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

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Concrete construction is hostage to cement production's embodied CO_2 intensity: So what can be done now?

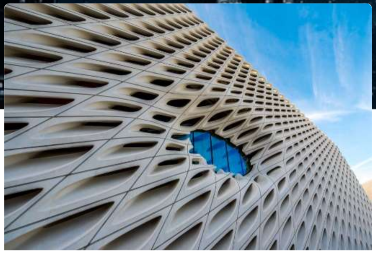
Cement production emits nearly 10% of global CO_2

0.9 tons of CO_2 are emitted per ton of cement produced; 4.5 billion tonnes of cement produced annually

Global concrete **market ~ $ 1 trillion / year**

Ready mixed concrete has the largest market share

The Increasing use of **prefabricated components is a rising industry trend**



Precast and masonry production allow for controlled conditions, and for better quality control

CO_2 utilization (mineralization) implies producing $CaCO_3$

is based on the use of $Ca(OH)_2$
which can be produced thermally, and
electrochemically (without CO_2 emissions)

Carbonation is insensitive to SO_x and NO_x
enables direct stack-tap of flue gases –
without a need for a CO_2 capture step

Mineralization is the only
“thermodynamically downhill” route
for CO_2 utilization

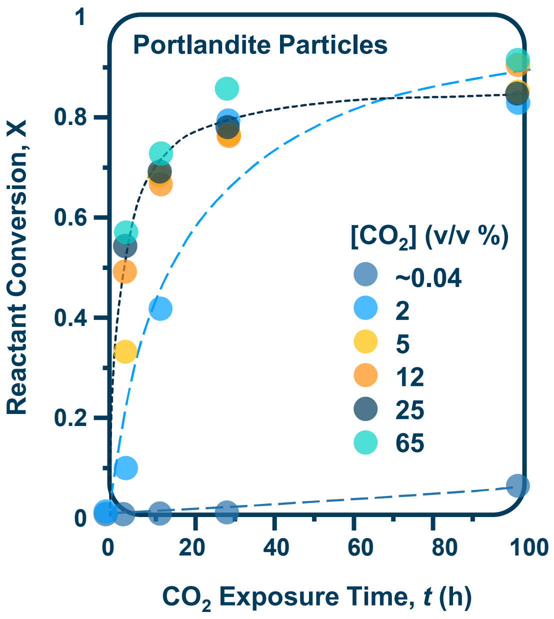
Concrete construction provides a gigaton
scale sink for CO_2 emissions annually

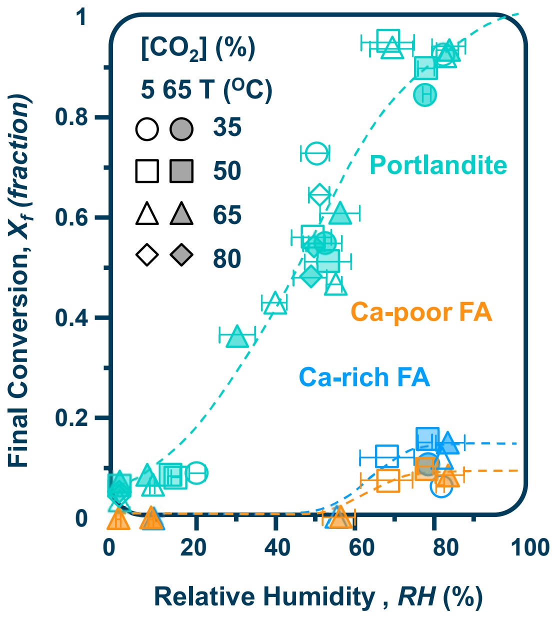
Mobile calcium is available in low-cost
reactants, including coal combustion
residues (CCRs) and steel slags

Alternate cementation methods may
unlock further advantages: fabrication
methods (3DP), greater control

Why choose $Ca(OH)_2$ as a mineralization reactant?

- **Carbonation occurs rapidly** at ambient temperature and pressure without carbon capture step, or gas clean-up (insensitive to SO_x and NO_x)
- **Lower kiln temperature** (800°C) than cement (1500°C) allows reduced energy and CO_2 intensity of production
- **Reaction is downhill:** thermodynamically favorable and requires little, if any, extrinsic energy



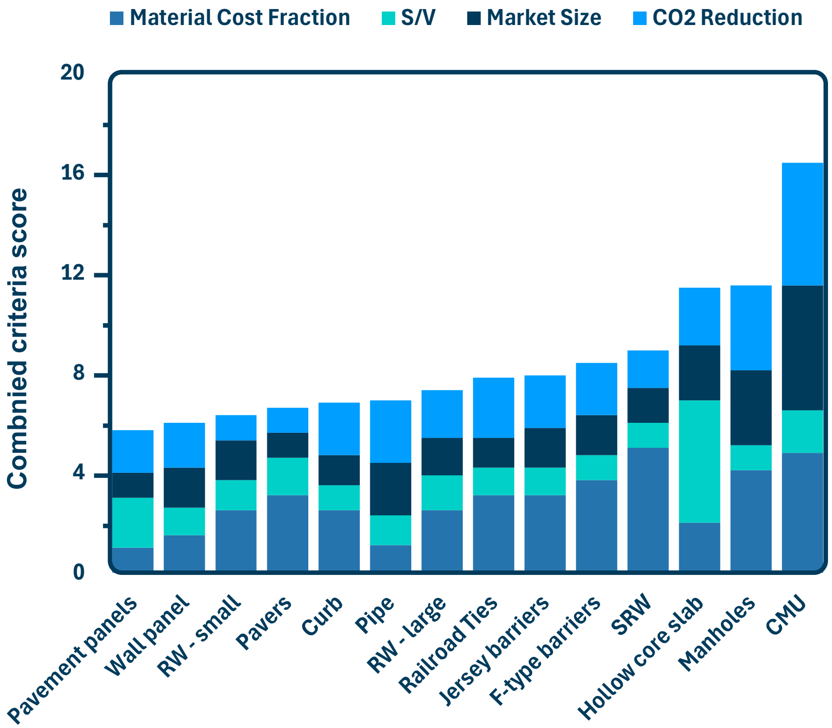


Selecting which product geometries to produce, and why?

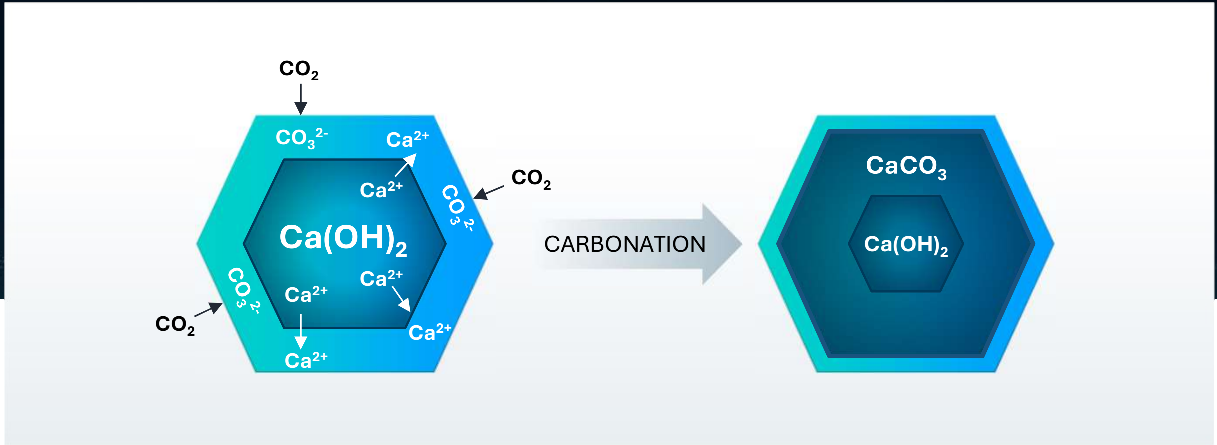
Selected three concrete products for mineralization processing:

- **Defined criteria:** Exposed surface-to-volume ratio, estimated CO_2 reduction (reduction in embodied carbon intensity: eCI), market size, cementitious materials cost
- The analysis was informed by data about processing conditions and product performance (e.g., strength)
- Based on combined scoring criteria, we selected: CMU, segmented retaining walls (SRW), and manholes (MAN)

Unit type	Representative S/V (mm^{-1})	CO_2 uptake rate $gCO_2/gCa(OH)2$ (K_s - s^{-1})
CMU	0.08	9.54E-04
SRW	0.05	6.16E-04

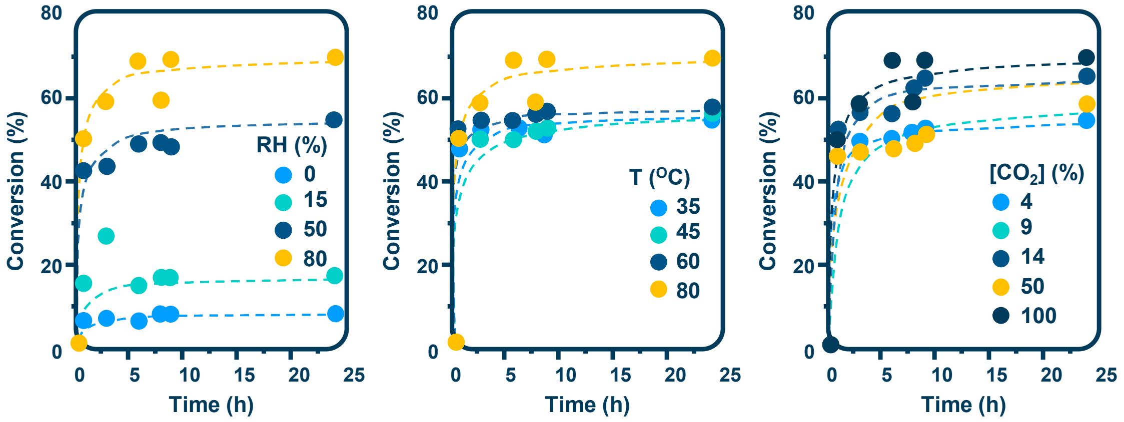


Maximizing reactant consumption and mineralization



Carbonation potentials of reactants – portlandite ($Ca(OH)_2$)

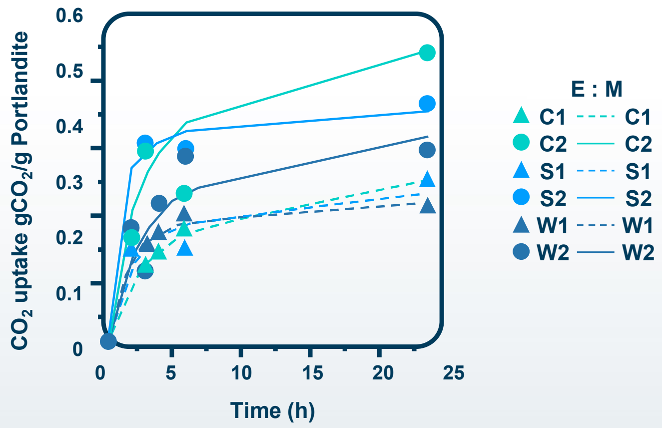
- Portlandite carbonation largely dependent on dissolution and precipitation of $Ca(OH)_2$ and $CaCO_3$, respectively
- T and [CO_2] have minor affect on extent of reaction which allows ambient conditions
- Carbonation is near-complete within 24 h
- **The Significance:** Pressurization, CO_2 enrichment, or significant heating is not required for portlandite carbonation

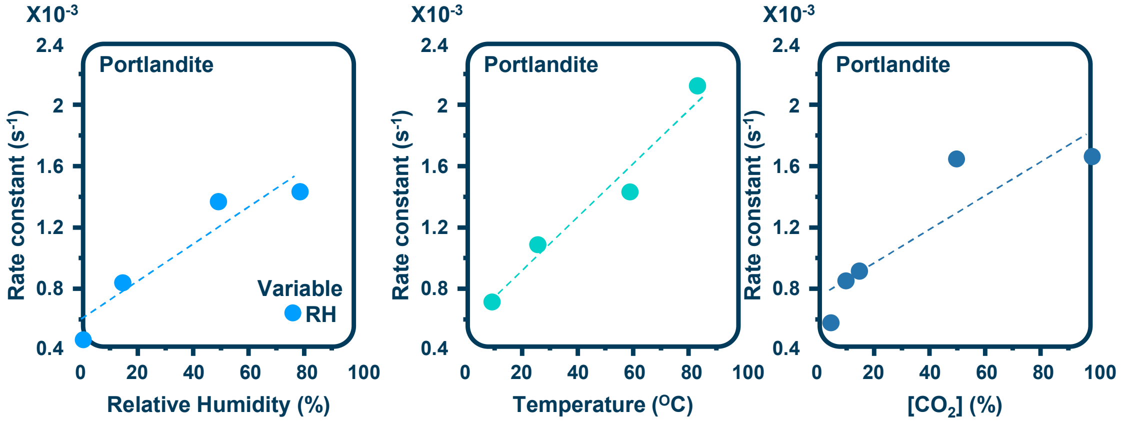


Microstructural influences on carbonation kinetics

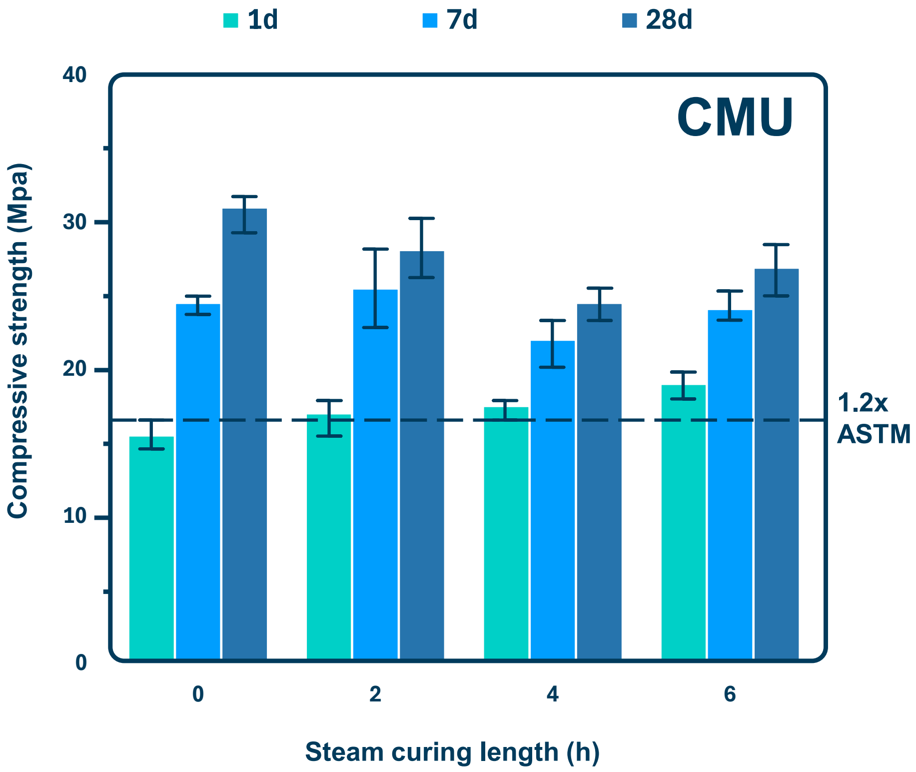
Carbonation kinetics of CO_2Concrete mixture compositions

- Kinetics of particulate carbonation depend on relative humidity, T and $[CO_2]$.
- Composite mixture formulation: Cement, portlandite and fly ash that were formed into geometries with suitable surface-to-volume (s/v, m^{-1}) ratios
- Carbonation data was collected across range of operating conditions to simulate flue gas conditions: T: 20-to-65°C, relative humidity (RH): 10-to-80%, and CO_2 concentration: 3-to-15 vol.%
- Important to match the “testing” surface area to volume ratio (s/v) of concrete products/components. In general, the carbonation rates for each component are $K_S > 1E\text{-}05\ s^{-1}$





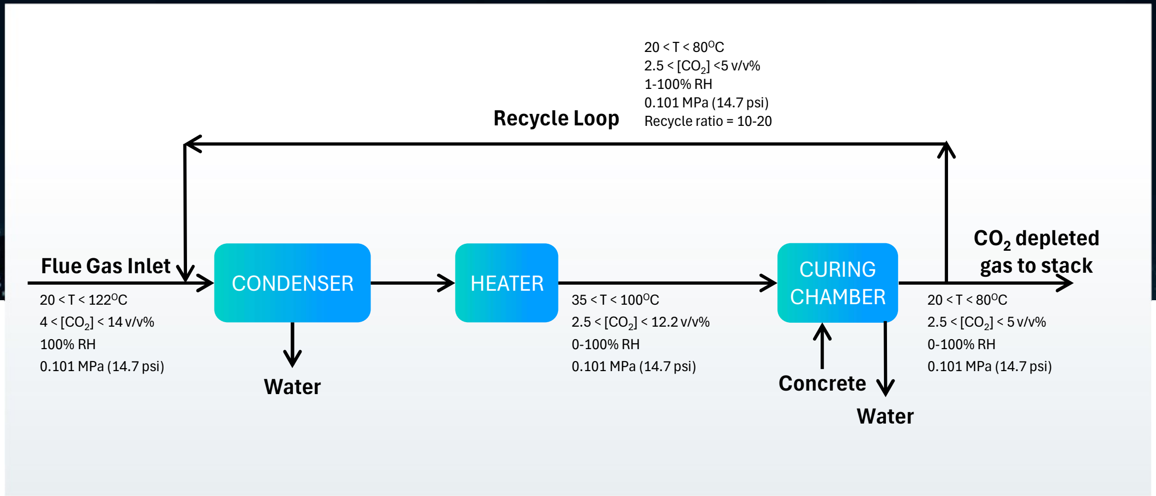
The influence of carbonation on strength gain?



Establishing processing-property relations

- Measured strength gain of carbonated materials as a function of the duration of steam curing cycle
- In general, a shorter steam curing duration enhances carbonation by reducing the surface coverage of reactant particles – which are otherwise passivated
- Carbonated concrete exceeds the strength requirement for relevant product selections while ensuring CO_2 uptake

AspenPlus© model of carbonation conditions, in reactor, over time



Recycle Loop

20 < T < 80°C
2.5 < $[CO_2]$ <5 v/v%
1-100% RH
0.101 MPa (14.7 psi)
Recycle ratio = 10-20

Flue Gas Inlet

20 < T < 122°C
4 < $[CO_2]$ < 14 v/v%
100% RH
0.101 MPa (14.7 psi)

CONDENSER

Water

HEATER

35 < T < 100°C
2.5 < $[CO_2]$ < 12.2 v/v%
0-100% RH
0.101 MPa (14.7 psi)

CURING CHAMBER

Concrete

Water

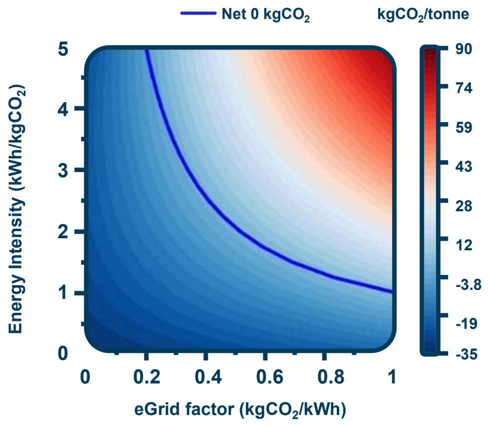
CO_2 depleted gas to stack

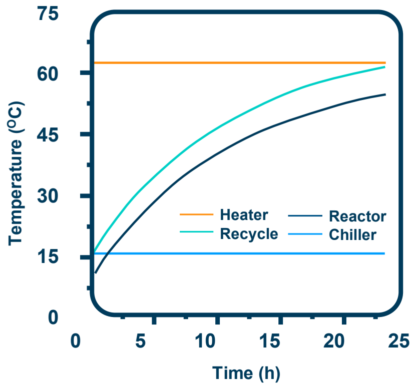
20 < T < 80°C
2.5 < $[CO_2]$ < 5 v/v%
0-100% RH
0.101 MPa (14.7 psi)

Development of carbonation/mass transfer model at the bench-scale

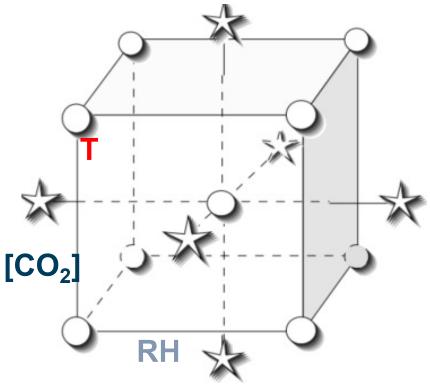
Two Aspen Plus© based models were developed:

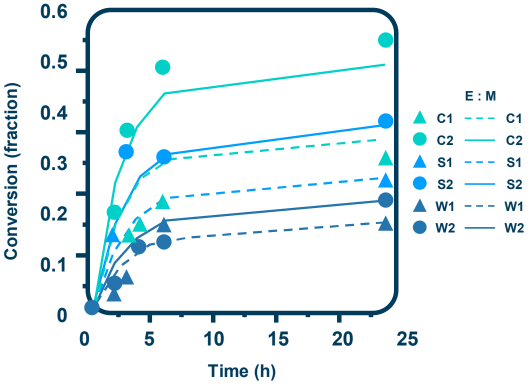
1. Steady-state model that assesses 24-h average CO_2 uptake based on reactor conditions (RH, $[CO_2]$, T)
2. Dynamic model to simulate the reactor and the process conditions in time over 24-h operating period
3. The dynamic model incorporates a carbonation regression model to determine how time-dependent conditions affect reactant conversion/CO_2 uptake
4. As appropriate, the simulation data was used for developing stream tables for the design basis memorandum (DBM)





Developing predictive (DOE) model to ascertain CO_2 uptake

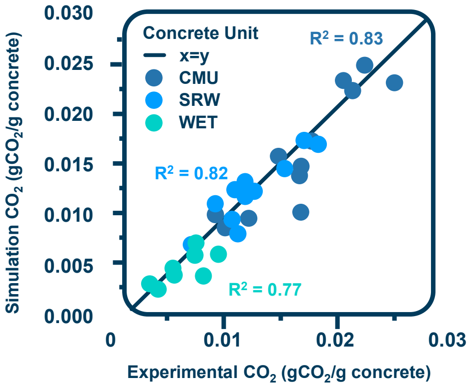


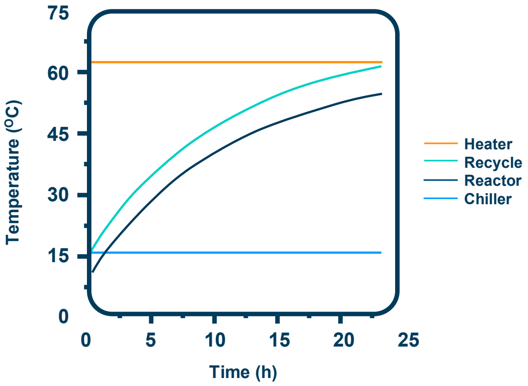


Developed predictive mode for the carbonation of CO_2Concrete™ components at the bench-scale

- This model is developed using a “Design-of-Experiments” approach that is used to assess the parametric dependence of T, RH and [CO_2] on CO_2 uptake
- The model estimates CO_2 uptake across varying carbonation conditions for each product geometry across a range of temperatures, RH and CO_2 concentration
- The regression model makes use of Aspen Plus© simulation data to assess how process variables and conditions affect mineralization across diverse conditions

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



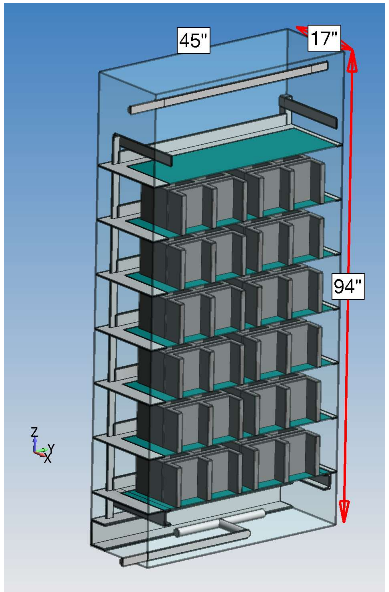


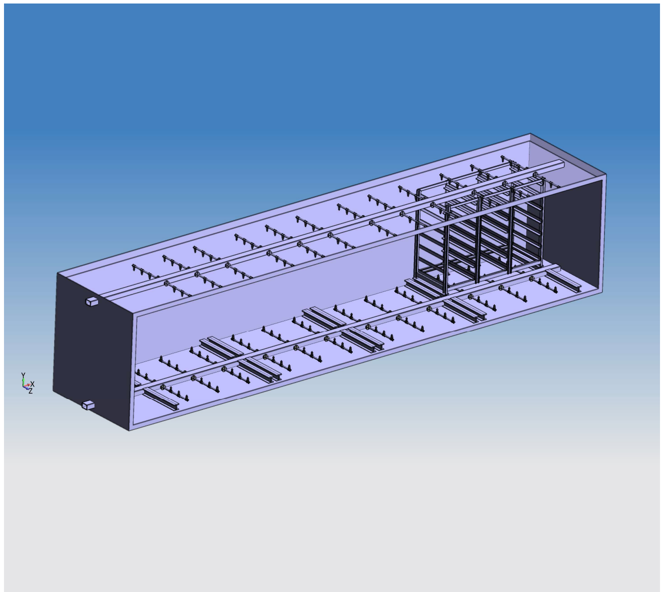
Design modifications to existing mineralization system

OBJECTIVES

Identify modifications required to the existing CO_2 mineralization system or design and fabricate new system for selected precast concrete components

- **Subtask A** – CFD model development
- **Subtask B** – System design modifications/fabrication
- **Subtask C** – HAZOP





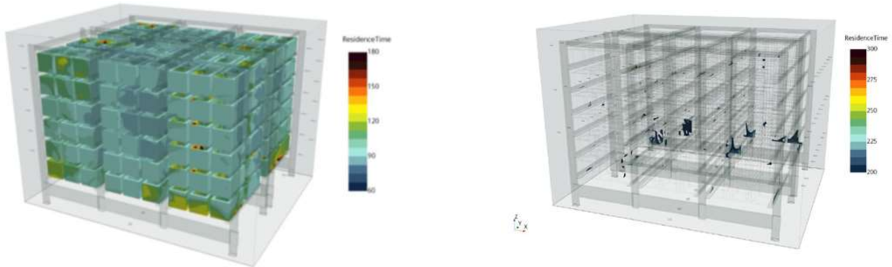
Design modifications to existing mineralization system

SUBTASK 6.1

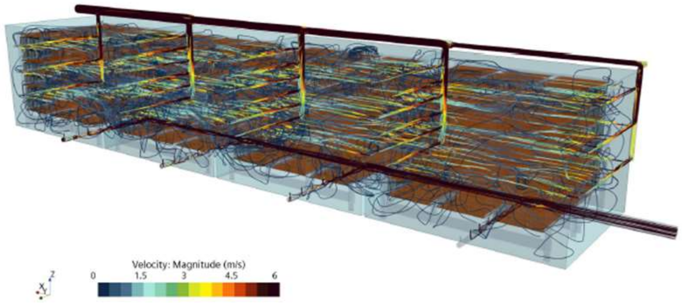
CFD Model Development

- Computational fluid dynamics (CFD) used to optimize gas flow and internal reactor geometry for concrete elements
- CFD helped guide the required concrete component flowrate coverage to meet conditions indicated by the process model
- System gas control skid was modified and a redesign of the carbonation reactor was completed based on the CFD simulation results
- An updated design basis memorandum (DBM) was submitted for fabrication

TRANSIENT HEAT AND MASS TRANSFER ANALYSIS



GAS FLOW DISTRIBUTION OPTIMIZATION



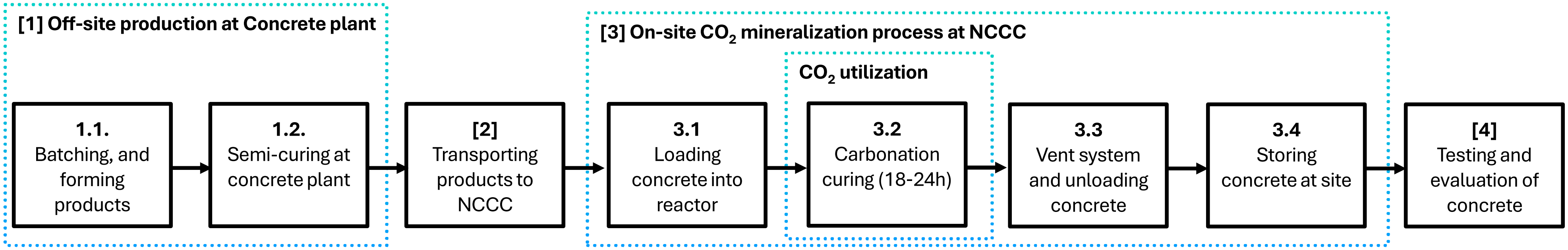
System fabrication, installation and commissioning

- The system was fabricated, and post-FAT (for functionality, and quality) was shipped to the NCCC for installation
- At the NCCC, internal reactor instrumentation was installed and tested including:
    - RH-T sensors
    - Flow and pressure sensors
    - CO2 concentration sensors
    - Electric power meters
    - Water flow meters
- System functionality and heating rate of the reactor were evaluated following commissioning
- Following system commissioning, multiple test runs were carried out to produce concrete products with support of local precast/masonry producers

National Carbon Capture Center (NCCC), AL, 2024

Concrete product manufacturing, and performance validation of carbonated products

- Concrete was semi-cured at concrete facilities (Blair Block and Alcrete)
- This method of offsite production required substantial “green strength” for the products to be transported which resulted in more cement use
- The formed products were shipped to NCCC and loaded into carbonation reactor for 18-to-24 hours of processing
- Once completed, the concrete was unloaded and stored for ASTM testing (carried out by 3rd-party testing entity)
- **Total mass produced:** CMU: 31 tonnes, SRW 51 tonnes, Manholes: 40 tonnes; with a production rate of >10 tonnes of production per day



[1] Off-site production at Concrete plant

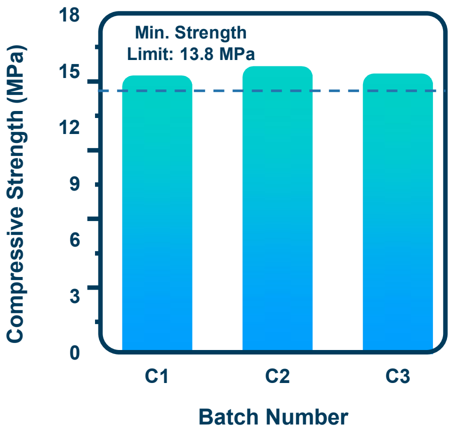
1.1. Batching, and forming products → **1.2.** Semi-curing at concrete plant → **[2]** Transporting products to NCCC →

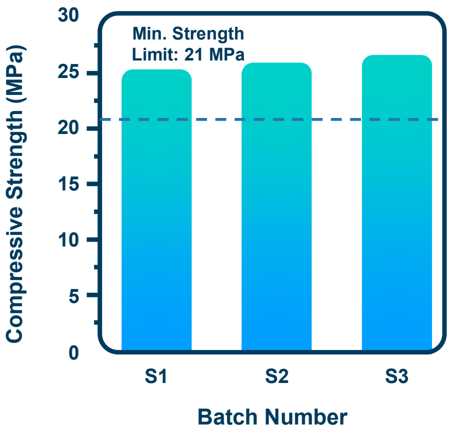
[3] On-site CO_2 mineralization process at NCCC

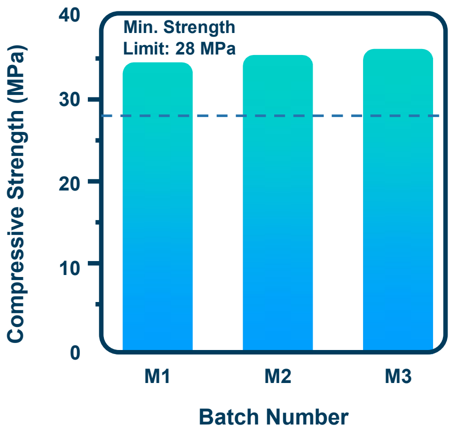
3.1 Loading concrete into reactor → **CO_2 utilization:** **3.2** Carbonation curing (18-24h) → **3.3** Vent system and unloading concrete → **3.4** Storing concrete at site →

[4] Testing and evaluation of concrete

Performance validation, and product compliance (with existing ASTM standards) with emphasis on strength properties







- Carried out standardized testing for each product based on existing standards (e.g., by NCMA’s testing laboratories)
- Each concrete product passed ASTM strength requirements. And, each test run exceeded target 0.2 gCO_2/g reactant
- Despite variation in CO_2 uptake – minimal variations in strength observed in concrete samples

Technoeconomic analysis, lifecycle assessment, and overall commercialization strategy

- Key success of demonstration was to produce a concrete product with reduced embodied carbon intensity (ECI)
- Net CO_2 reduction via replacement of raw materials and CO_2 uptake
- Lifecycle analysis identified net CO_2 reduction across all products:
  - CMU: 30.1%
  - SRW: 31.3%
  - MH: 19.8%
- These values are below project target of 45% but this is a function of the green strength requirement for transport

BLOCK MAKING ≈ STANDARD BLOCKS

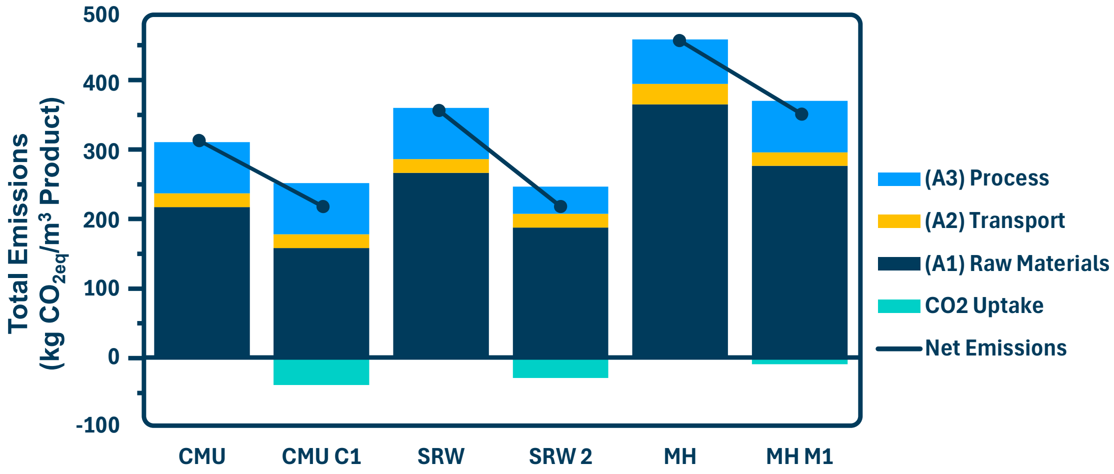
TRANSPORTATION≈ STANDARD BLOCKS

CARBONATION PROCESS > STANDARD BLOCKS

RAW MATERIALS << STANDARD BLOCKS

CO_2 UPTAKE >> STANDARD BLOCKS

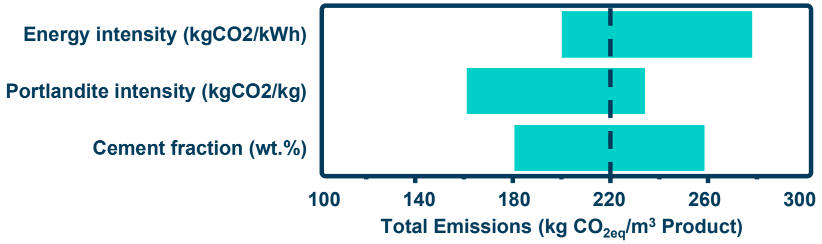
NET CO_2 EMISSIONS << STANDARD BLOCKS



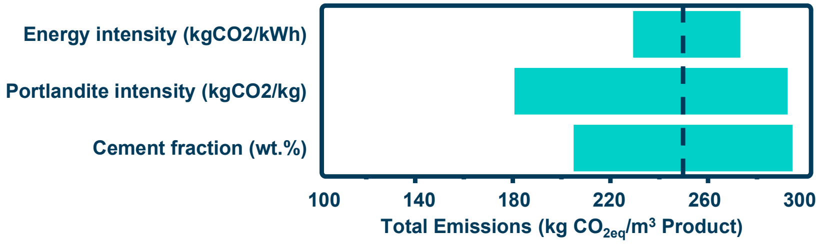
Technoeconomic analysis, lifecycle assessment, and overall commercialization strategy

- Limitations of performing demonstration at host-site influenced final eCI reductions:
  - **Cement mass fraction** – minimum required to achieve transport strength
  - **Hydrated lime eCI** – future scenarios could obtain from renewable sources
  - **Site energy supply** – limited to local eGrid values. Plan to retrofit sites with biomass generators -> CO_2 supply and energy
- Sensitivity analysis was conducted for each product to assess these key areas

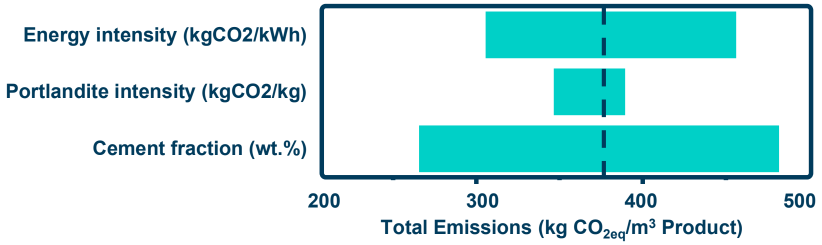
CMU



SRW

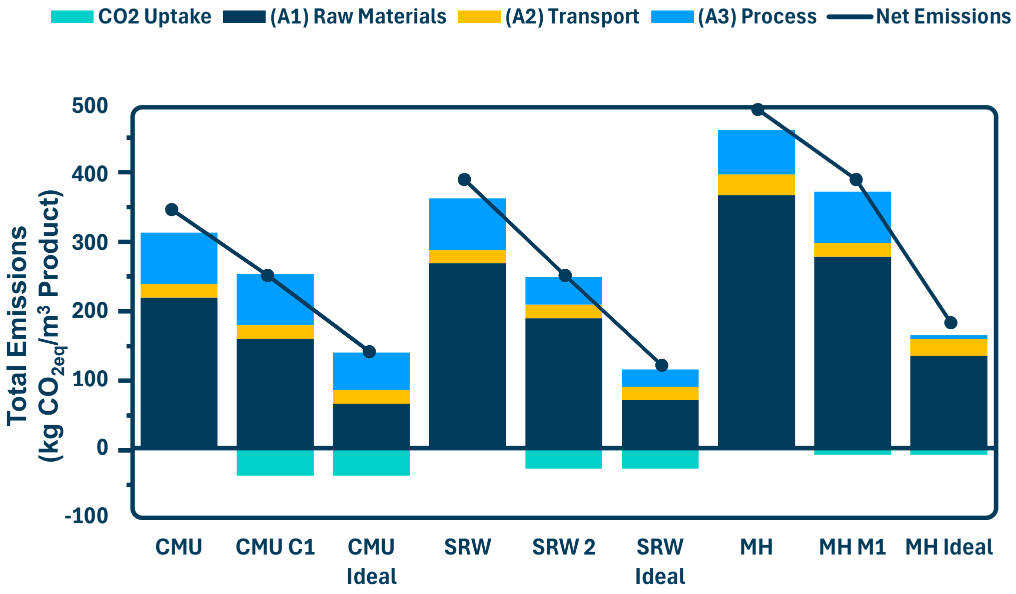


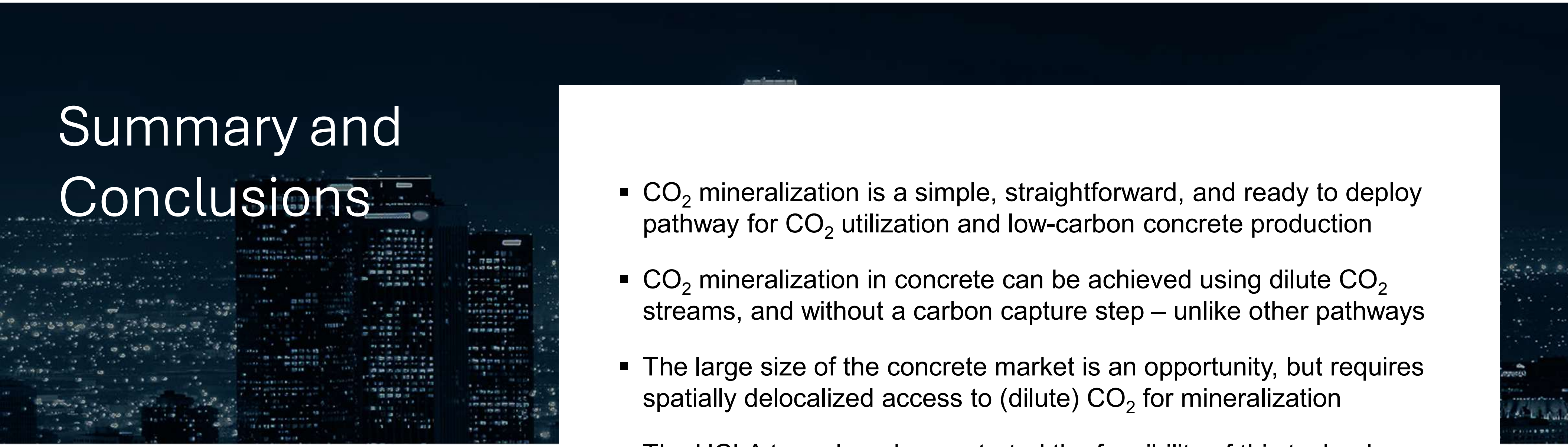
Manhole



Technoeconomic analysis, and lifecycle assessment: What we've accomplished, and what more can be done?

- Demonstrated an approach to reduce eCI of precast and concrete masonry units by up to 30% by: reducing cement use, and enabling CO_2 mineralization
- The reduction was lower than targeted due to the need to use more cement to ensure "green-strength" during transport prior to carbonation
- There are three clear pathways to reduce eCI further: **Reduce cement use, use low(er) eCI lime and lime containing residues, use green(er) electricity**
- With these reductions, for typical onsite production, eCI reductions of up to 70% can be realized quickly
- CarbonBuilt is delivering on this approach as is in commercial operations today (in Alabama, with other projects in the pipeline).





Summary and Conclusions

- CO_2 mineralization is a simple, straightforward, and ready to deploy pathway for CO_2 utilization and low-carbon concrete production
- CO_2 mineralization in concrete can be achieved using dilute CO_2 streams, and without a carbon capture step – unlike other pathways
- The large size of the concrete market is an opportunity, but requires spatially delocalized access to (dilute) CO_2 for mineralization
- The UCLA team has demonstrated the feasibility of this technology at pilot-scale and exceeded project milestones
- This project has advanced the technology from TRL 3+ to TRL 6^+
- This technology is already being commercialized by CarbonBuilt at concrete masonry plants across the United States