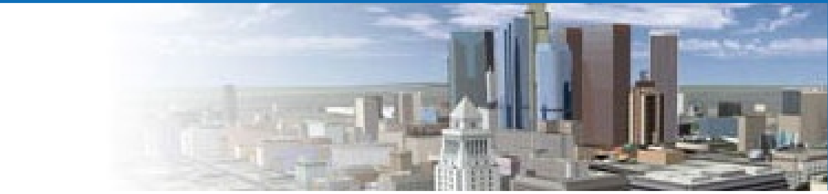


A Scalable Process for Upcycling Carbon Dioxide (CO_2) and Coal Combustion Residues into Construction Products

Project Number: DE-FE0031718
Project Manager: Andrew P. Jones

Presented by: Prof. Gaurav N. Sant
Laboratory for the Chemistry of Construction Materials (LC^2)
UCLA Samueli School of Engineering

Prepared for: DOE-NETL Virtual Integrated Project Review Meeting - Carbon Utilization
October 22nd, 2020

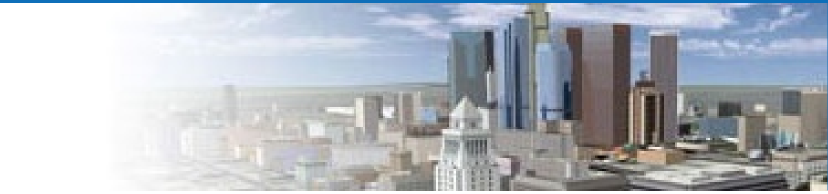
Presentation outline

Project overview

Technology section

Technical approach/project scope

Progress and current status of project



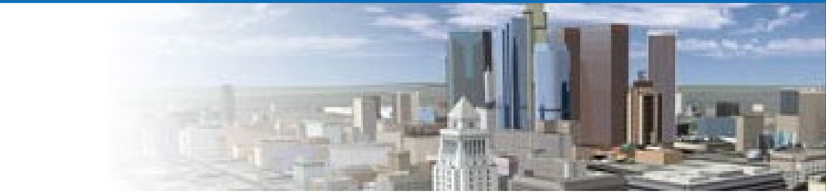
Project budget

The project funding profile over its two-year duration.

	Gov't Share	Cost Share
UCLA	$1,500,000	$460,265
Susteon Inc.	$300,000	$0
Total ($)	$1,800,000	$460,265
Cost Share (%)		**20.36%**

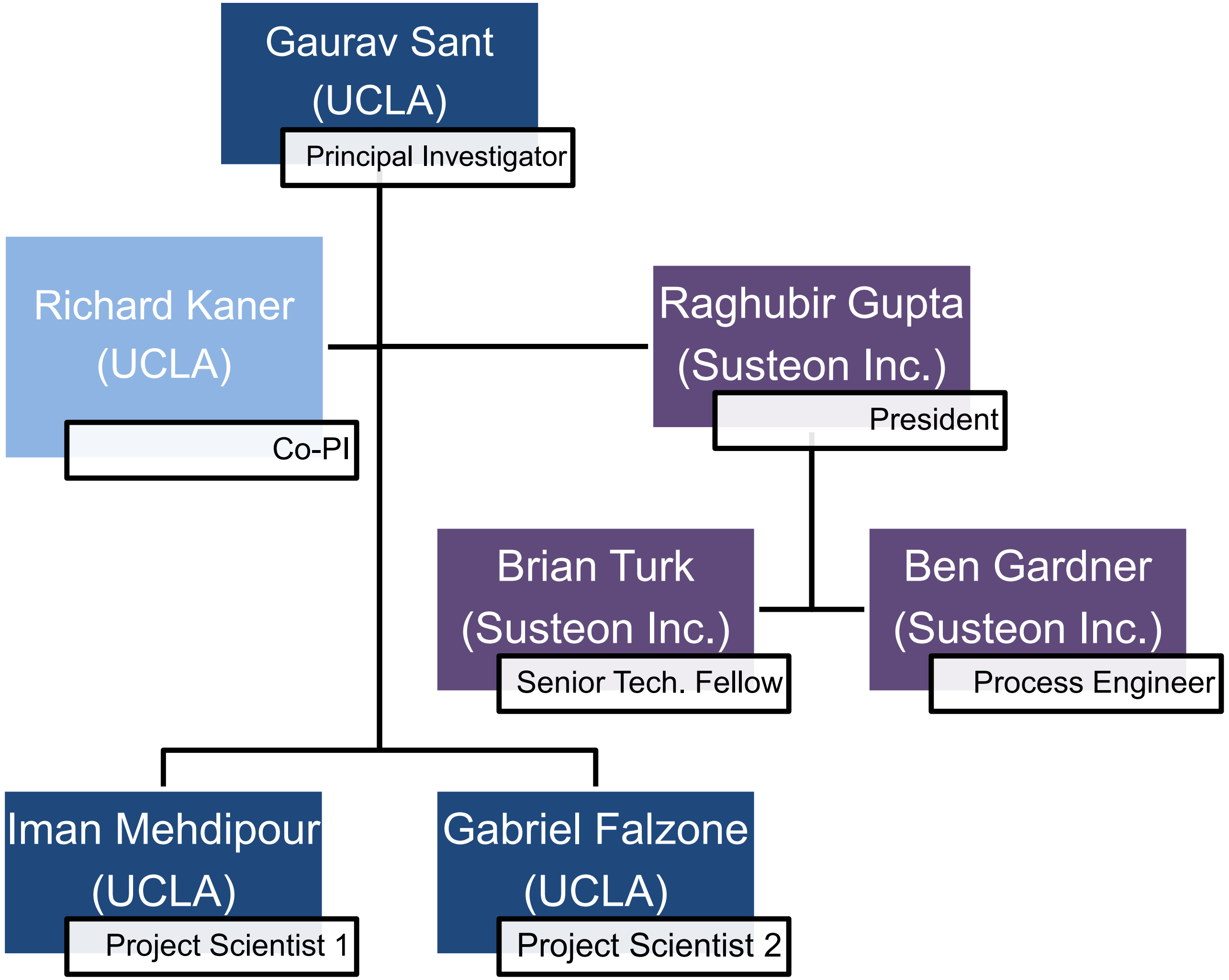
The project's spend plan on a monthly basis.

Month	FY 2019	FY 2020
January	$5,496	$222,097
February	$711	$56,516
March	$49,494	$55,667
April	$2,003	$66,597
May	$107,149	$225,519
June	$32,632	$76,753
July	$39,475	$221,966
August	$52,411	$128,006
September	$48,326	$206,040
October	$56,317	*$24,878*
November	$32,785	*$24,878*
December	$39,406	*$24,878*
Total ($)	**$466,207**	***$1,333,793***



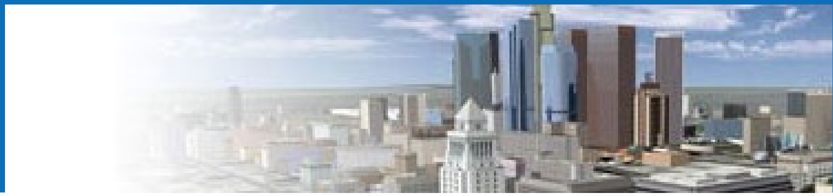
Project dates and participants

- **Project performance dates:** 01/01/2019 – *12/31/2020*
- **Participants:**
  - PI: Gaurav N. Sant
  - Co-PI: Richard Kaner
  - Project Scientists: Iman Mehdipour and Gabriel Falzone
  - Susteon Inc.



Overall project objectives

- ***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
- ***System design*** **–** Develop operational procedures to inform scale-up process design of a "bolt-on" CO_2 mineralization system at coal-fired power plants
- ***Field test CO_2 processing system*** **–** Fabricate and demonstrate a unique CO_2 mineralization system to consume ~100 kg of CO_2 per day from coal-fired flue gas
- ***Product compliance*** **–** Assess and verify product compliance to construction standards; demonstrate potential utilization in construction applications



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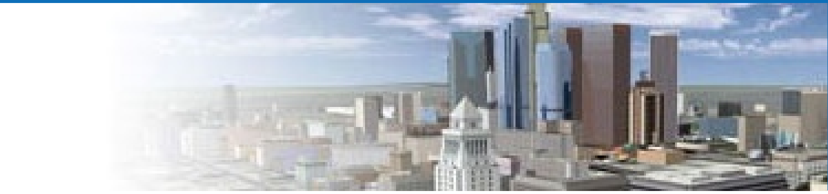
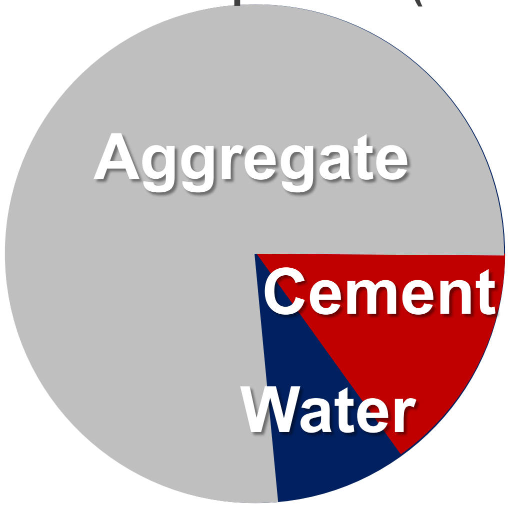
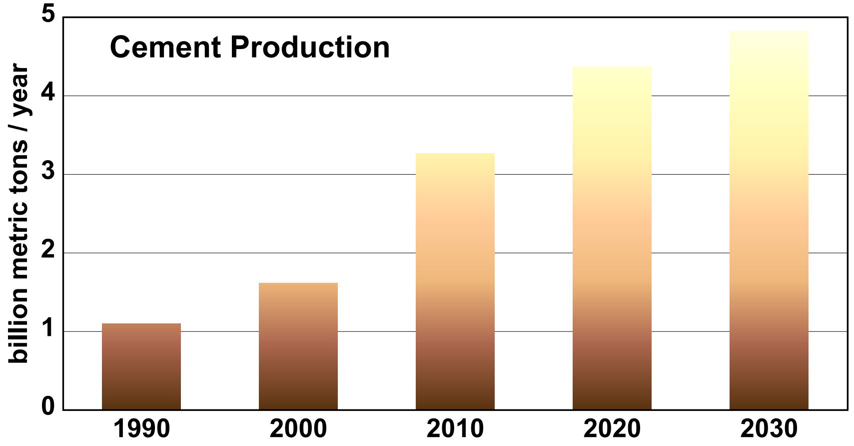


The problem at hand – CO_2 emissions from cement/concrete

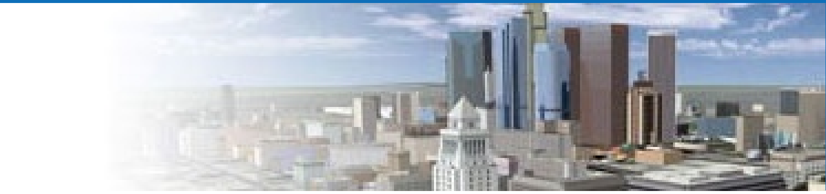
- The most-widely used material (for good reason)
  - Over 20 billion tons of concrete are produced per year
  - Cheap, abundant and resilient
- Cement production emits approximately 10 % of global CO_2 emissions
  - Cement is the most emissions-intensive component of concrete, despite being only 15% of its mass
  - ~ 0.9 tons CO_2 emitted per ton cement
  - ~ 4 billion tons cement produced per year
- Emissions from calcination are the unavoidable majority

Concrete Composition (mass)



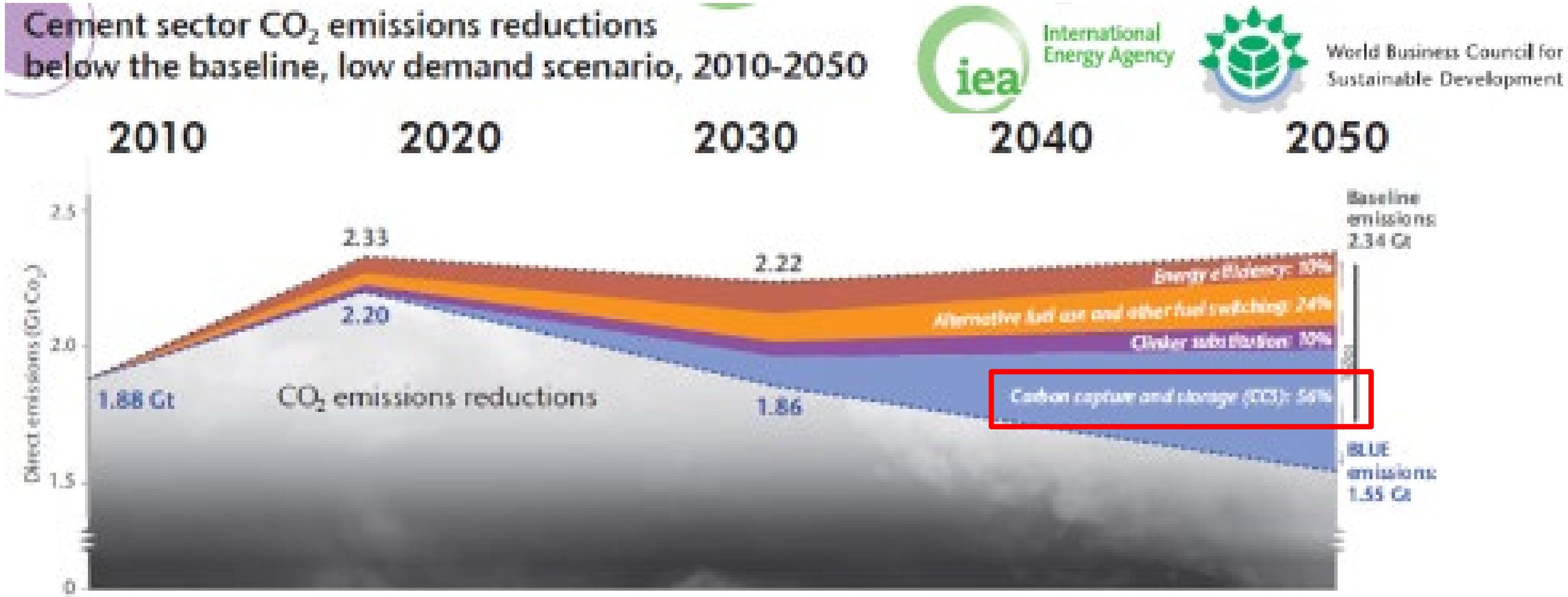


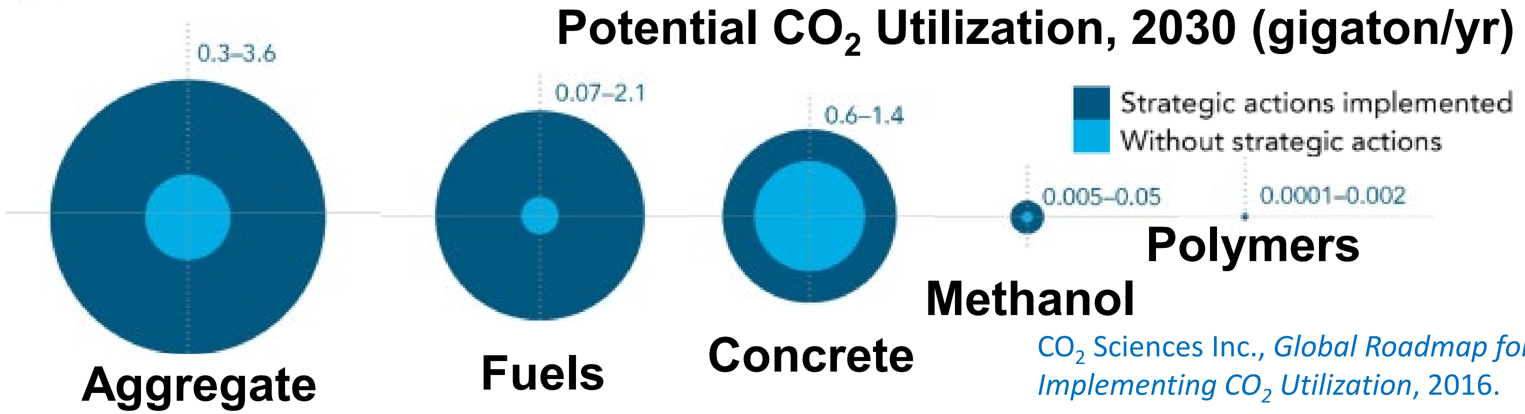
https://www.statista.com/statistics/373845/global-cement-production-forecast/



The need for CO_2 utilization within the concrete/construction sector

- Large gap in emissions reductions of cement sector needs to be filled by CO_2 management
- Geologic sequestration is costly and difficult to achieve
- Cementation agents and aggregates could present a gigaton-scale sink for CO_2 emissions





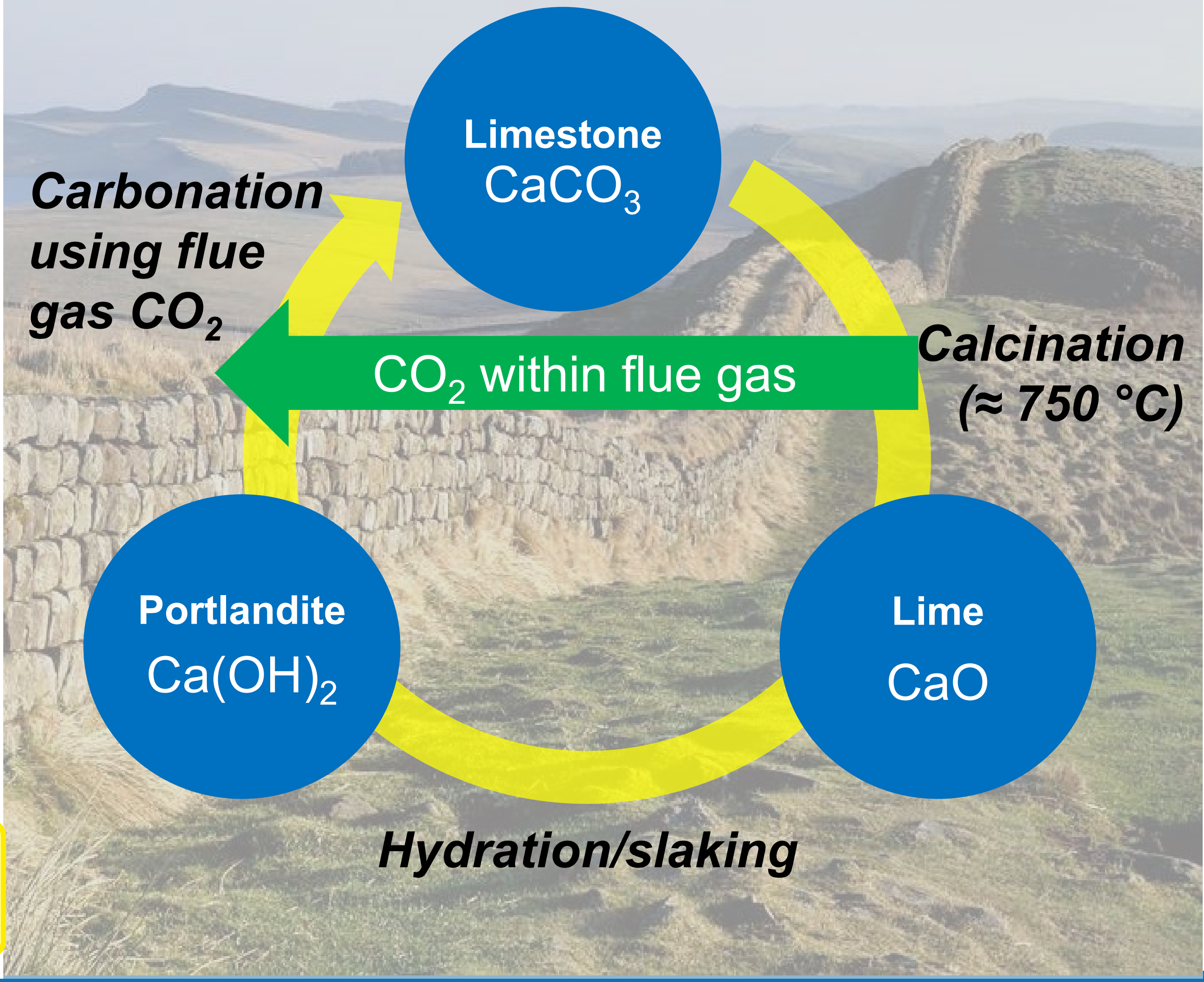
CO_2 Sciences Inc., *Global Roadmap for Implementing CO_2 Utilization*, 2016.

The lime cycle enables scalable CO_2 mineralization

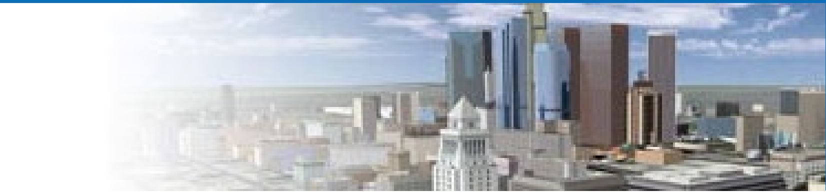
- Lime mortars (based on calcium hydroxide / portlandite: $Ca(OH)_2$) are historically proven cementation agents

Advantages of this approach

- Portlandite offers high CO_2 uptake, low cost
- Reduced processing temperatures vis-à-vis OPC
- No carbon capture step needed (directly use flue gas borne CO_2)
- Mineralization is thermodynamically downhill
- Maintain reaction temperature and pressure similar to native flue gas conditions



The Challenge: Accelerate CO_2 mineralization reaction rates while minimizing energy inputs



Process flow for producing low-carbon concrete by CO_2 mineralization

Raw materials

$Ca(OH)_2$
OPC, CCRs
Aggregate
Water

Green body forming

Green body

CO_2 mineralization

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

Concrete products

Flue gas stream

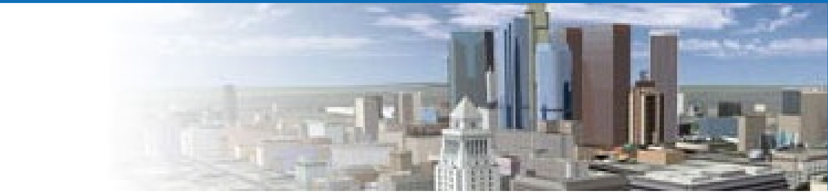
CO_2, N_2, O_2, H_2O, NO_x, SO_x

CO_2 lean gas

Water

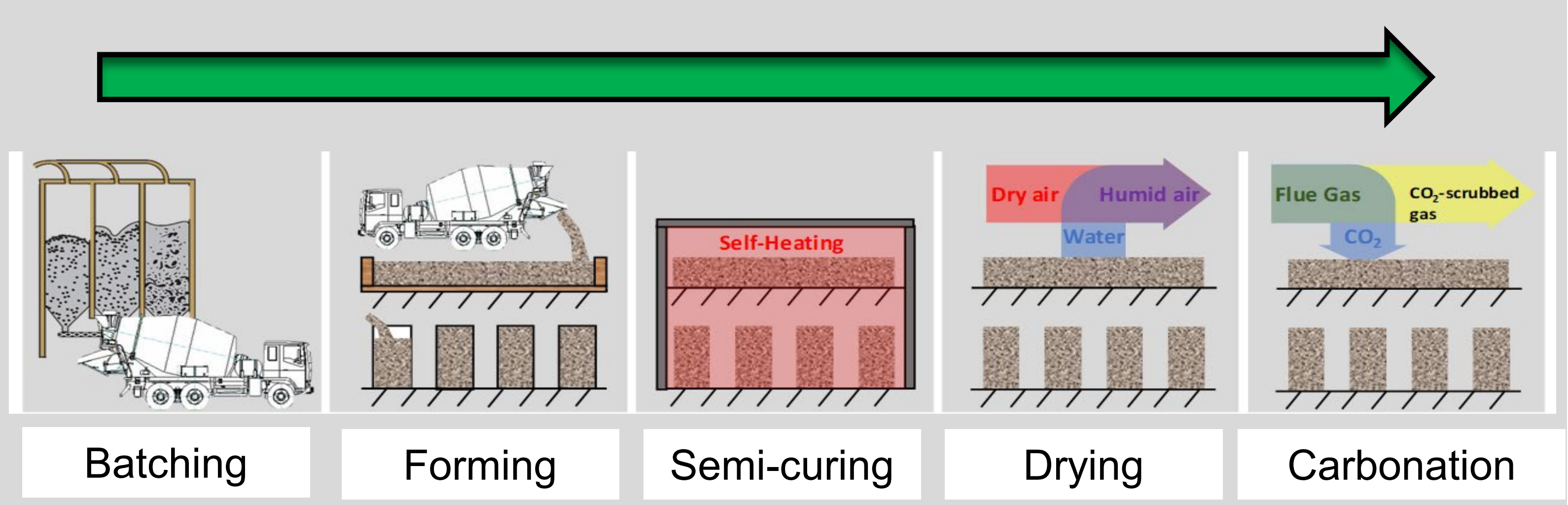
Concrete masonry unit (CMU)

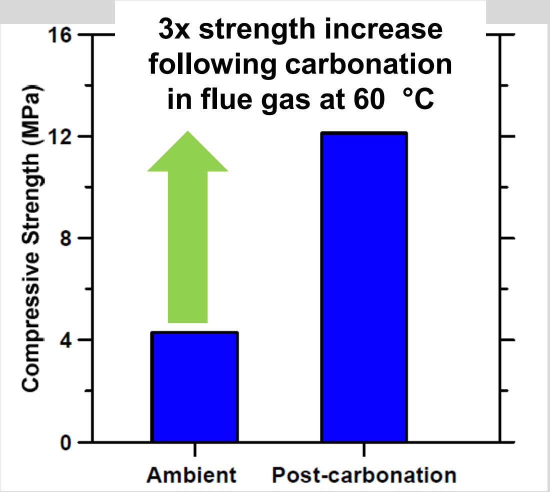
Hollow-core slabs



Demonstration of *alpha*-prototype CO_2 mineralization system

- Alpha-pilot used simulated natural gas and coal flue gas (7% - 18% CO_2) input streams
- Process designed for wet-cast concrete cylinders (water/ binder mass ratio, w/b ≈ 0.5)
- Input 200 kg CO_2 within 24 h, 65 % of which was taken up into concrete products
- Embedded 0.2 g of CO_2 / g of reactant in concrete product, which induced strengthening





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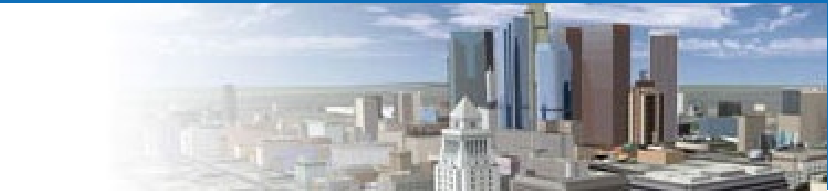


Scope of work and project success criteria

Project tasks:

- **Task 1.0 –** Project Management and Planning
- **Task 2.0 –** Material specifications, acceptance criteria, and component performance
- **Task 3.0 –** Bench-scale studies to acquire critical data for system design
- **Task 4.0 –** Design and fabrication of modular CO_2 processing system
- **Task 5.0 –** Commissioning and trial operation of the CO_2Concrete system
- **Task 6.0 –** Field demonstration of CO_2Concrete carbonation system
- **Task 7.0 –** Design and scalability analysis for commercial-scale CO_2Concrete system
- **Task 8.0 –** Techno-economic analysis and life cycle assessment

Key project success criteria:

- CO_2Concrete formulations demonstrate CO_2 uptake between 0.05 to 0.50 g CO_2/ g reactant and compressive strength > 13.8 MPa for hollow-core block applications
- Field testing demonstrates 50 to 90 % CO_2 utilization efficiency using real flue gas at host site
- CO_2Concrete produced has a lifecycle footprint that is > 25 % smaller than OPC concrete of equal performance

Project milestones

Task #	Milestone description	Planned completion	Verification method
1	Updated Project Management Plan (PMP) submitted	1/31/19	PMP file
2	Reactants demonstrating theoretical carbonation potential in excess of 0.05 g CO_2/ g reactant will be sourced and characterized for use in carbonation experiments	3/1/19	Oxide composition data from XRF will be used to calculate the theoretical carbonation potential. Results reported in the quarterly RPPR.
1	Project kickoff meeting convened	3/31/19	Presentation file
2	Reactant mixture formulations identified that demonstrate CO_2 uptake between 0.05 to 0.50 g CO_2/ g reactant	4/30/19	Thermogravimetric analysis will establish CO_2 uptake achieved during bench scale carbonation experiments of different reactants performed at fixed process conditions. Results reported in the quarterly RPPR.
3	Performance of CO_2Concrete components produced in bench-scale reactor meets applicable product standards (e.g., compressive strength > 13.8 MPa for concrete block, ASTM C90)	6/29/19	Laboratory testing of compressive strength following ASTM C90 procedures; performance data for various mixtures and processing conditions will be compiled. Results reported in the quarterly RPPR.

Project milestones (cont.)

Task #	Milestone description	Planned completion	Verification method
8	Technology Maturation Plan (TMP) submitted	6/30/19	TMP file
3	Establish process conditions that maximize rate of CO_2 uptake (in excess of 5.8 x 10^{-7} g CO_2 / g reactant / second)	8/28/19	Thermogravimetric analysis will establish CO_2 uptake kinetics during bench-scale carbonation experiments of reactants performed under varying process conditions. Results reported in the quarterly RPPR.
4	Beta reactor system performance maintained within 20% of set point during 24-hour duration of operation using simulated flue gas	6/23/20	In-line instrumentation will monitor and record performance data (i.e., temperature, relative humidity) which will be analyzed and compiled. Results reported in the quarterly RPPR.
4	Bench-scale unit fabricated and factory-acceptable test completed	9/21/20	Description and photographs provided in the quarterly RPPR.

Project milestones (cont.)

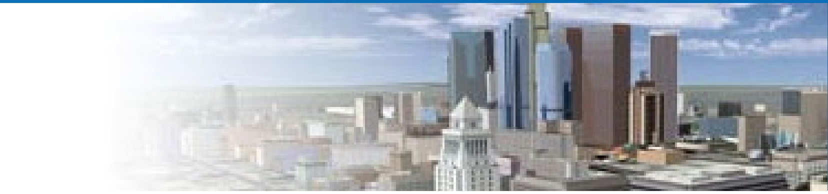
Task #	Milestone description	Planned completion	Verification method
2	Performance of CO_2Concrete components produced in beta system **using simulated flue gas** meets applicable product standards (e.g., compressive strength > 13.8 MPa for concrete block, ASTM C90); CO_2 uptake in excess of 0.05 g CO_2 / g reactant is achieved within 24 hours of processing	9/21/20	Laboratory testing of compressive strength following ASTM C90 procedures; performance data for various mixtures and processing conditions will be compiled. Results reported in the quarterly RPPR.
6	Host Site Agreement obtained (NCCC)	9/21/20	Host Site Agreement submitted to DOE/NETL
6	Beta reactor system performance maintained within 20% of set point during 24-hour duration of operation using real flue gas at host site	11/1/20	In-line instrumentation will monitor and record performance data (i.e., temperature, relative humidity) which will be analyzed and compiled. Results reported in the quarterly RPPR.

Project milestones (cont.)

Task #	Milestone description	Planned completion	Verification method
2	Performance of CO_2Concrete components produced in beta system **using real flue gas at host site** meets applicable product standards (e.g., compressive strength > 13.8 MPa for concrete block, ASTM C90); CO_2 uptake in excess of 0.05 g CO_2 / g reactant is achieved within 24 hours of processing.	12/31/20	Laboratory testing of compressive strength following ASTM C90 procedures; performance data for various mixtures and processing conditions will be compiled. Results reported in the quarterly RPPR.
8	Lifecycle analysis of CO_2Concrete components demonstrates embodied CO_2 intensity at least 25% less than conventional concrete products	12/31/20	LCA will be performed using openLCA or similar program in accordance with relevant product category rules and compiled into a report that describes the results and methodology (MS Word file). Results reported in the LCA Topical Report.
8	Techno-Economic Analysis topical report completed	12/31/20	Topical Report and summary in Final Report
8	Life Cycle Analysis topical report completed	12/31/20	Topical Report and summary in Final Report
8	Technology Gap Analysis topical report completed	12/31/20	Topical Report and summary in Final Report

Risk management approach

- Close monitoring of scientific/financial aspects by PI and a project manager
- *Risk register* to help in the identification and mitigation of risks
- A detailed risk register is provided in the project management plan
- Probabilities and impact classifications are based on current understanding of the readiness of the technology and the team's competencies
- The risks with highest risk scores (probability × impact) are discussed in the following slides



Project risks

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Budget shortfalls	Moderate	High	Closely monitor project costs and scope and set spending priorities based on timelines and milestones. Conduct periodic (weekly) meetings with team and utilize detailed task tracking application.
Integration issues (e.g., connection of system to host site, control of flue gas into system)	Moderate	High	Get sign-off on integration strategy from host site operators in design reviews; develop and discuss operational plan
Insufficient product storage and/or delayed product transportation	Moderate	Moderate	Develop strategy for on-site product storage including transportation schedule; identify secondary off-site storage near host site

Project risks (cont.)

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Environmental permitting	Moderate	High	Begin permitting discussions early in the project's lifecycle to fully understand permitting requirement and timing
Control of flue gas exhaust and fugitive dust	Moderate	Moderate	Provide proper engineering controls to mitigate exposure to dust/flue gas in full compliance with State and Federal requirements

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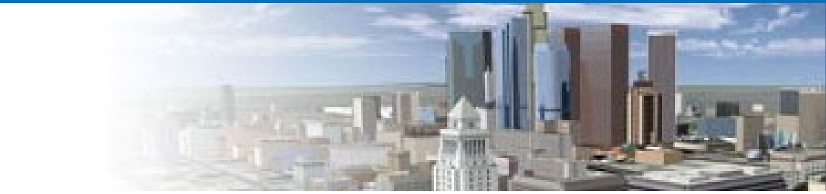
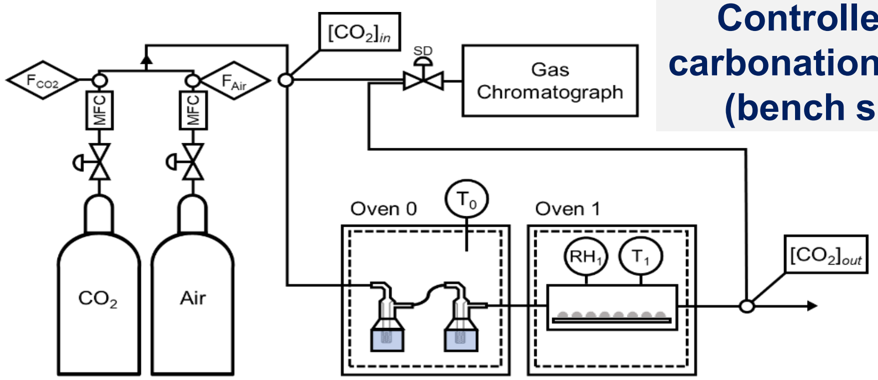
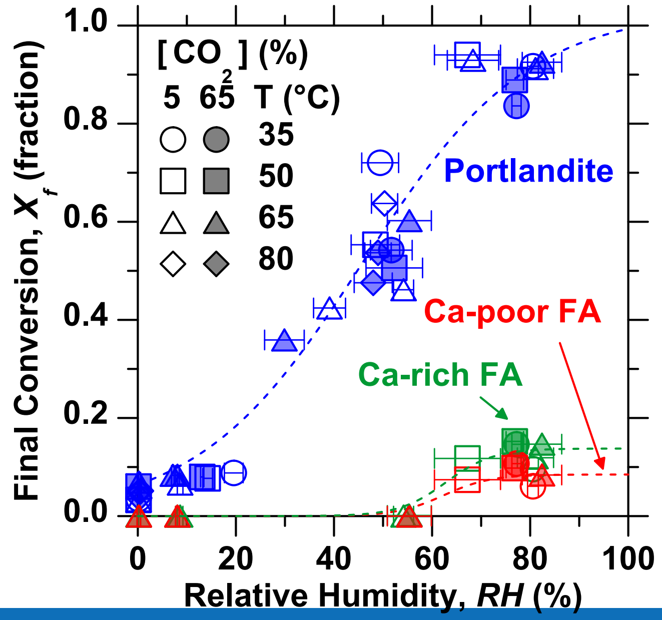


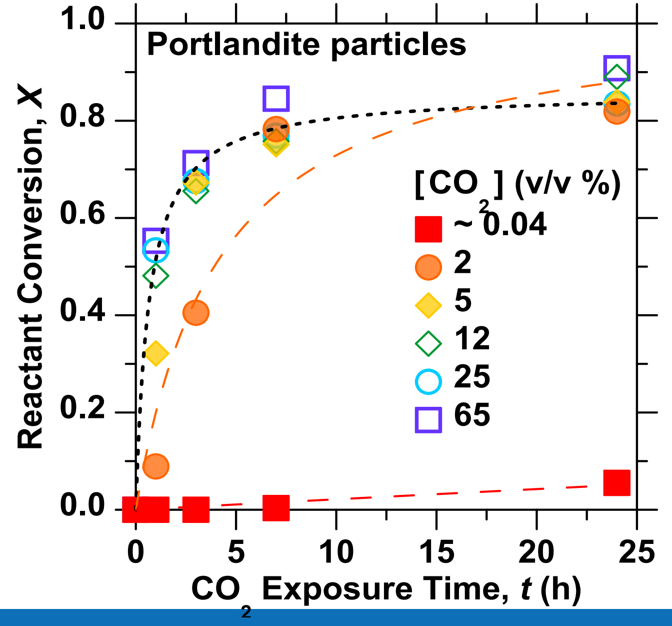
Portlandite carbonates at dilute CO_2 concentrations

- **T and [CO_2] do not affect extent of reaction**
- Carbonation is near-complete within 24 h
- 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/mo when transport barriers may form
- **The Significance:** Pressurization, CO_2 enrichment, or significant heating is not required for portlandite carbonation



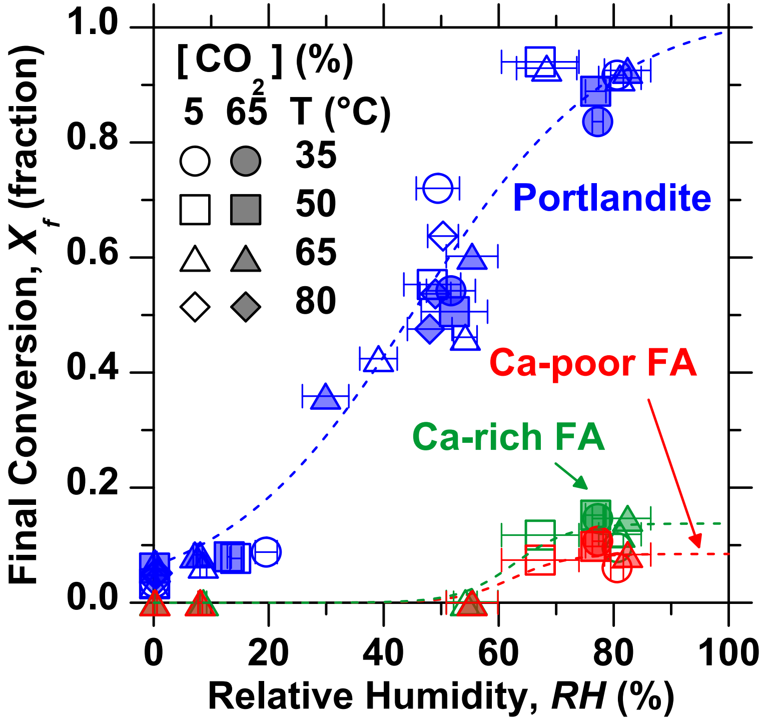
Controlled-RH carbonation reactor (bench scale)

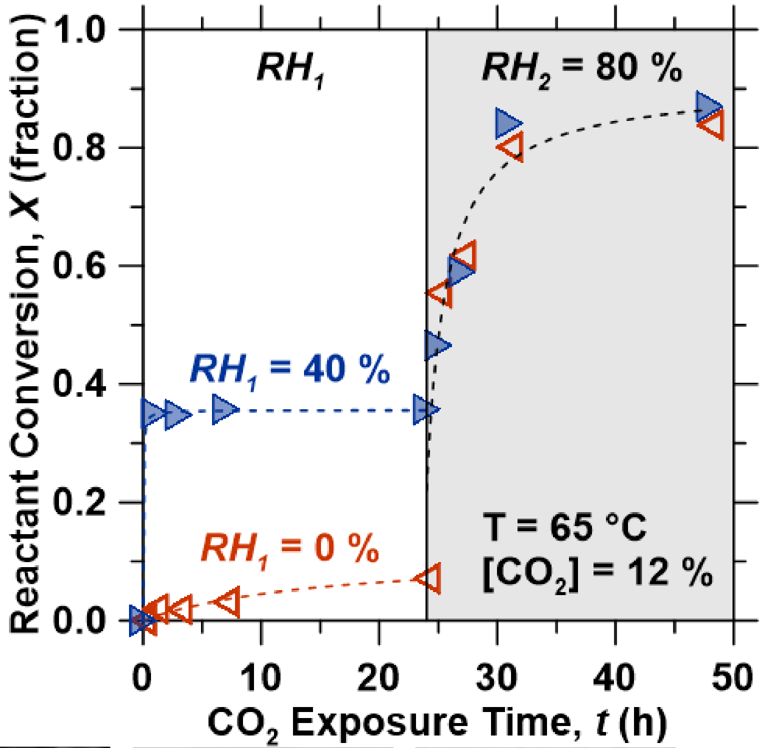


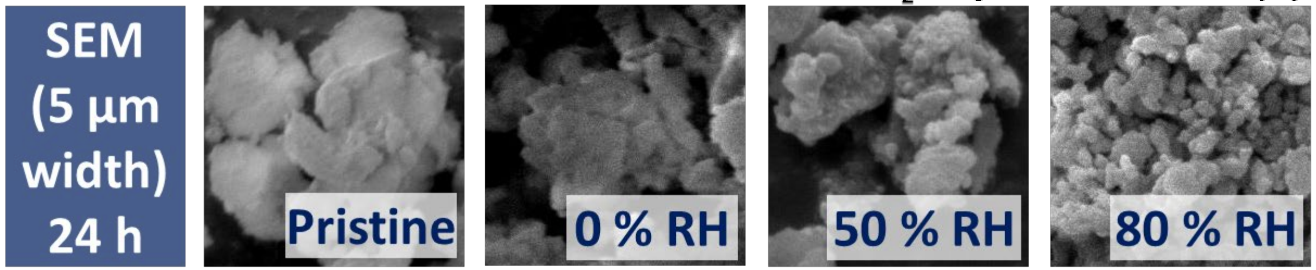


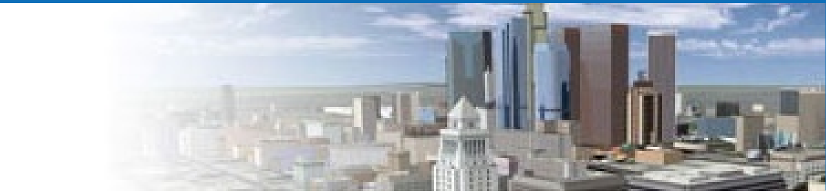
How water affects the extent of carbonation of $Ca(OH)_2$

- Minimal carbonation occurs in dry CO_2 gas
- Dissolution-precipitation pathway at higher RH allows higher extent of conversion
- "Stepped-RH" experiments revealed no surficial passivation impact
  - Conversion limit of portlandite is dictated by the RH of the CO_2 stream in immediate contact – and independent of prior history/processing/exposure conditions





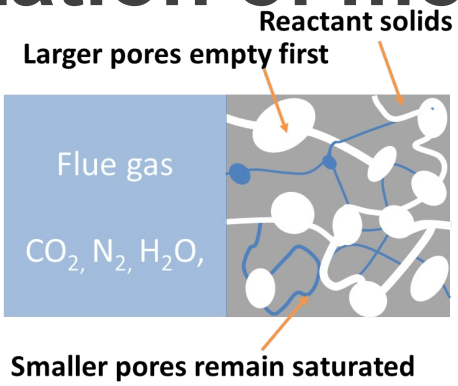


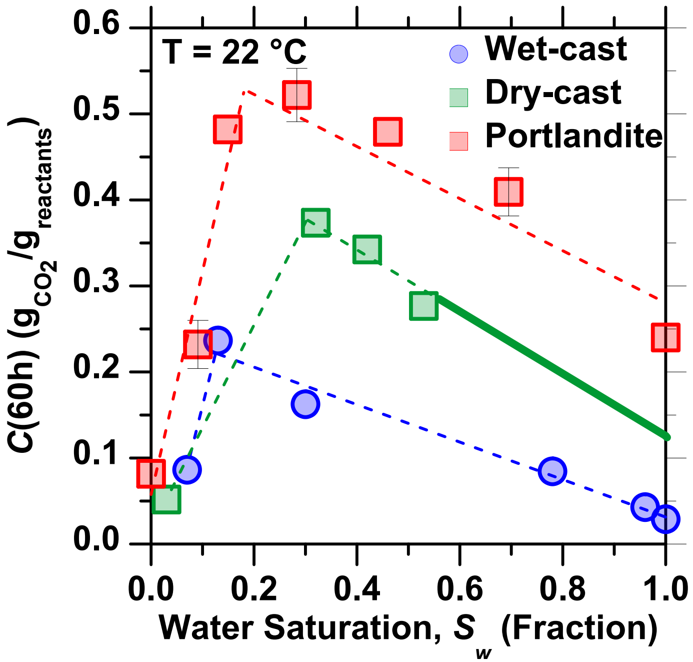


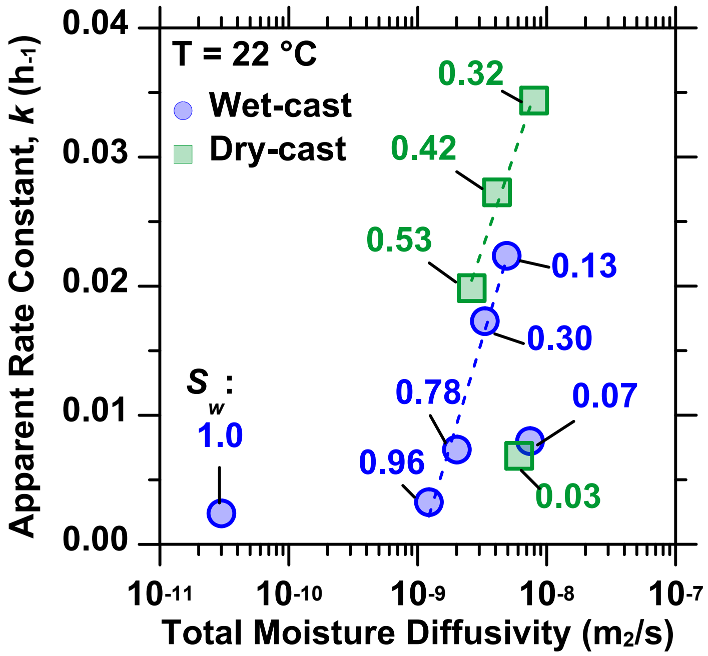
Saturation's effect on CO_2 mineralization of monoliths

- Unlike particles, CO_2 diffusion through pore structure limits reaction rates; especially in water-saturated pores
- $S_w \approx 0.1$-0.2: critical level for CO_2 uptak
  - Below this level, carbonation is water-limited
- Reaction kinetics scale with the body's moisture diffusivity
  - Similar dependence regardless of the forming method (wet-cast vs. dry-cast)
  - Enhanced kinetics in dry-cast are attributed to a lower extent of cement hydration and particle occlusion

Mehdipour et al., ACS Sustainable Chem. Eng. 7 (2019) 13053–13061.







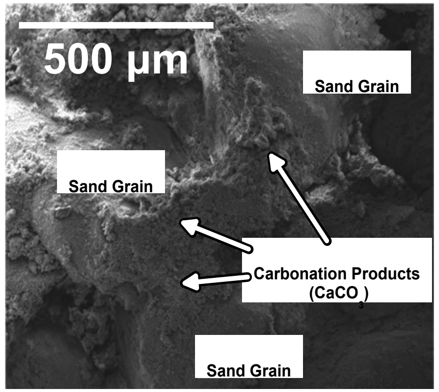
Carbonation strengthening in portlandite composites

- Carbonate solids 'bind' mineral aggregates and reduce porosity, which controls strength
- Strength gain per unit CO_2 uptake depends on gas processing conditions
- Portlandite carbonation and cement hydration occur simultaneously
  - Strengthening contributions are additive in relation to reaction extent

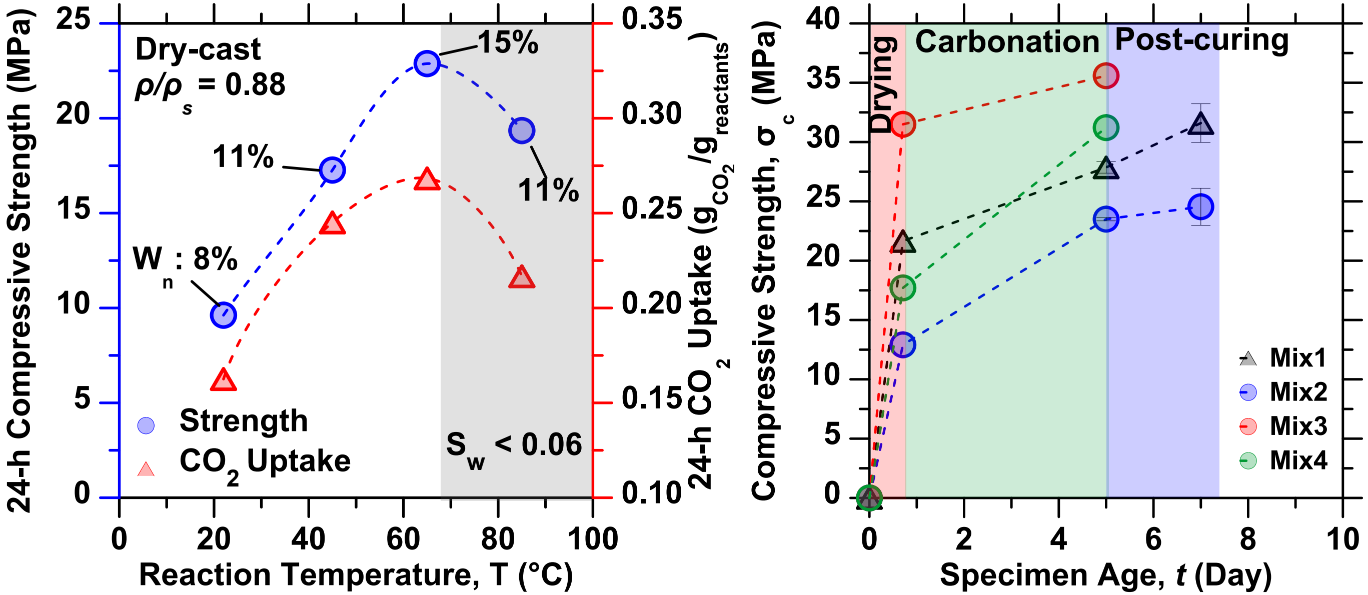
$$\sigma_{c(t)} = A \cdot C(t) + B \cdot w_n(t)/m_{OPC}$$

where: A = 14.7 MPa / ($g_{CO2}/g_{reactants}$) [Carbonation]

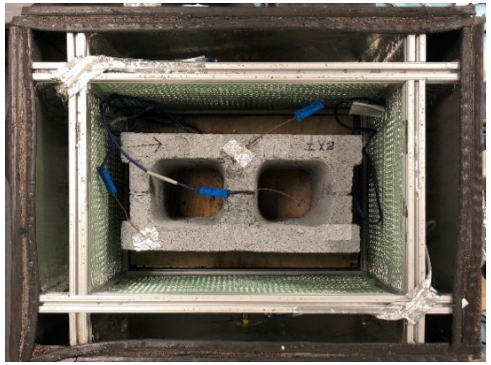
and B = 0.38 MPa / (w_n/m_{OPC}) [OPC hydration]

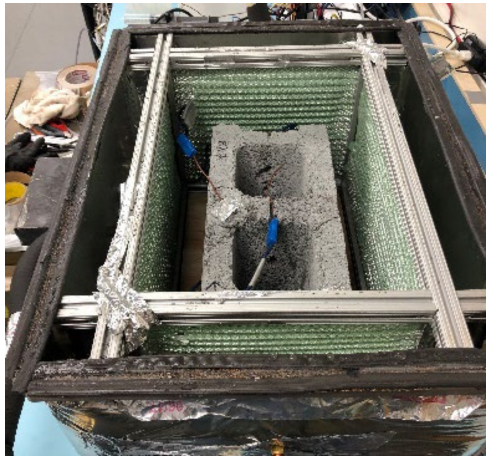


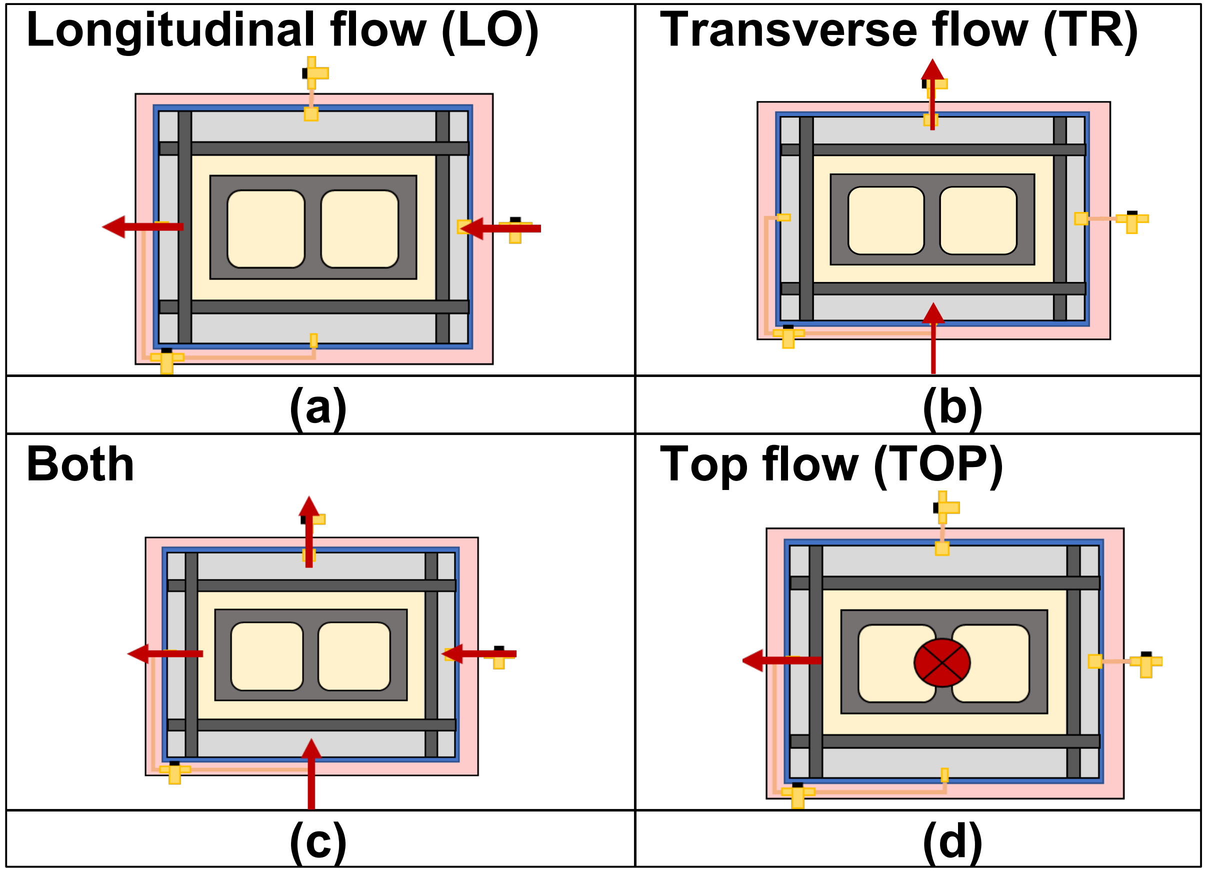
Vance et al., Ind. Eng. Chem. Res. 54 (2015) 8908–8918.



Block carbonation experiments informing process design







Concrete masonry units were produced and carbonated using simulated coal flue gas with varying gas flow direction, flow rate, relative humidity, and temperature

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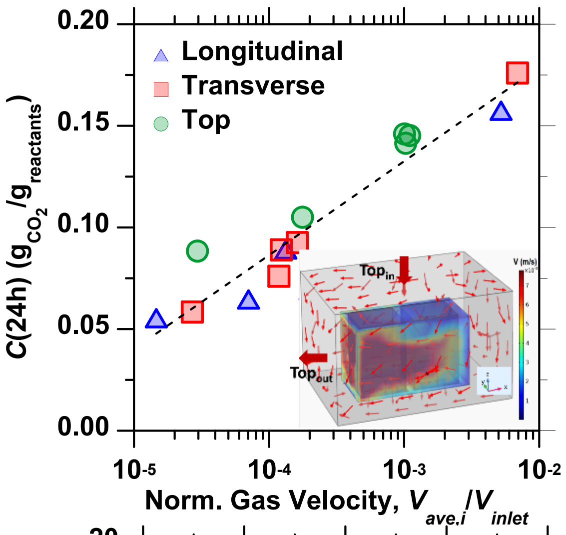
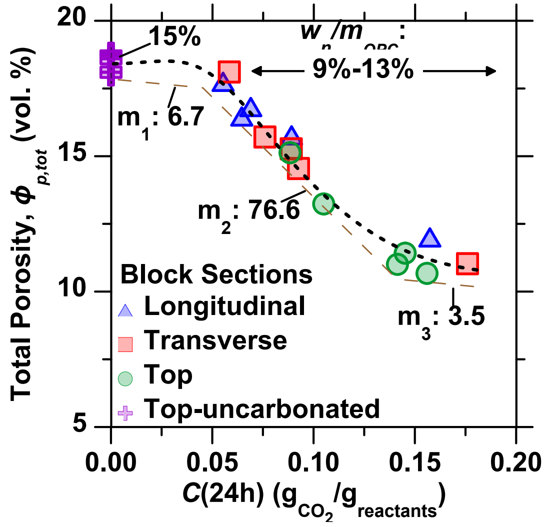
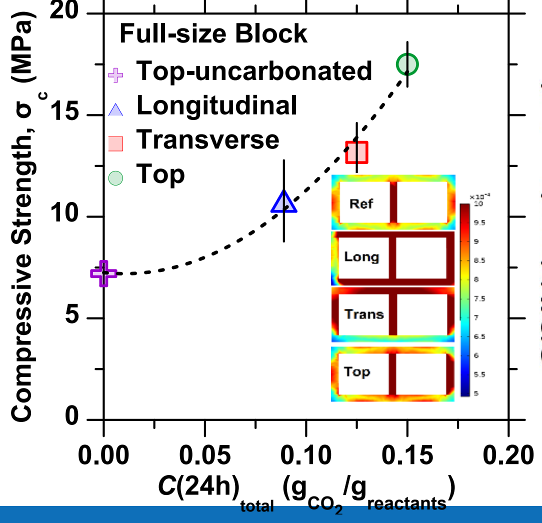
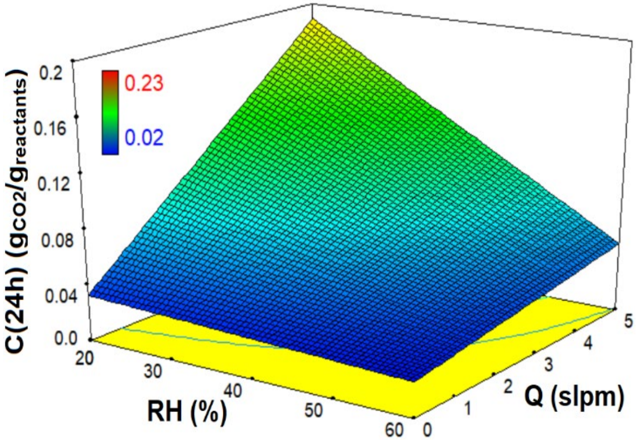
Spatial variations in CO_2 uptake: Microstructure alteration

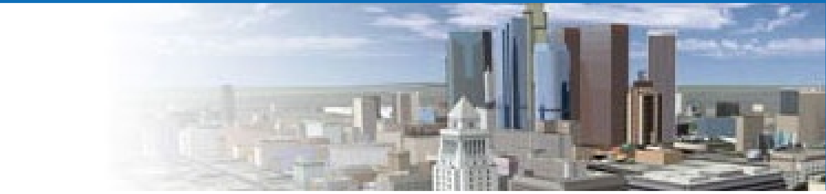
- Spatial distribution of CO_2 uptake is significantly affected by gas flow configuration
  - Greater gas velocity and homogeneity produce higher CO_2 uptake across the block in agreement with our CFD simulations
- Local strength/porosity correlated well to local CO_2 uptake due to carbonation cementation
- Block strength scales linearly with mechanical anisotropy imposed by extent of CO_2 uptake supported by FEM simulations
- Response surface generated to derive statistical models and predict spatial CO_2 uptake as a function of gas processing conditions
- ***Top-down flow selected for curing chamber***





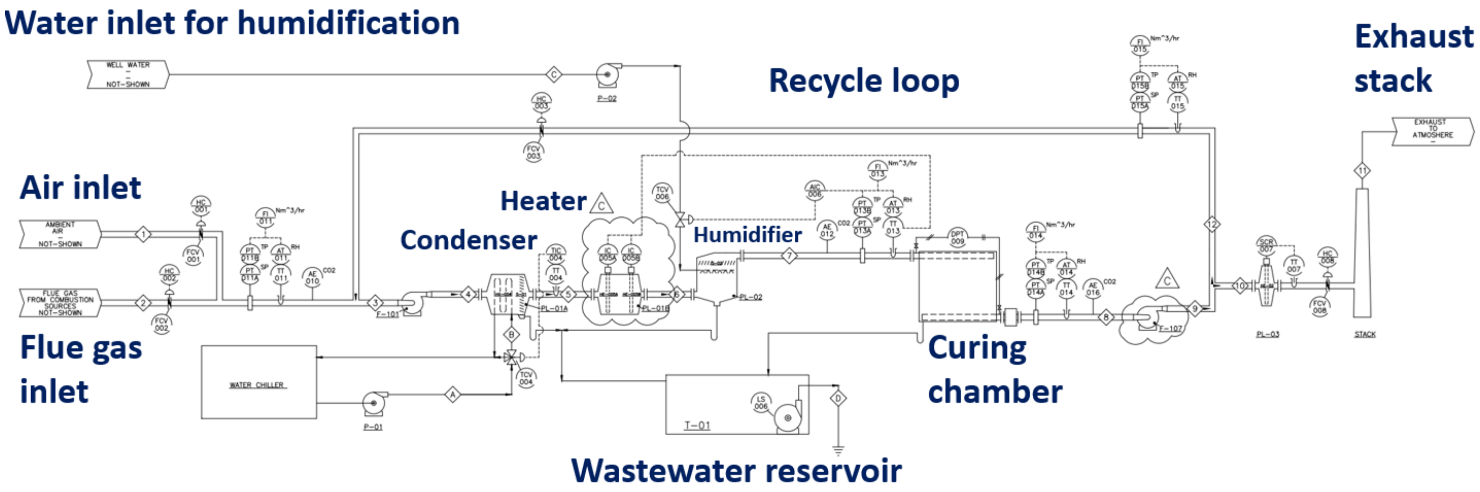


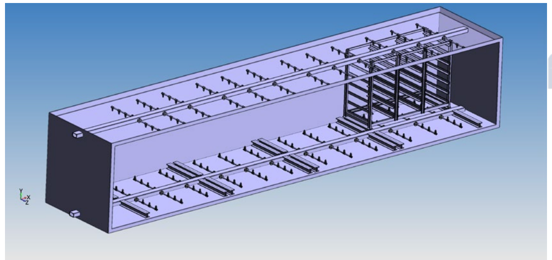




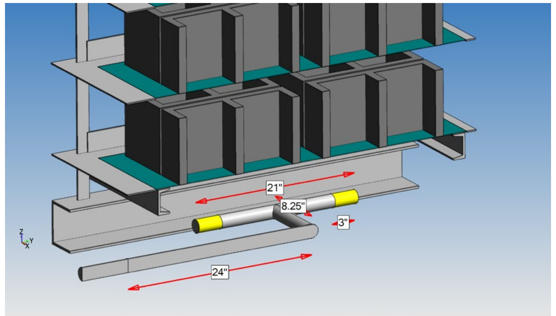
Design and fabrication of CO_2 mineralization system

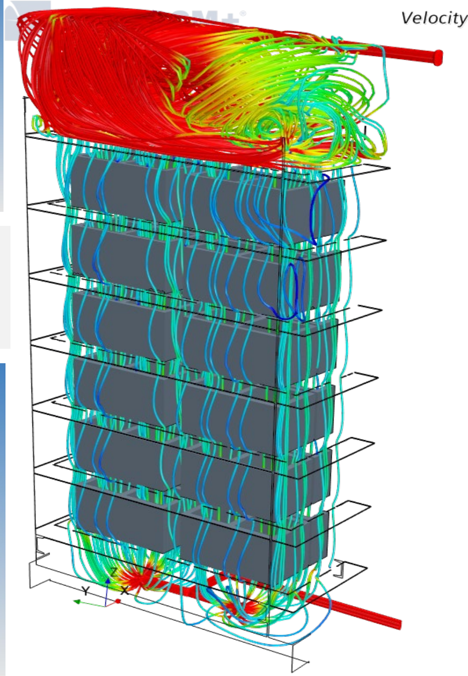
- Developed process model and system design documentation for the carbonation of CO_2Concrete blocks informed by bench-scale studies (producing ~860 CMUs each batch)
- Performed CFD simulations to design modular gas flow distribution and product arrangement within carbonation reactor





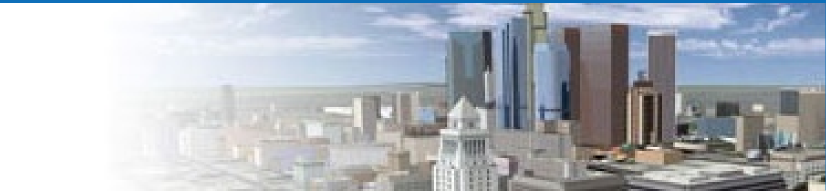
Gas flow distribution optimization





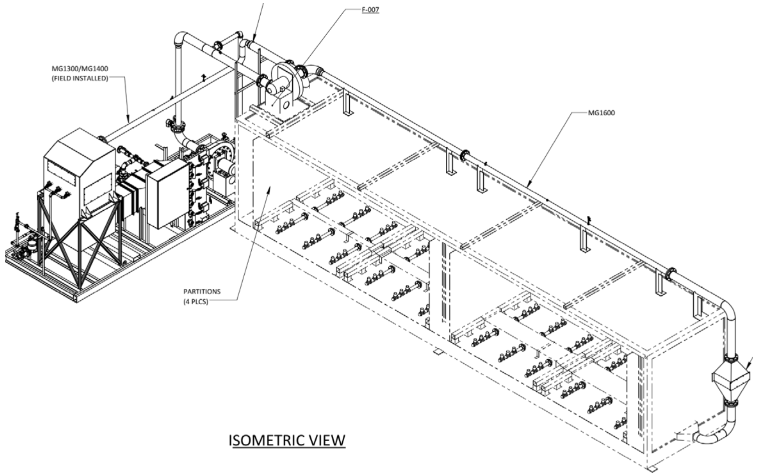
Laboratory for the Chemistry of Construction Materials

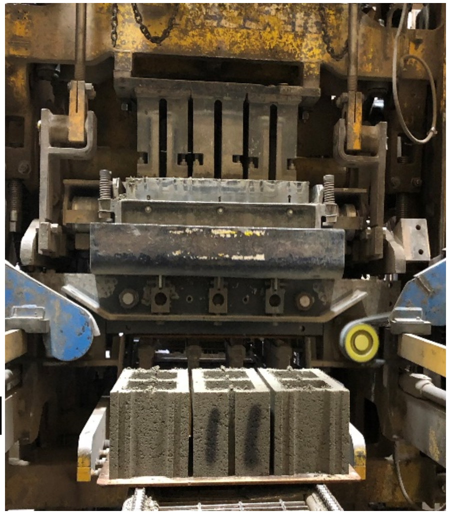
UCLA Samueli School of Engineering

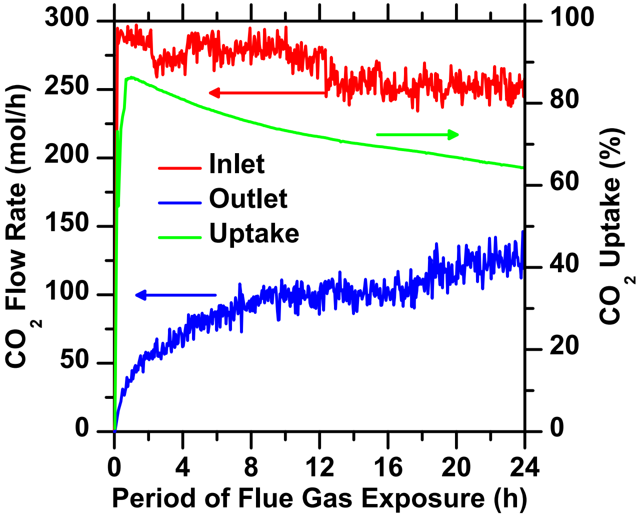


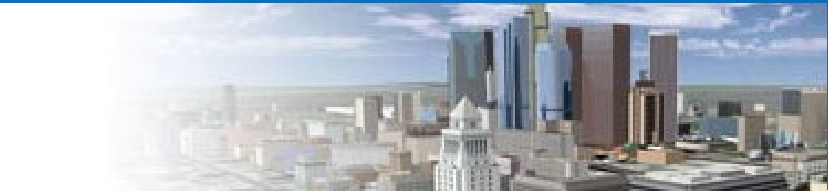
Demonstration at "pilot scale" at Integrated Test Center, Wyoming

- The CO_2Concrete process was deployed at the Integrated Test Center (ITC) in Gillette, Wyoming (June 2020)
- Produced around ~200 tonnes of CO_2Concrete blocks ("CMU") over 12 demonstration runs that featured nearly 5 tonnes of CO_2 uptake
- System performance fulfilled all design specifications: (1) achieved in excess of 75% CO_2 utilization efficiency, (2) utilized greater than 250 kg of CO_2 per run (3) products complied with industry standard specifications (strength > 14 MPa)
- Process conditions optimized to reduce the energy input to achieve production price parity as compared to conventional concrete block









In-progress demonstration of pilot CO_2 mineralization system

- **January 2021:** The system will be deployed at the National Carbon Capture Center in Wilsonville, Alabama (1,880 MW)
- Both coal- and natural gas-combustion flue gas streams will be utilized in this demonstration

Objectives of demonstration:

- Refine system design following ITC demonstration to further optimize system performance and system energy input
- Demonstrate robustness with respect to flue gas and material inputs, and environmental conditions
- Utilize high-volume of CCRs in CO_2Concrete blocks formulation
- Assess product compliance to construction standards
- Develop code compliance reports in collaboration with ICC-ES (certification partner)

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PROPOSED ACCEPTANCE CRITERIA FOR CO_2CONCRETE-BASED CONCRETE MASONRY UNITS

AC520

Proposed for October 2020 Meeting

In progress: Techno-economic analysis and life cycle assessment

Techno-economic analysis

- Perform a techno-economic analysis (TEA) of a CO_2Concrete facility, including accounting of capital, operation, and maintenance costs

Life cycle analysis

- Compare environmental impact of CO_2Concrete and conventional CMU production
- Quantify net GHG emissions reduction offered

Technology gap analysis

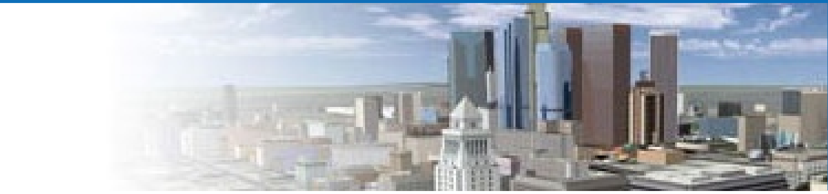
- Prepare and submit a Technology Gap Analysis (TGA) in accordance with SOPO Appendix B

Summary and conclusions

- CO_2 mineralization enables an approach to produce low-carbon concrete products while utilizing CO_2 emissions and CCRs, with strong market potential
  - CO_2 utilization into concrete without CO_2 capture step
  - Impactful potential due to the large market size of concrete
- Direct carbonation of $Ca(OH)_2$ using dilute CO_2 streams is a viable route towards large-scale CO_2 utilization. CO_2 mineralization occurs rapidly, and results in the rapid development of strength, indicative of cementation
- The UCLA team has demonstrated a pioneering technology at the field scale to produce structural concrete masonry units
- This project will advance the technology to the next stage of development

Project timeline

Task #	Task Name	Start	Finish	Duration	2019				2020			
					Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
0	**Project Start**	**01/01/19**	**01/01/19**	**0**								
1	**Project Management and Planning**	**01/01/19**	**12/31/20**	**730d**								
2	**Material specifications, acceptance criteria, and com**	**01/01/19**	**12/30/20**	**730d**								
2.1	Sourcing and characterization of CCRs and portland	01/01/19	03/01/19	60d								
2.2	Carbonation kinetics of reactants	03/02/19	04/30/19	60d								
2.3	Component performance	05/01/19	06/29/19	60d								
2.3	Component performance	08/01/20	09/29/20	60d								
2.3	Component performance	11/01/20	12/30/20	60d								
3	**Bench-scale studies to acquire critical data for syst**	**06/30/19**	**10/27/19**	**120d**								
3.1	Process conditions of simulated flue gas	06/30/19	08/28/19	60d								
3.2	Quantification of heat and mass transfer in CO2NCF	08/29/19	10/27/19	60d								



Project timeline (cont.)

Task #	Task Name	Start	Finish	Duration	2019 Q1	2019 Q2	2019 Q3	2019 Q4	2020 Q1	2020 Q2	2020 Q3	2020 Q4
4	**Design and fabrication of modular, scaled CO2 proc**	**10/28/19**	**04/24/20**	**180d**								
4.1	Component selection and system design	10/28/19	12/26/19	60d								
4.2	System construction	12/27/19	04/24/20	120d								
5	**Commissioning and trial operation of the CO2NCRE**	**04/25/20**	**09/21/20**	**150d**								
5.1	System start-up/commissioning	04/25/20	06/23/20	60d								
5.2	System performance validation	06/24/20	09/21/20	90d								
6	**Field demonstration of CO2NCRETE carbonation sys**	**06/24/20**	**12/30/20**	**190d**								
6.1	Host site preparation	06/24/20	09/21/20	90d								
6.2	Test plan development	07/24/20	09/21/20	60d								
6.3	Installation and operation	09/22/20	12/20/20	90d								
6.4	Decommissioning	12/21/20	12/30/20	10d								
7	**Design and scalability analysis for commercial-scal**	**10/02/20**	**12/30/20**	**90d**								
8	**Techno-economic analysis (TEA) and life cycle asse**	**05/01/19**	**12/30/20**	**610d**								