

1. ***Upcycle industrial wastes and CO_2* –** Produce low-carbon CO_2Concrete products from coal combustion residues, flue gas CO_2, and low-grade waste heat
2. ***Design CO_2 mineralization system* –** Develop process models to inform scale-up design of a "bolt-on" system at coal-fired power plants
3. ***Field test system using real flue gas* –** Fabricate and field test CO_2 mineralization system to capture around 100 kg of CO_2 per day from coal-fired flue gas
4. ***Product compliance* –** Ensure CO_2Concrete product compliance with industry standards; demonstrate potential utilization in construction applications

Process flow for developing low-carbon concrete by CO_2 mineralization

Lime cycle enables scalable CO_2 mineralization





Concrete masonry unit (CMU)

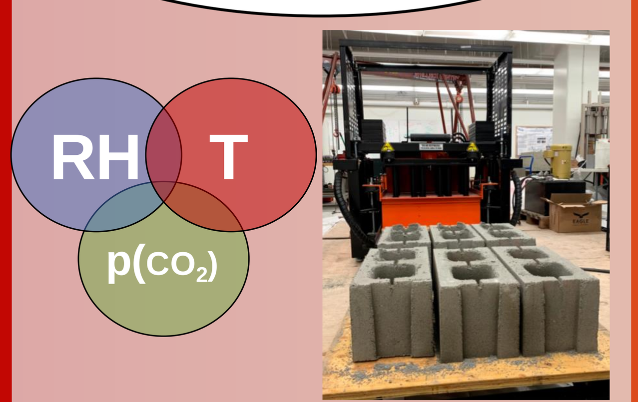
Hollow-core slabs

Topology-optimized 3D-printed beams

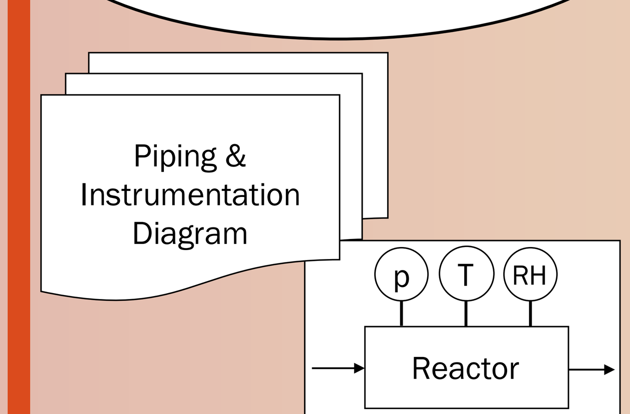
- Portlandite ($Ca(OH)_2$) is a highly efficient reactant for CO_2 mineralization (CO_2 uptake 0.59 g/g) that is also abundant and near cost parity to cement
- Carbonation occurs rapidly at ambient temperature and pressure without carbon capture step, pressurization or gas clean-up (insensitive to SOx and NOx)
- "Green bodies" are shape-stable components that are exposed to flue gas in a carbonation reactor
- Process is flexible: Simple integration at any CO_2 emissions source ("stack-tap") which enables co-location and low-cost processing

Project overview and milestones

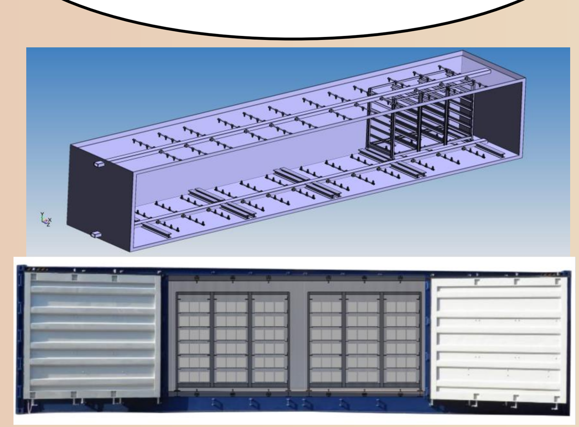
Bench-scale experiments for design inputs



Process design development



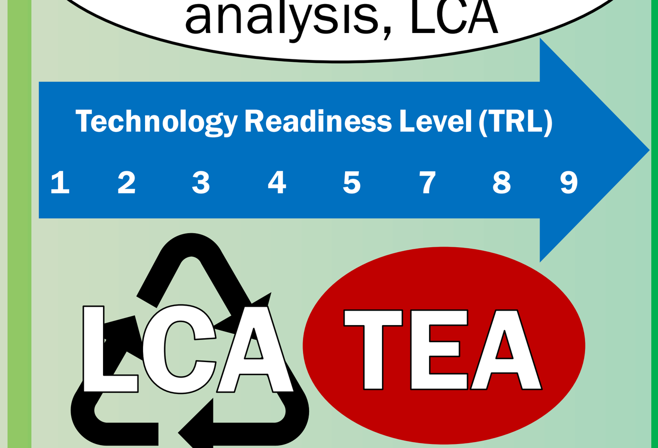
System fabrication



System installation and commissioning

Field testing of mineralization system

Design scaling, technoeconomic analysis, LCA



Carbonation kinetics, system performance, and product compliance

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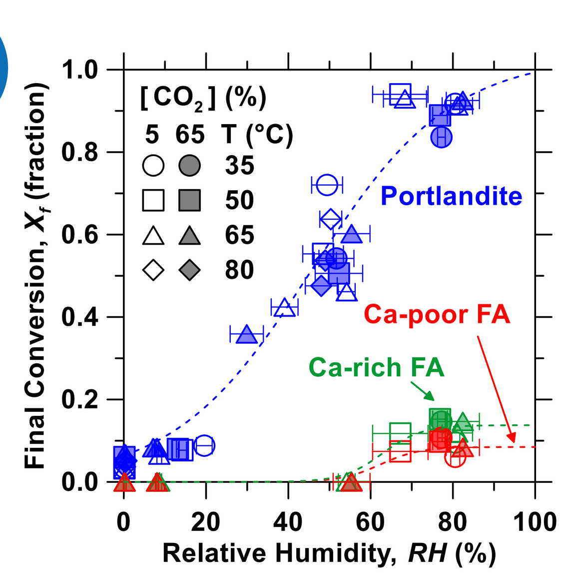

Portlandite carbonation at dilute CO_2 concentrations:

- Reaction kinetics are largely independent of CO_2 concentration for flue gas concentrations (≥ 2 %)
- Activation energy is rather low: initial surface reaction (3 kJ/mol) and (22 kJ/mol) when transport barriers may form; confirming that no pressurization, CO_2 enrichment, or significant heating required for portlandite carbonation

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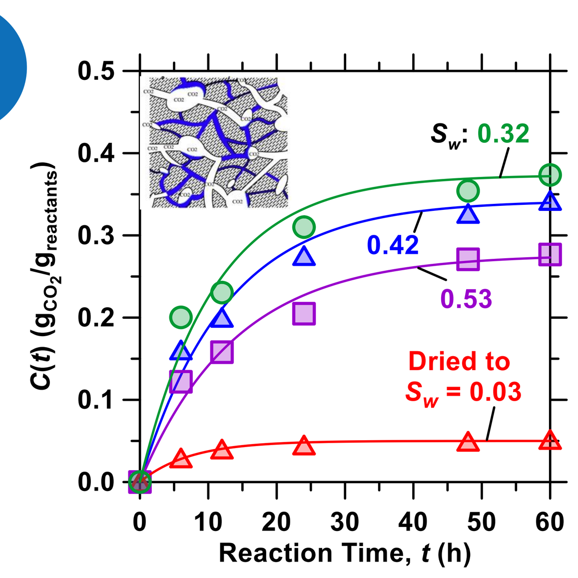

Effects of microstructure and pore saturation on carbonation:

- CO_2 diffusion through pore structure limits reaction rates which scales with scale with body's moisture diffusivity
- Liquid water saturation (S_w) in porous cementing microstructures influences carbonation kinetics; S_w ≈ 0.1 - 0.2: critical level for CO_2 uptake

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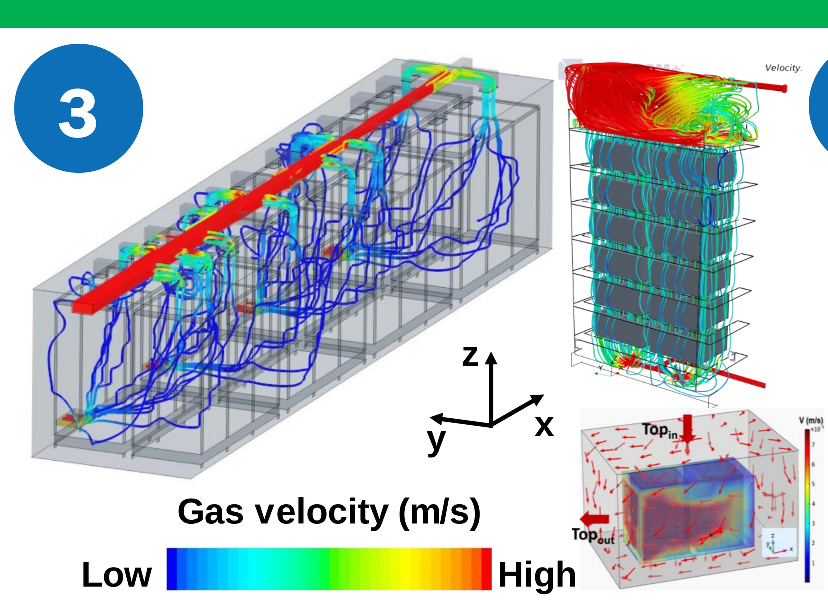

Computational fluid dynamics (CFD) modeling for reactor design:

- Performed CFD to inform design of flue gas handling and distribution equipment within the CO_2 mineralization reactor
- Spatial distribution of CO_2 uptake is significantly affected by gas flow configuration. Greater gas velocity and homogeneity offer higher CO_2 uptake

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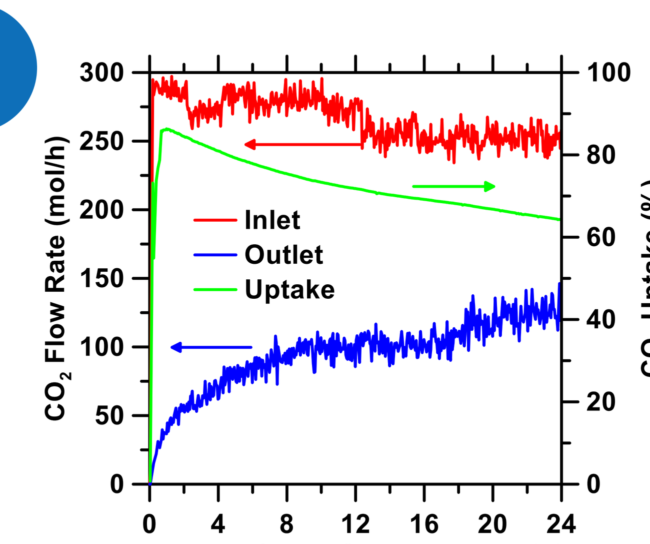

Pilot scale system demonstration at Integrated Test Center, Wyoming:

- Produced around ~200 tonnes of CO_2Concrete blocks over 12 demonstration runs that featured nearly 4 tonnes of CO_2 uptake
- System performance fulfilled all design specifications: (1) achieved in excess of 75% CO_2 utilization efficiency and (2) utilized greater than 250 kg of CO_2 per 24-h run

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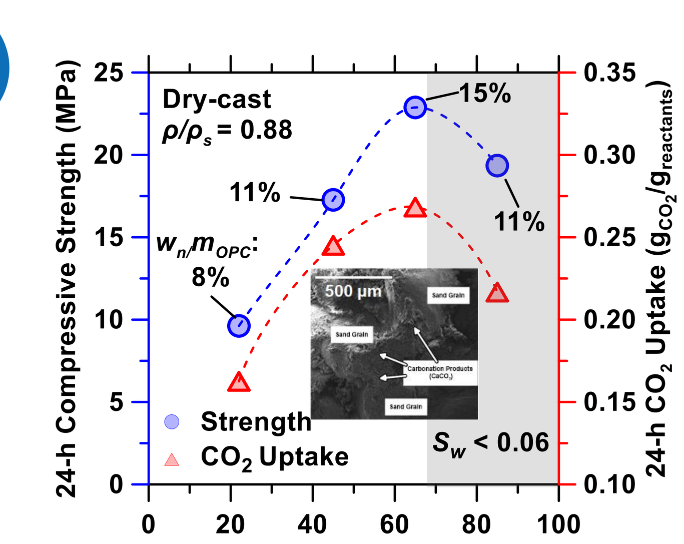

Performance of CO_2Concrete products:

- CO_2Concrete products complied with industry standard specifications: strength > 13.8 MPa and water absorption < 208 kg/m^3
- Preliminary lifecycle analysis (LCA) indicated ~ 65 % CO_2 emissions reduction relative to conventional CMUs

References

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