Achieving Unprecedented CO_2 Utilization in CO_2Concrete™: System Design, Product Development and Process Demonstration

Project Number: DE-FE0031915

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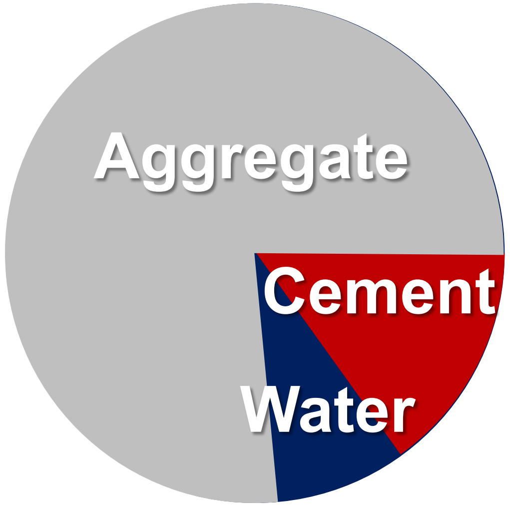
Where: Pittsburgh, PA

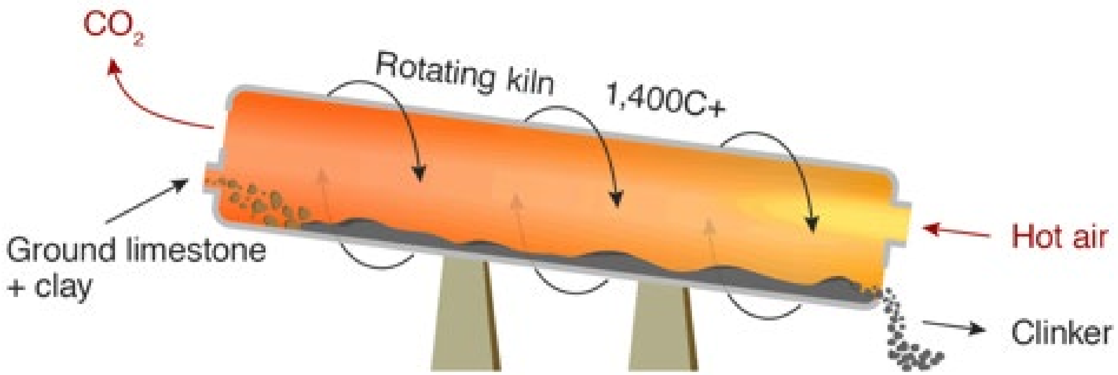
The problem at hand – CO_2 emissions from cement/concrete

- **Concrete ~ 8% of global CO_2 emissions**
  - Most widely used substance after water
  - 90% of emissions from production of cement
- **No broadly-applicable alternatives**
  - 2x the combined volume of steel, plastics, wood, aluminum
- **CO_2 curing appears promising, but…**
  - Enabling materials have been expensive or scale-limited
  - Traditionally has required concentrated and purified CO_2
- **Large-scale demonstrations needed**
  - Technology feasibility needs to be rigorously proven



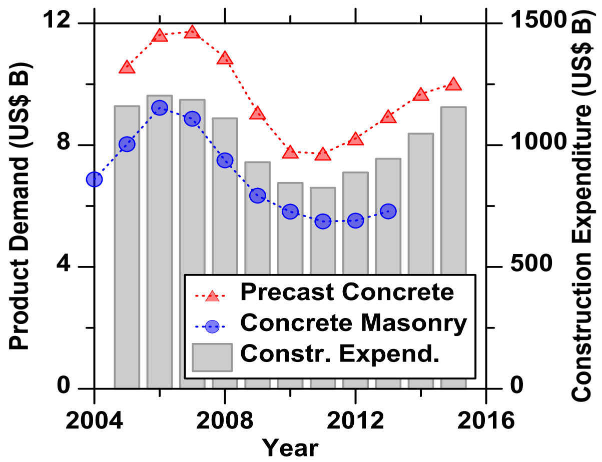
Concrete Composition (mass)

CO_2 Emissions are Inherent to Ordinary Portland Cement



Concrete construction industry

- Global concrete market ~ $ 1 trillion / year
- Ready mixed concrete has the largest market share
  - Lower construction quality, increased safety risks
- Increasing use of prefabricated concrete is a rising industry trend
- Precast concrete
  - Architectural and structural
- Concrete masonry
  - CMUs (i.e., blocks), Bricks, pavers, etc.



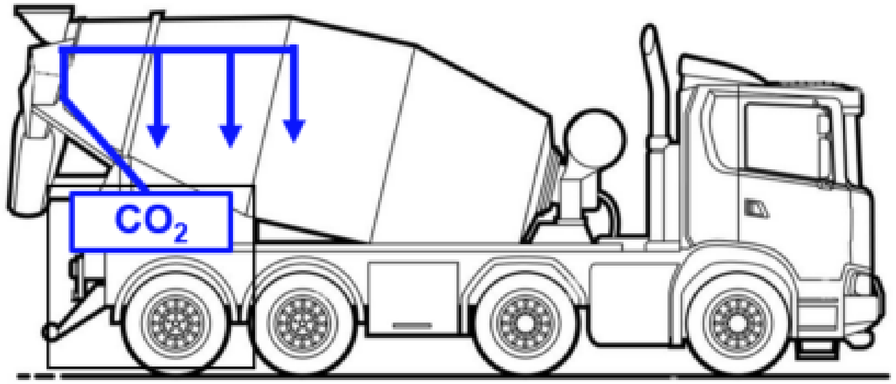
Ready-mix concrete casting on-site

Concrete Masonry Unit (CMU)

Architectural precast concrete façade

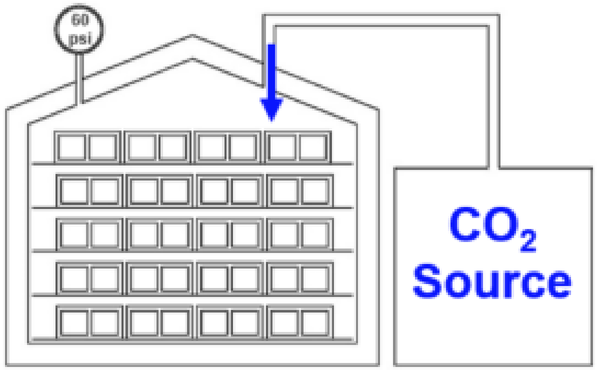
Accelerated concrete carbonation curing pathways

Carbonation during mixing

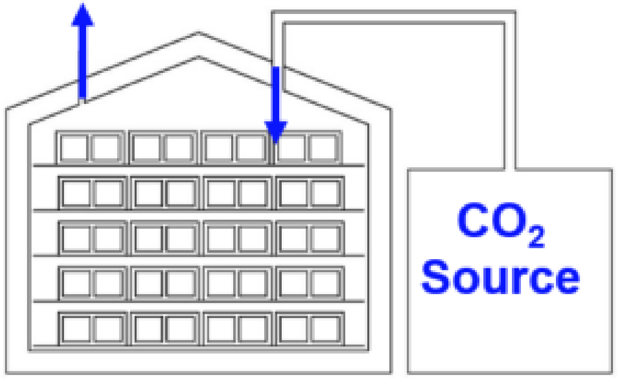


- Utilizes 100% CO_2
- Requires processing to purify CO_2
- Additional transport required to obtain CO_2

Carbonation post-forming



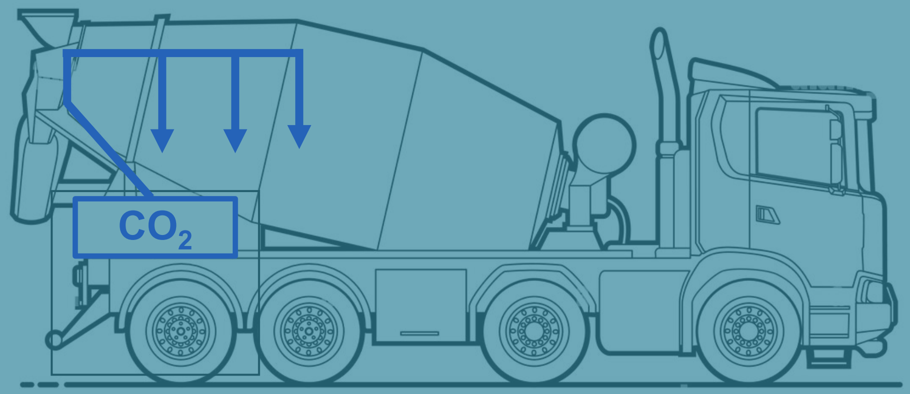
- **Pressure reactor** – CO_2 steadily released into reactor to maintain specified pressure
- Utilizes 100% CO_2



- **Flow through reactor** – uses CO_2 straight from emitter
- Requires gas processing
- Utilizes 2-100% CO_2

Accelerated concrete carbonation curing pathways

Carbonation during mixing



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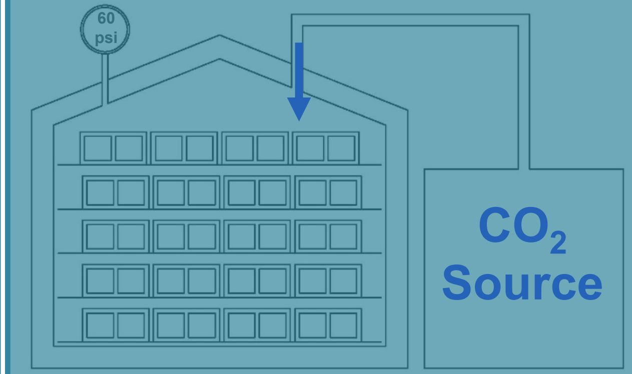

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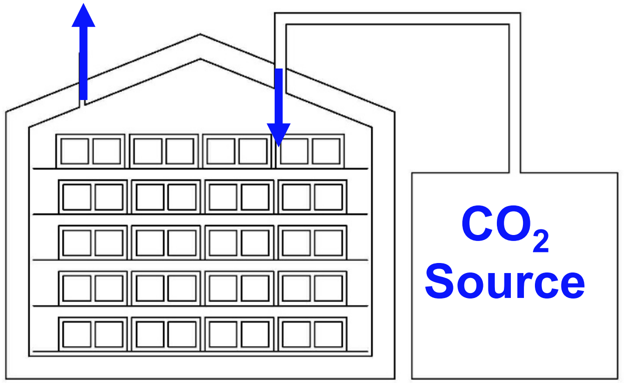

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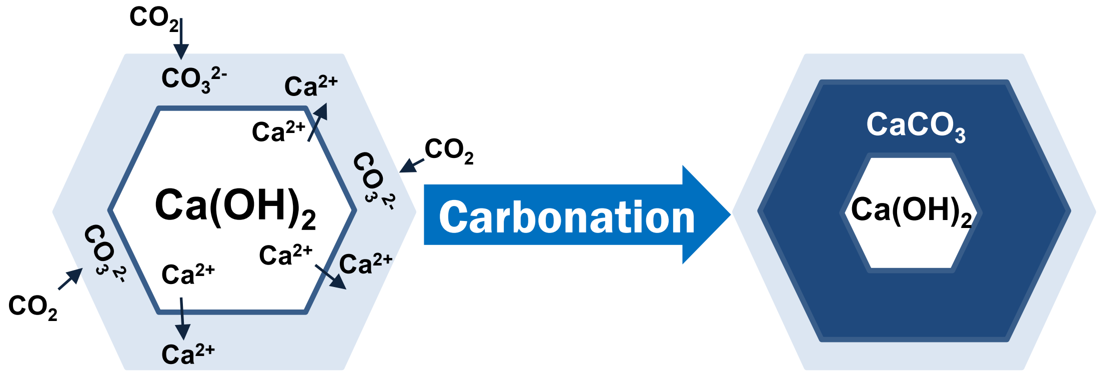
- Requires gas processing
- Utilizes 2-100% CO_2

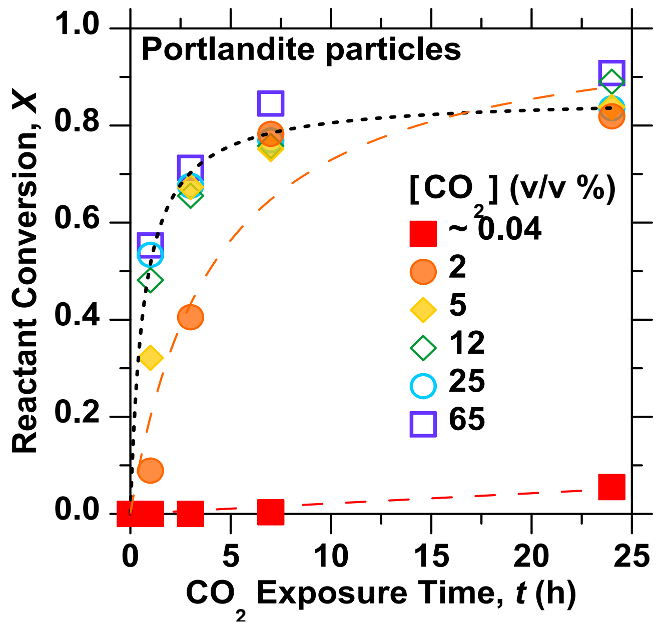
Carbonation of primary feedstock – Portlandite ($Ca(OH)_2$)



- Portlandite carbonation is key reaction in concrete carbonation

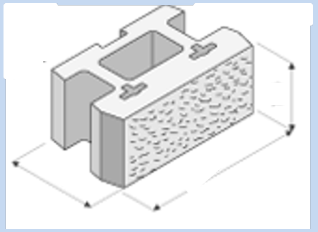
$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$$

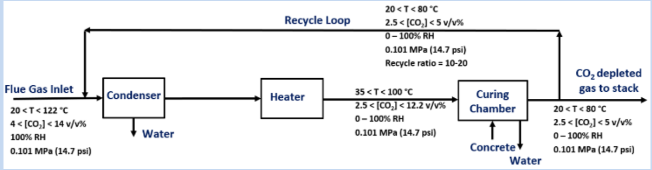
- Carbonation of portlandite particles is near-complete within 24 h
- Reaction kinetics are largely independent of CO_2 concentration for flue gas concentrations (≥ 2 %)
- **The Significance:** Pressurization, CO_2 enrichment, or significant heating is not required for portlandite carbonation

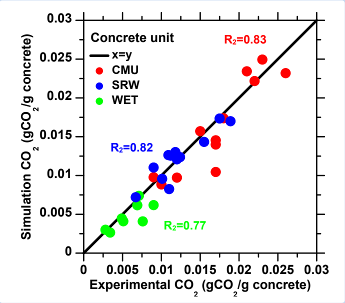


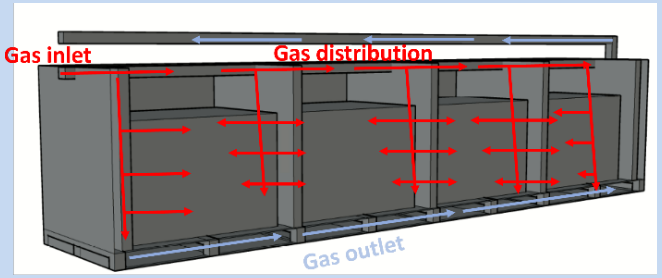
Targets for ongoing project: DE-FE0031915

- Identification of three most-preferred geometries compatible with the Reversa™ process
- Development of a process model that informs the scale-out of the process to produce diverse precast (structural) components
- Modification and validation of existing prototype
- Completion of TEA and LCA to quantify the market viability and lifecycle impact of the Reversa™ technology

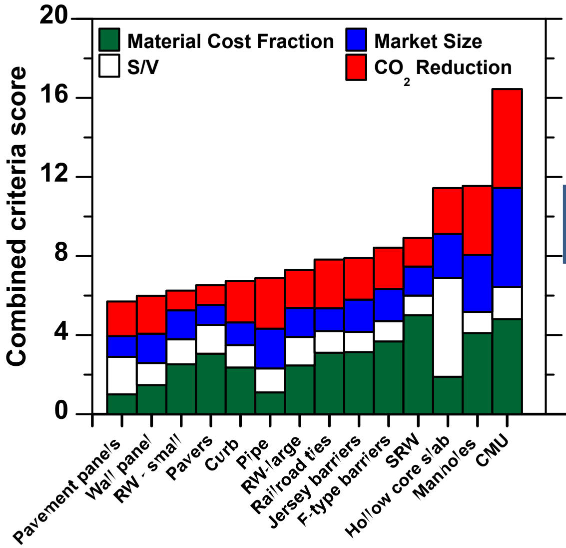



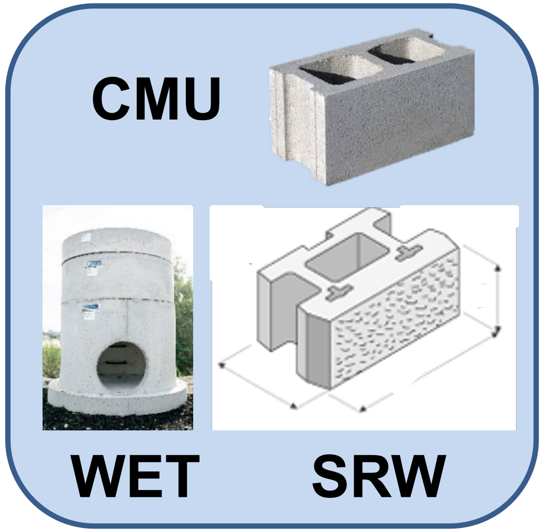




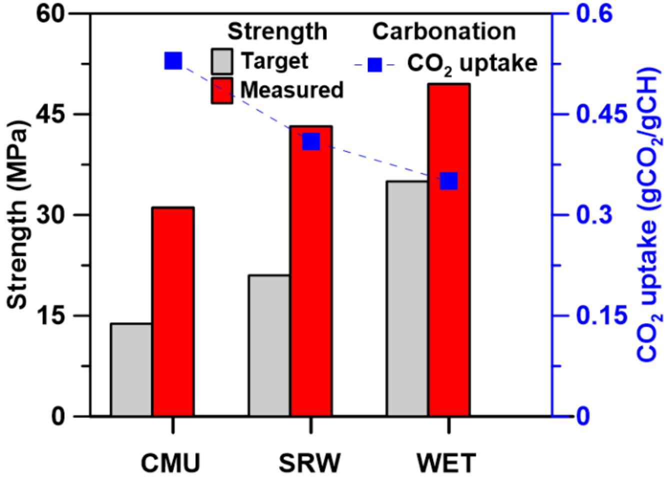
Concrete component selection and strength targets

- Concrete units were chosen based on technical and market prospects
- Based on combined scoring criteria: concrete masonry units (CMU), segmented retaining walls (SRW), and wet-cast manholes were selected
- Optimized processing and mixture formulation produced for each product exceeded ASTM strength targets
- Portlandite was used as main feedstock and exceeded conversion targets of 0.2 gCO_2/gCH





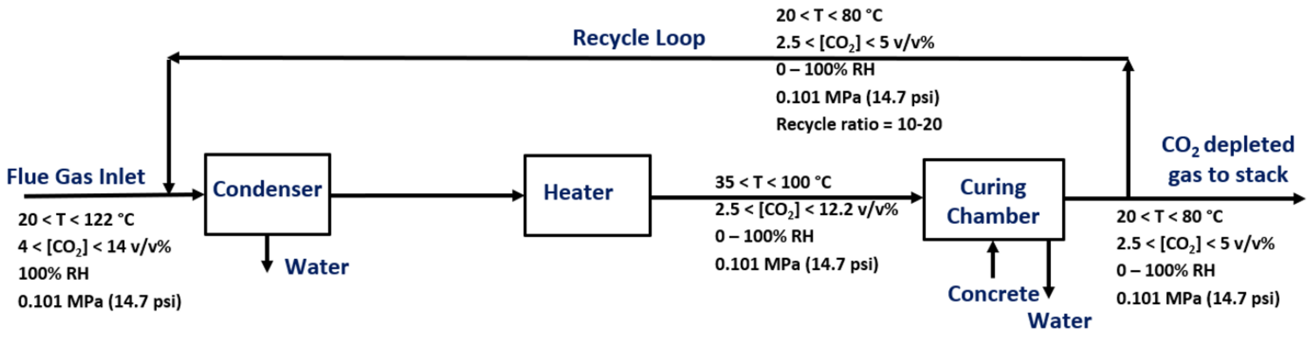
Strength of carbonated concrete and CO_2 uptake

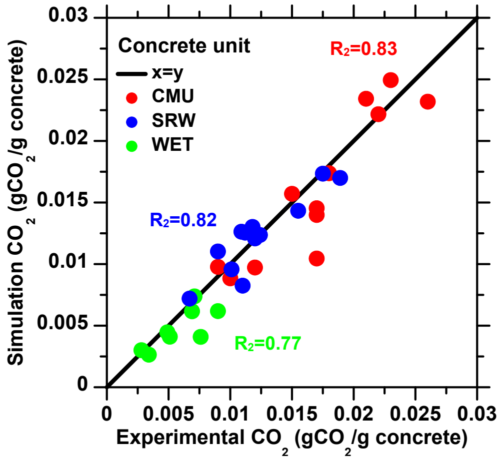


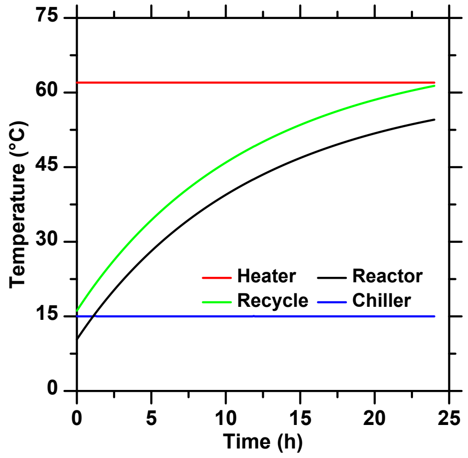
Process modeling development

- Process flow diagram was developed to account for gas processing requirements
- Based on the process flow diagram, two Aspen models were developed:

1. Steady-state model that assesses 24-h average CO_2 uptake based on reactor conditions (RH, $[CO_2]$ and T)
2. Dynamic simulations capable of simulating the reactor and the process conditions across the full 24-h operating window



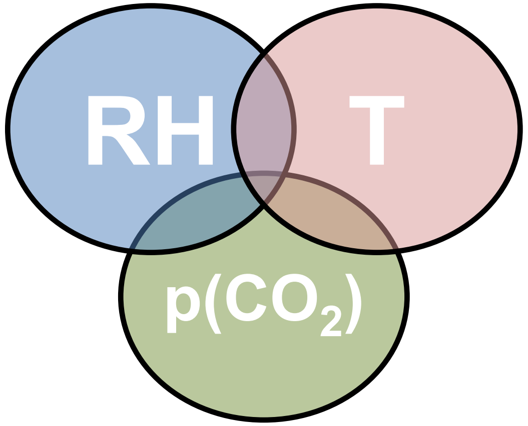


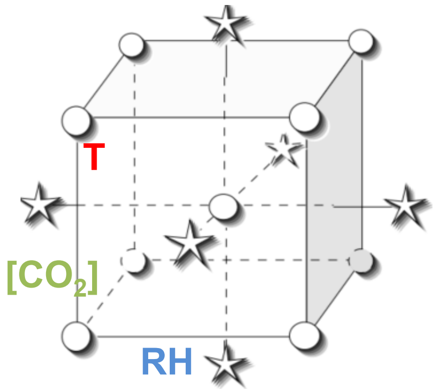


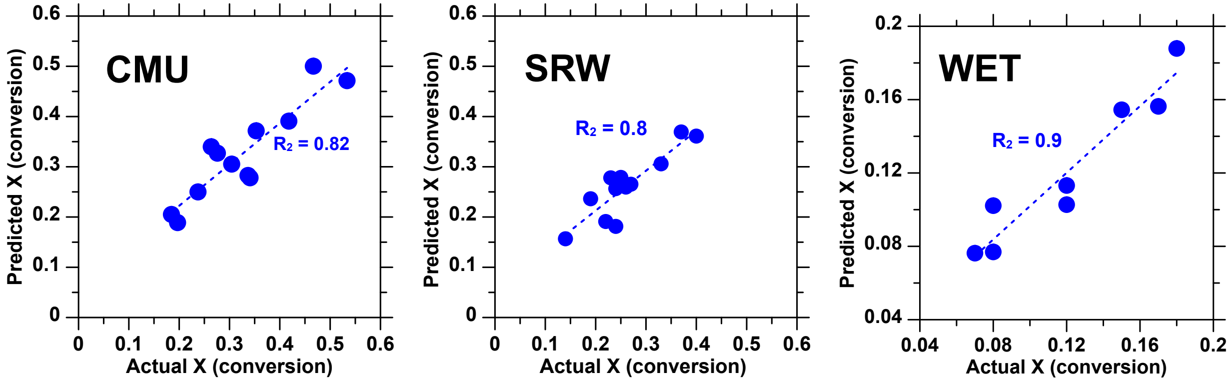
CO_2 uptake regression conversion models developed

- Regression models were developed to estimate CO_2 uptake across varying carbonation conditions for each product
- Inputs:
  - Temperature (20-to-65 °C)
  - Inlet gas relative humidity (10-to-80%)
  - CO_2 concentration (4-to-14 vol.%)
- Model based on maximum conversion of available hydrates.
- Model parameters:

$$\boldsymbol{X\ (conversion) = x + a[CO_2] - bRH + cT}$$

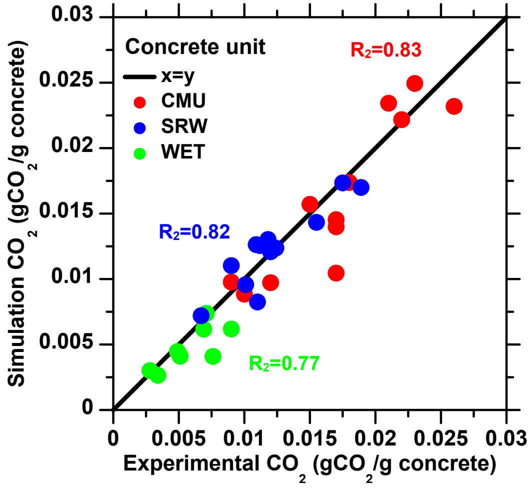




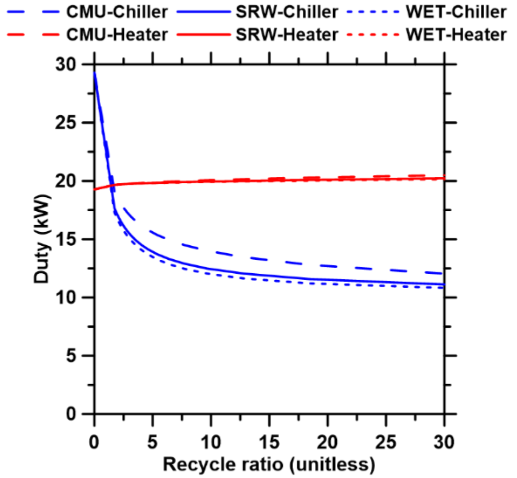


Steady-state simulations

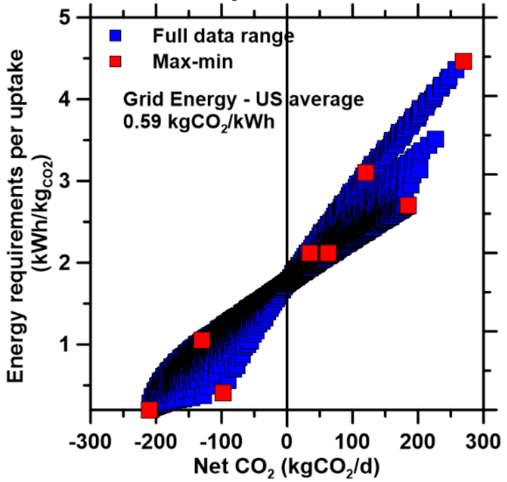
- Integrated regression models uses 24-h conversion of concrete component using [CO_2], T and RH parameters – fitted well to bench-scale data
- A protocol has been developed for changing the Aspen simulation for different concrete components
- Approach allows for scalable design based on concrete inclusion in reactor and inlet gas flow conditions
- This simulation approach is ideal for high volume sensitivity analysis to determine effect of average operating conditions on net CO_2 uptake



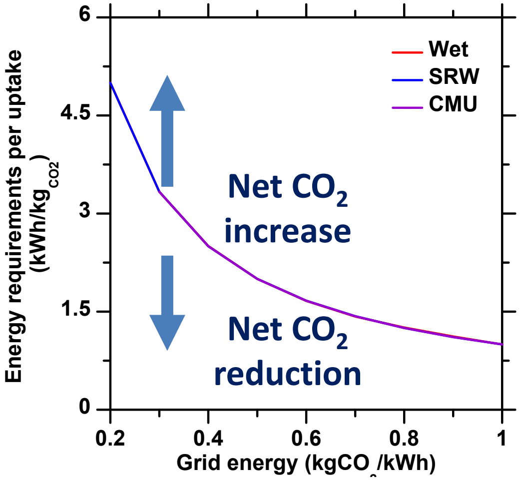
Simulations match experimental data across process conditions



Aspen simulations used to determine unit duties



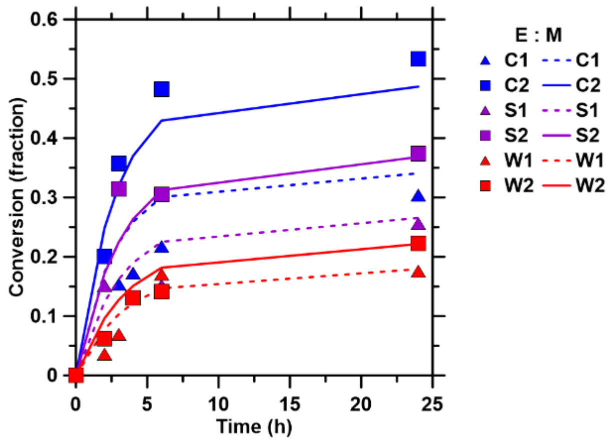
Processing conditions effecting net CO_2 uptake



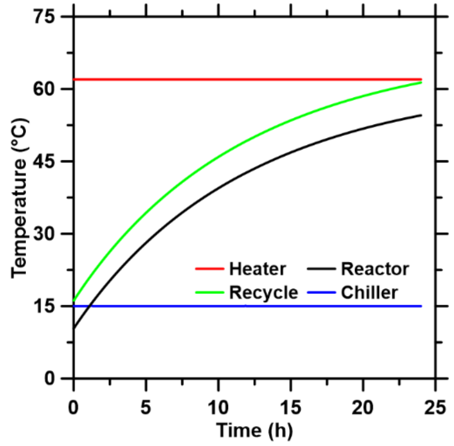
Minimum efficiency to produce net reductions

Dynamic Aspen simulations

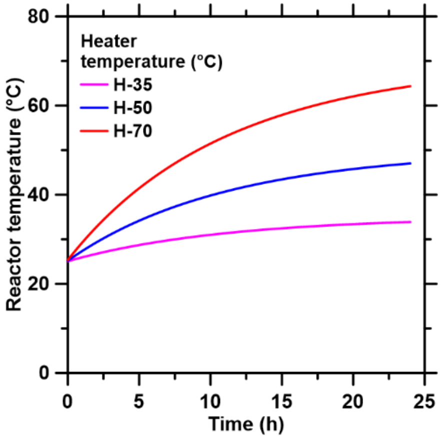
- Rate kinetics data included with regression models for time dependent conversion
- Coupled heat mass transfer model from inlet gas conditions to concrete within reactor determines reactor and unit conditions
- Based on calculated reactor conditions – conversion of concrete altered
- Estimated CO_2 uptake based on concrete type and reactor conditions is possible

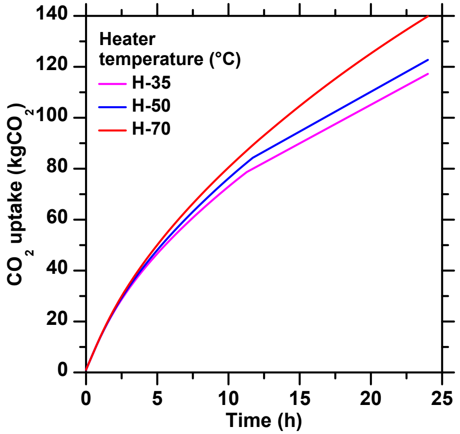


Rate constants determined for each concrete unit



Heat transfer models incorporated





Reactor conditions determine CO_2 uptake from concrete components based on RH, T and [CO_2]

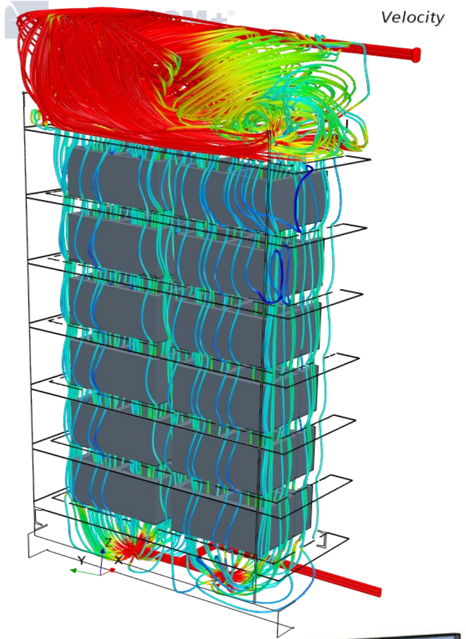
Presentation takeaways

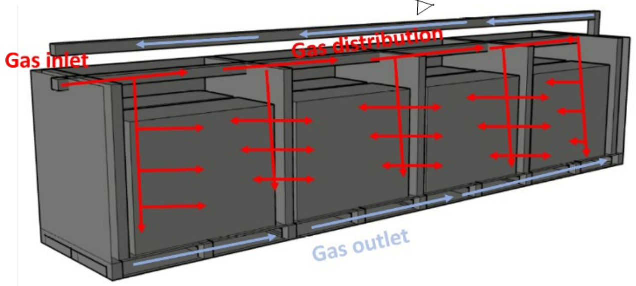
- CO_2 mineralization enables an approach to produce construction products while utilizing CO_2 emissions, with strong market potential
  - CO_2 utilization in concrete without a CO_2 capture step
  - Impactful potential due to the large market size of concrete
- The UCLA team has successfully identified suitable concrete products for the Reversa process
- Appropriate mixture designs and operating conditions have been identified for optimum CO_2 uptake for each selected concrete component
- A process model has been developed to assist with scaling system design and assisting design work for system fabrication

Future Work

- System design underway to incorporate carbonation gas processing requirements
- Computational fluid dynamics will be employed to ensure equal gas flow distribution across reactor
- System build will aim to process 10-to-30 tonnes of concrete per day
- The process will be deployed at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama in 2023
- Completion of TEA and LCA to quantify quality of system design post-demonstration

Computational fluid dynamics and reactor design





NATIONAL CARBON CAPTURE CENTER

Thank you for listening

Questions??

Contact information

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  - **Email: [gsant@ucla.edu]**

Useful links:

Carbon built website:

https://www.carbonbuilt.com/

Institute for Carbon Management:

https://icm.ucla.edu/

Production of Inorganic Materials – Concrete and Cement

Technology Performance Data

	Units	Measured/Current Performance	Projected/Target Performance
Reaction Thermodynamics[1,2]			
Chemical Equation	mol^{-1}	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$	
ΔH°_{rxn}	kJ/mol	-115.102	
ΔG°_{rxn}	kJ/mol	-74.953	
Reaction Conditions			
CO_2 Source[3]		Synthetic coal-fired flue gas	Coal-fired flue gas
Pressure	bar	1.01325	1.01325
CO_2 Partial Pressure	bar	0.02-0.14	0.02-0.14
Temperature	°C	25-75	25-75
Nominal Residence Time – batch reactor[4]	h	18-24	18-24
Alkaline Reactant Source[5]		$Ca(OH)_2$	$Ca(OH)_2$
Process Route[6]	(direct/ indirect)	Direct	Direct
Once-Through Performance[7]			
CO_2 Conversion[8]	(%)	NA	NA
CO_2 Uptake Potential[9]	(g-CO_2/g material)	0.59	0.59
CO_2 Uptake Actual[10]	(g-CO_2/g material)	0.35-0.53	0.2
Product Properties[11]			
Desired Product			
Compressive Strength[12]	(MPa)	20-49	13.8-42
Density	(kg/m^3)	2000	2000
Product Production	(kg/h)		
Commercial Product Properties[13]		**Current**	
Commercial Product		Concrete Masonry Units, Segmented retaining walls, and concrete manholes	
Compressive Strength[12]	(MPa)	13.8-42	
Density	(kg/m^3)	2000	
U.S. Market Size	(Tonnes/yr)	500 M	
Global Market Size	(Tonnes/yr)	>10 B	
Market Price	($/kg)	0.06-0.40	