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

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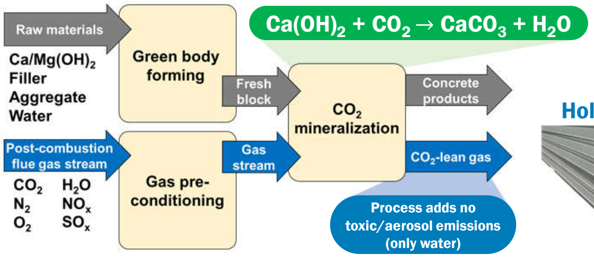
Motivation and project objectives

Concrete, a mixture of portland cement, aggregate, and water is indispensable in construction (> 30 billion tons produced / year).[A] But nearly 1 ton of CO_2 is emitted for each ton of portland cement produced (> 4 billion tons / year),[A] accounting for around 8 % of global CO_2 emissions.[B] The vast concrete market provides an impactful sink for CO_2 emissions, which may be fixed within solid products by thermodynamically favorable CO_2 mineralization reactions.

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*** – Produce data supporting heat and mass balances for design of a "bolt-on" system at coal-fired power plants
3. ***Field test system using real flue gas*** – Fabricate and field test a CO_2 mineralization system to consume about 100 kg of CO_2 per day from coal flue gas

CO_2 mineralization process



$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Process adds no toxic/aerosol emissions (only water)

Low-carbon concrete products

Concrete masonry units

Hollow-core slabs

Topology-optimized 3D-printed beams

Process may be tailored to produce a variety of precast concrete/concrete masonry products

Initial product is hollow-core block (concrete masonry units), which follow ASTM C90 performance criteria:

- Compressive Strength (> 13.8 MPa)
- Density (determines weight classification)
- Water absorption (< 320 kg/m^3)
- Physical appearance/dimensional tolerances

Preliminary lifecycle analysis (LCA) indicates ~ 65 % CO_2 emissions reduction relative to conventional CMU

- Portlandite (hydrated lime, $Ca(OH)_2$) is a highly efficient reactant for CO_2 mineralization (CO_2 uptake 0.59 g/g) that is also abundant and near cost-equivalent to cement
- Fillers may include coal combustion residues (CCRs) such as ASTM C618 non-compliant fly ashes, which are not typically usable in concrete mixtures
- "Green bodies" are non-strengthened, but shape-stable components that may have their surfaces exposed to flue gas to promote CO_2 mineralization reactions
- Flue gas pre-conditioning is limited to changing the temperature and/or relative humidity of the gas stream – CO_2 enrichment/capture or pressurization are unneeded

Reaction kinetics, heat/mass transfer, and component strength

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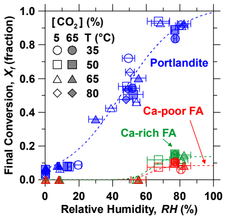

Conversion limits and kinetics of CO_2 mineralization reactions:

Process design is informed by data describing the CO_2 uptake of alkaline solids (e.g., $Ca(OH)_2$ and fly ashes (FA)) in contact with simulated flue gases of varying temperature, relative humidity (RH), and CO_2 concentration (near atmospheric pressure).[C,D,E]

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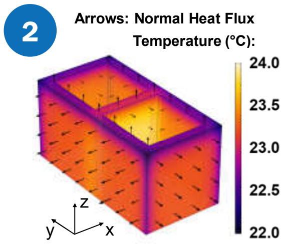

Heat generation and transfer in CO_2Concrete components:

Exothermic portlandite carbonation and cement hydration reactions generate heat that contributes to temperature rise and vaporization of water. A finite element model (FEM) is being developed to predict gradients in block properties that may result.

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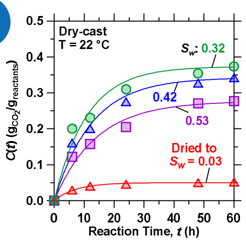

Effects of microstructure and pore saturation on carbonation:

The liquid water saturation (S_w) in porous cementing microstructures influences the rate and extent of CO_2 uptake. Reducing S_w increases CO_2 uptake until a critical limit of ≈ 0.1 is reached, below which carbonation is water-limited.[F]

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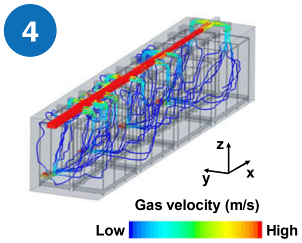

Computational fluid dynamics (CFD) modeling for reactor design:

The design of flue gas handling and distribution equipment within the CO_2 mineralization / curing chamber is informed by CFD simulations. In this way, the effects of various shelving and block arrangements on flow uniformity may be evaluated.

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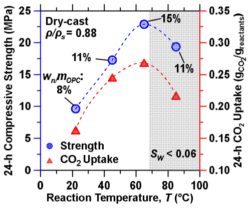
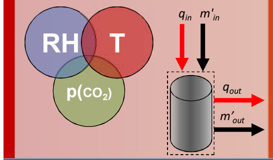


Compressive strength performance of dry-cast CO_2Concrete products:

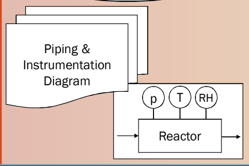
The compressive strength of concrete is a critical performance metric. CO_2Concrete formulations exceed the strength requirements of relevant product standards (e.g., ASTM C90) immediately after processing by optimizing process conditions.[F]

Project overview and milestones

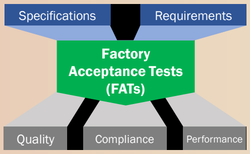
Bench-scale experiments for design inputs



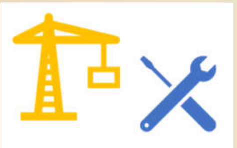
Process design and bid specification



System fabrication and FATs

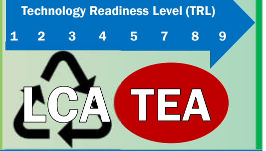


System installation and commissioning



Field testing of mineralization system

Design scaling, technoeconomic analysis, LCA



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