Upcycled "CO_2-negative" concrete for construction functions

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Developed for: NETL Carbon Capture, Utilization, Storage, Oil & Gas Technologies Integrated Review Meeting

August 26–30, 2019 in Pittsburgh, PA

Presentation outline

- Project Overview and Technology Background: Background and overall project objectives, *upcycled concrete* production process, advantages and challenges, timeline
- Technical Approach/Project Scope: Experimental design and work plan, key milestones
- Progress Highlights
- Current Status of Project
- Summary and Ongoing Work

Carbon dioxide emissions in concrete

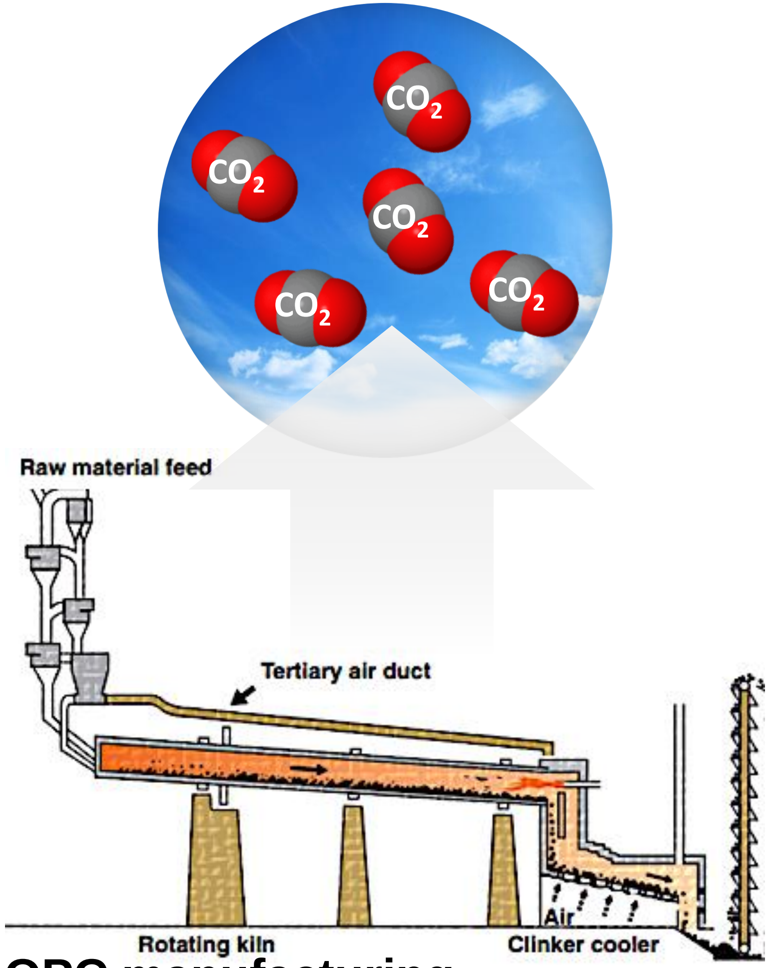
- >30 B tons of concrete*, >4 billion tons of portland cement (OPC) produced annually**
- 0.9 ton CO_2 emitted per ton OPC produced†; from energy input for processing at high temperature (~1600 °C) and CO_2 emitted during calcination

$$CaCO_3 \rightarrow CaO + CO_2$$

- Hydrated lime is an efficient material for CO_2 uptake (max. CO_2 uptake = **<u>59%</u>** by mass)

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

*Cement Sustainability Initiative, 2009; **USGS, 2018; †Gartner 2004



OPC manufacturing

Objectives of the *upcycled concrete* technology

Upcycling industrial wastes and CO_2

- Utilize coal combustion and metal processing wastes as precursors for scalable CO_2 mineralization

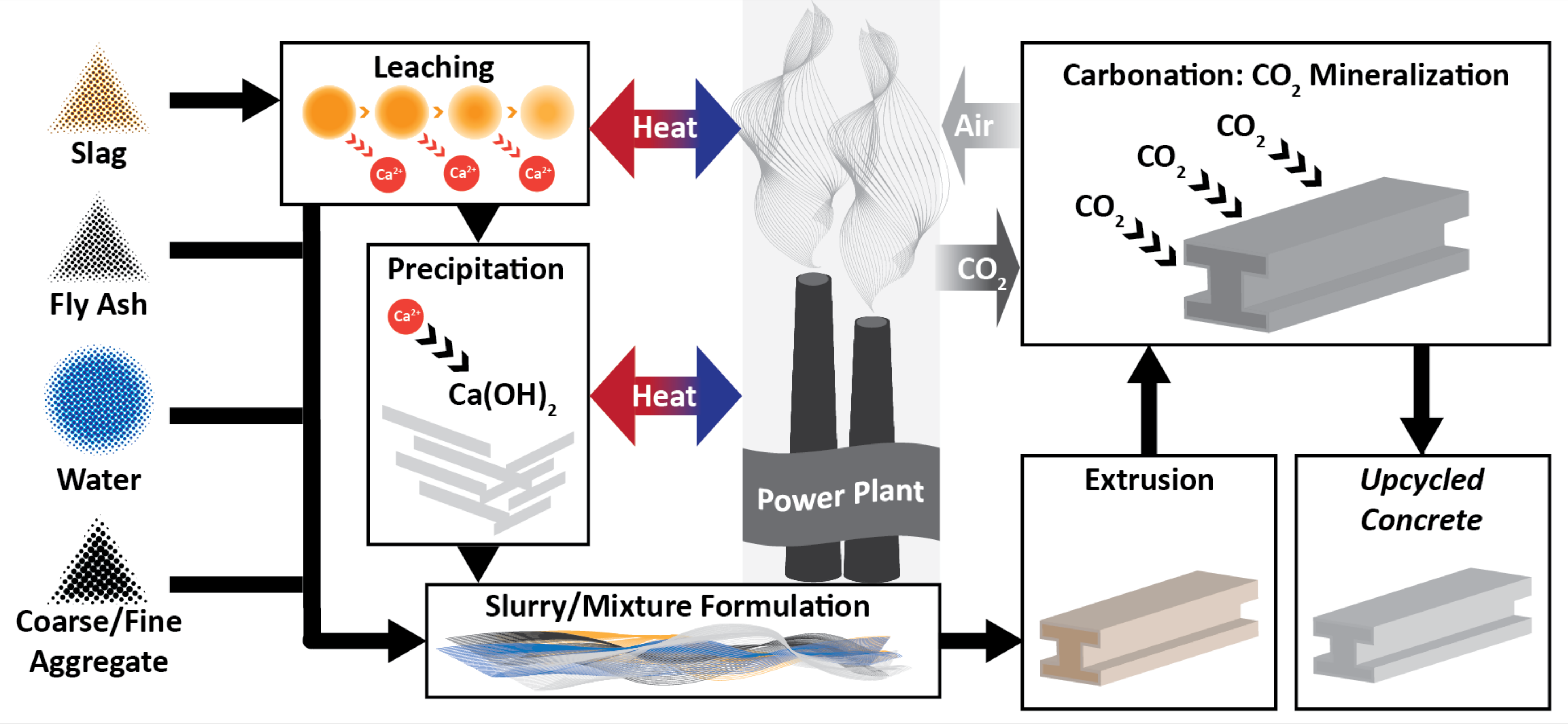
Process design

- Develop an integrated, ‘bolt-on’ technology solution for upcycled concrete production incorporating aspects of *Ca-leaching*, *$Ca(OH)_2$ precipitation*, *mixture formulation*, and *structural shape-stabilization*, while maximizing CO_2 uptake

OPC concrete replacement

- Develop a novel CO_2-negative *upcycled concrete* that is performance-equivalent or superior to OPC-based concrete

Overview of CO_2-negative upcycled concrete production process



Advantages of *upcycled concrete* and considerations

- Reduce construction period with precast/prefabricated components, compared to traditional "cast-in-place" construction, while ensuring repeatability and high quality
- Utilize CO_2 and waste heat in a typical coal-fired power plant (e.g., flue gas, blowdown steam), and reject waste streams (e.g., crystalline slags, non-compliant fly ash in landfills and ash ponds)
- Path to carbon neutral/negative cementation through the production of hydrated lime or portlandite, $Ca(OH)_2$
- Consider: (1) compositional heterogeneity (leaching/carbonation potential) of fly ash and slag, (2) carbonation kinetics, (3) concrete workability and (4) mechanical properties

Project scope and current status

YEAR 1
- Portlandite production by leaching of crystalline iron and steel slags
- CO_2 mineralization by accelerated carbonation

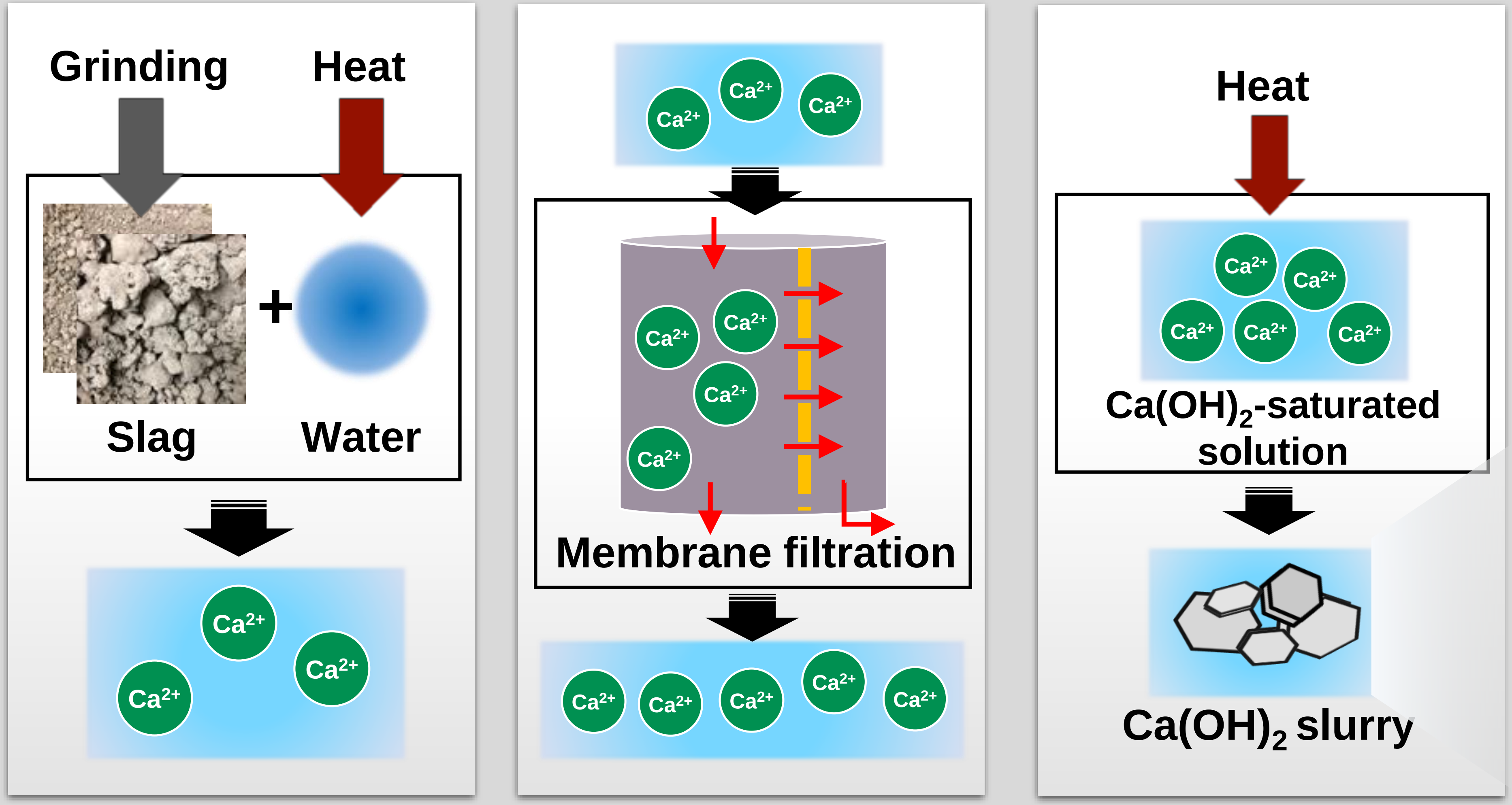
YEAR 2
- Upcycled concrete fabrication and properties
- Process design and scalability assessment

YEAR 3
- **System evaluation**
- **Final technology assessment**

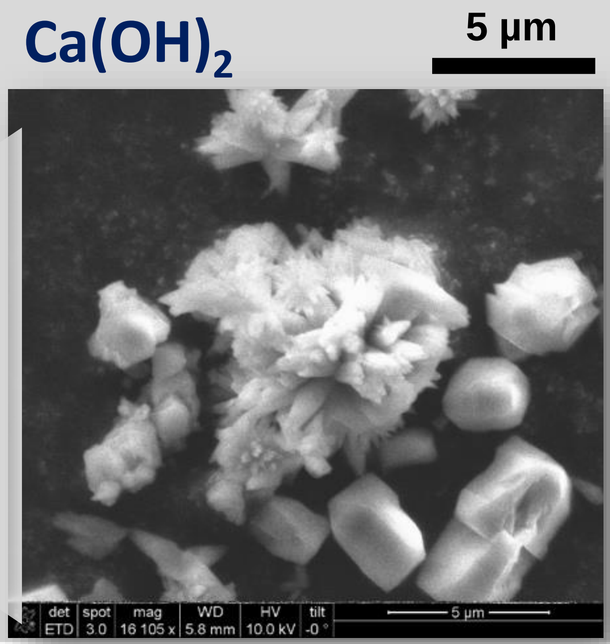
Key milestones

Milestones	Budget Period 1 4/1/17 - 6/30/18					Budget Period 2 7/1/18 - 6/30/19				Budget Period 3 7/1/19 - 3/31/20		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Leaching rate and extent for 3 slag types				■								
Uptake 0.06-0.12 g CO_2/g solid with blended fly ash and $Ca(OH)_2$					■							
Rheology of upcycled concrete (UC) with 3 fly ash-$Ca(OH)_2$ blends								■				
Shape-stable UC having compressive strength ≥ 15 MPa									■			
Process design for lab-scale test unit with production throughput of 10-100 kg/day UC									■			
Construction of lab-scale test unit											■	
Production throughput of 10-100 kg/day UC, with CO_2 uptake of 0.06-0.12 g CO_2/g solid												■
Scalability, lifecycle CO_2 footprint and techno-economic feasibility												■
Technology Gap Analysis												■

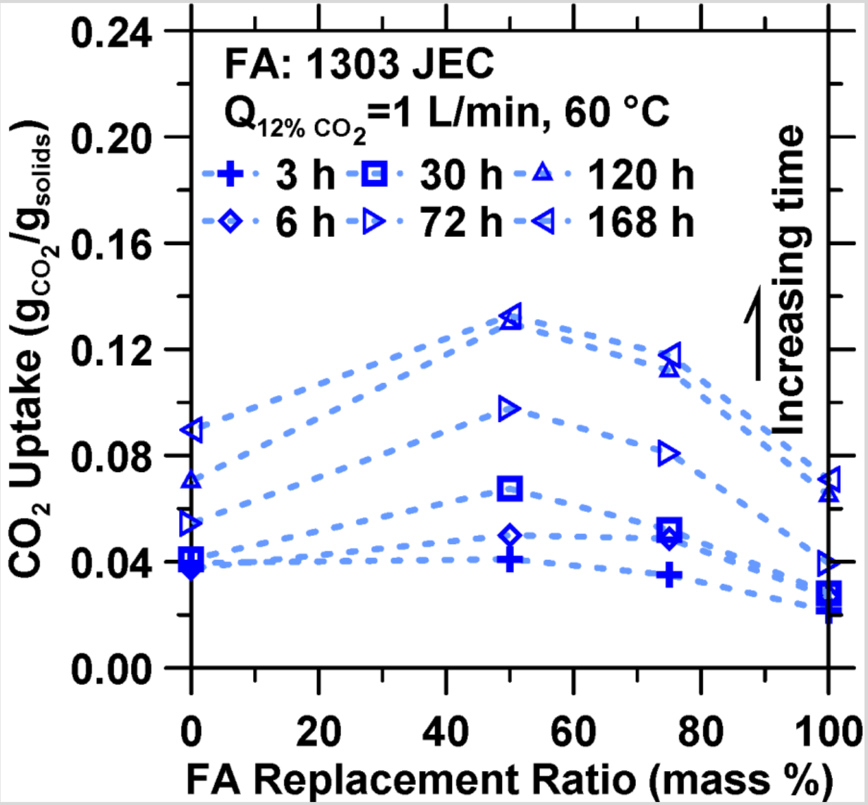
Highlights from BP 1: Low T portlandite synthesis



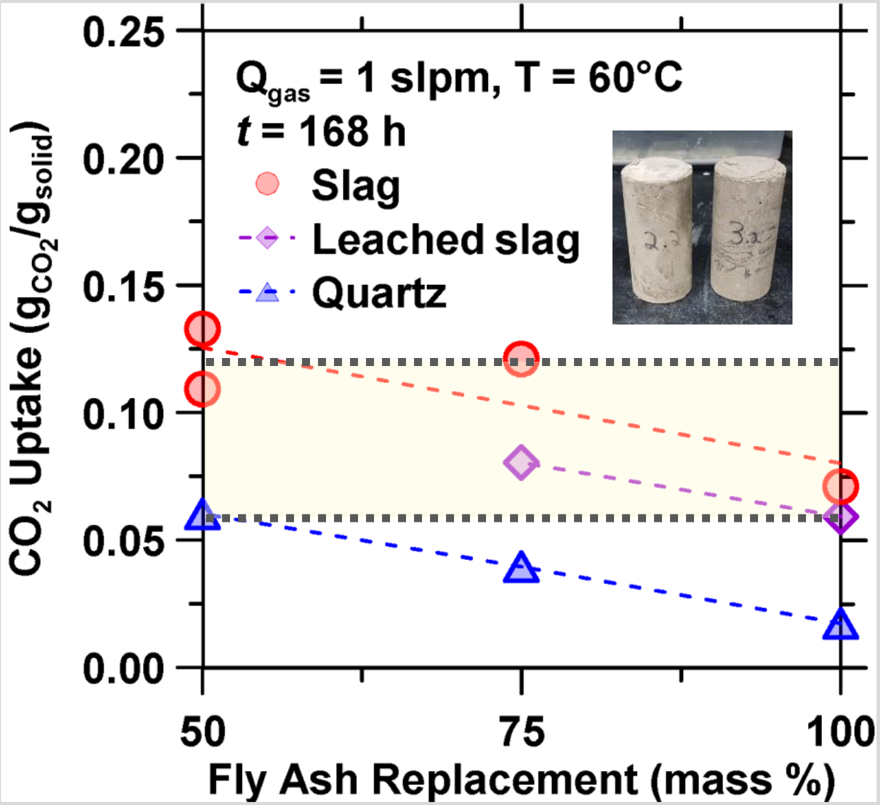
Precipitated $Ca(OH)_2$



Highlights from BP1: CO_2 mineralization in mortars



In mortars, the effect of CH content on CO_2 uptake is not a simple linear scaling

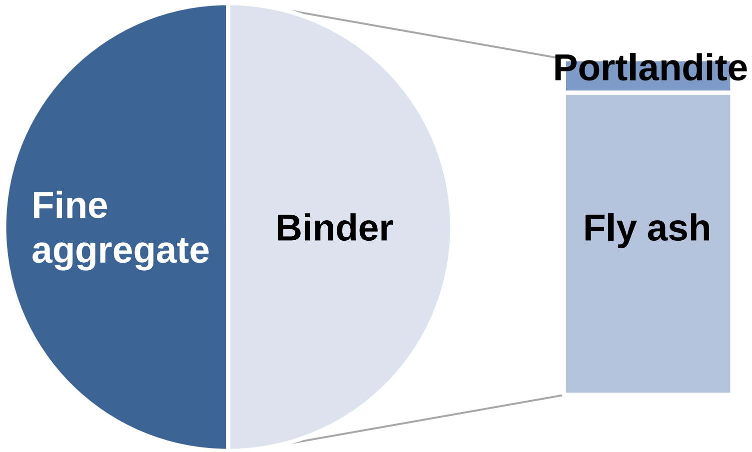


Target CO_2 uptake of 6–12% reached at 168 h for mixtures having ≤50% CH containing slag

BP2: *Upcycled concrete* fabrication and properties–Rheology

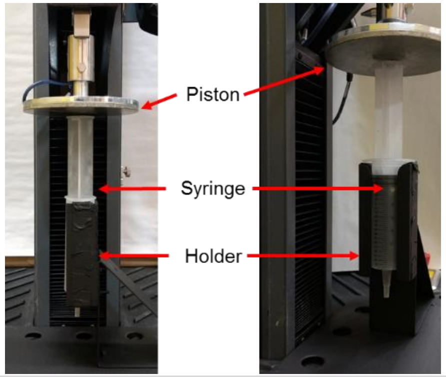
- Pastes consist of fly ash, portlandite (mortars consist of silica sand or basic oxygen furnace slag as fine aggregate)
- Water to binder mass ratios (w/b) vary from 0.2–0.5
- High-range water-reducing admixture (SP)
- Retarder used in Class C mixture to control setting
- ***Vane shear test:*** Reduction in w/b, increase in sand content increased plastic viscosity; higher yield strength for Class F pastes
- ***Squeeze test:*** High shear stress in mortars with 50% sand, and at low w/b
- ***Extrusion test:*** Cohesiveness and fluidity

Example *upcycled concrete* mixture proportions (volume basis)



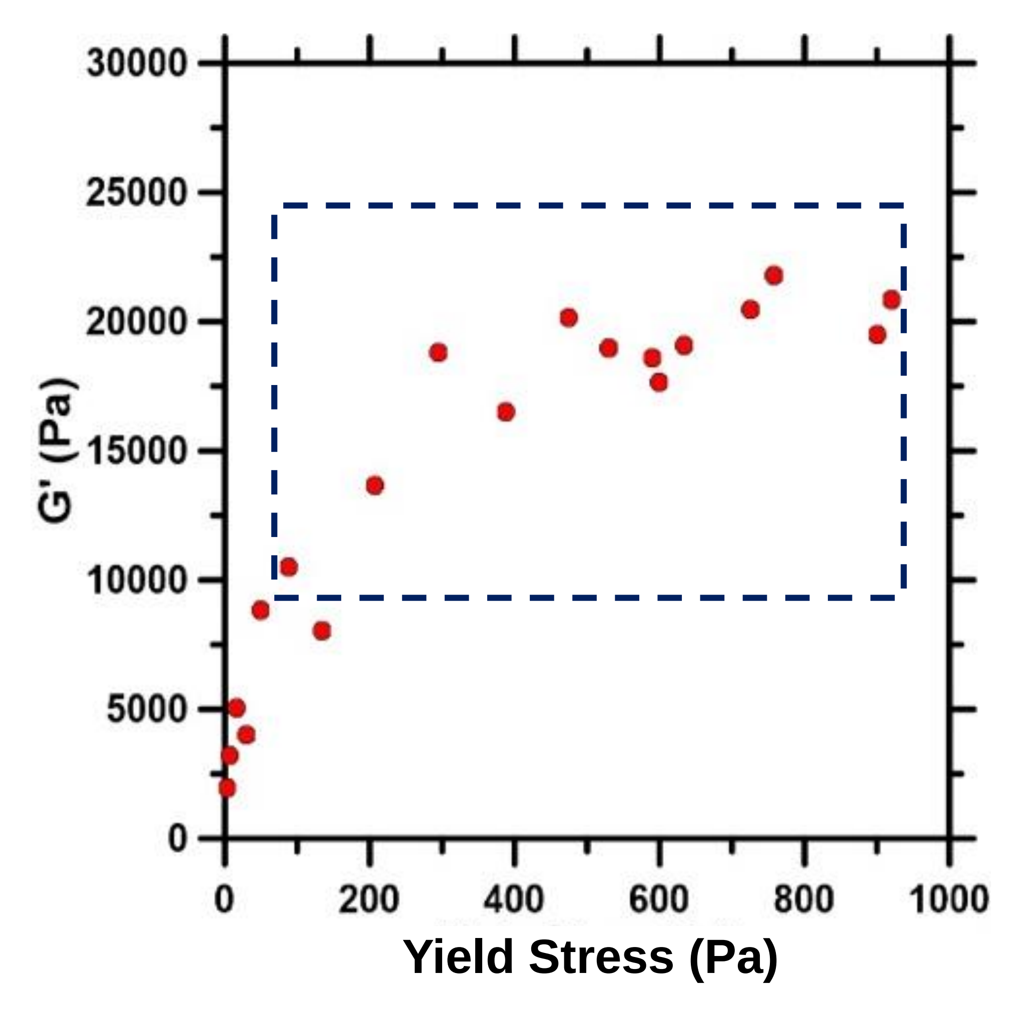
Squeeze test

Ram extrusion



BP2: *Upcycled concrete* fabrication and properties: Extrudability

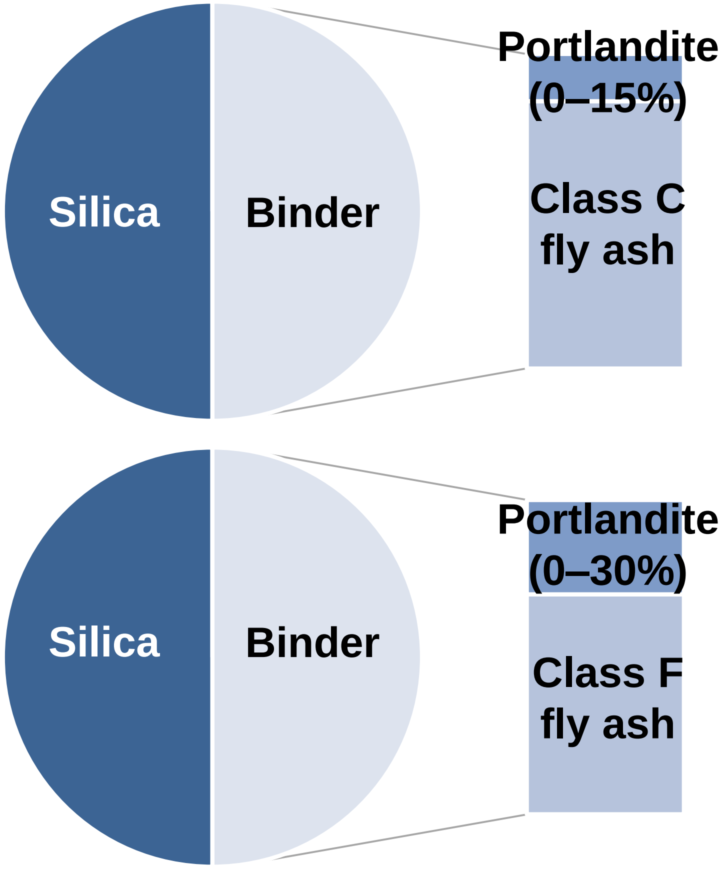
- Extrudability criteria defined based on rheological parameters: cohesion (ability to retain water under pressure), yield stress, storage modulus
- Cohesive mixtures with low yield stress unable to hold its weight during extrusion
- Adequate yield stress but low cohesiveness results in high degree of consolidation, thus requiring high extrusion pressure
- The team identified relevant rheological properties and criteria for *upcycled concrete* mortar formulations that can be shape stabilized by extrusion



BP2: *Upcycled concrete* fabrication and properties: Strength

- Molding and compaction identified as alternative shape stabilization methods
- Molded portlandite-containing mortars tested for their compressive strength upon carbonation (100% CO_2), achieving ≥ 15 MPa after 7 days
- Compressive strength increased upon carbonation, and with increasing portlandite content (particularly for Class F-containing mortars)
- All Class C mortars had compressive strengths ≥ 15 MPa (target value); ~30% portlandite replacement level needed for Class F mortars

Mortar proportions by volume



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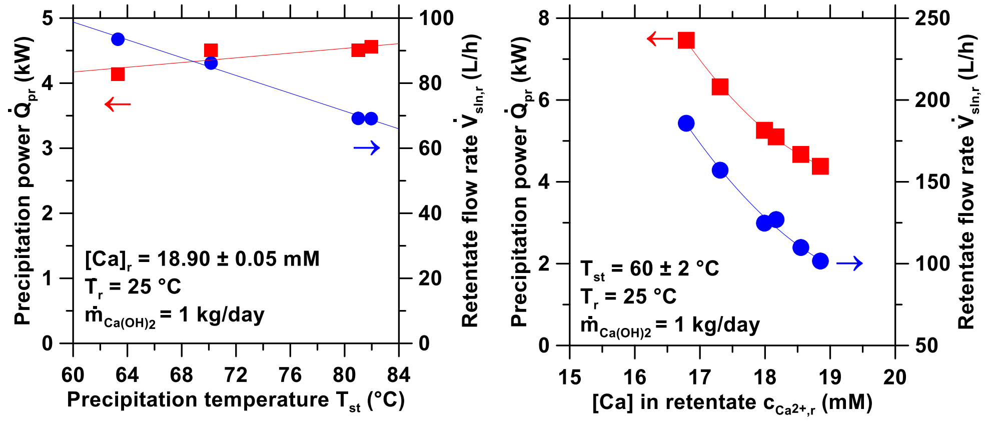
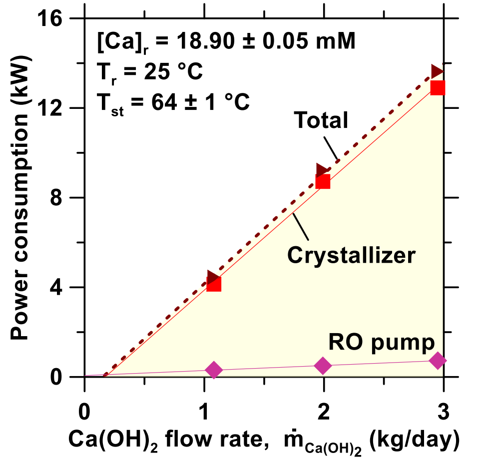
Mix ID	Compressive strength at 7 days (MPa)	
	Moist-cured	Carbonated
MCH0	16.9 (1.1)	19.3 (2.4)
MCH5	12.0 (1.8)	25.3 (4.1)
MCH10	27.7 (2.0)	29.3 (1.8)
MCH15	22.5 (0.2)	22.5 (2.1)
MFH0	0.4 (0.01)	0.5 (0.1)
MFH10	6.7 (0.3)	5.9 (0.6)
MFH20	6.8 (0.7)	9.9 (2.5)
MFH30	5.0 (0.5)	16.1 (0.4)

BP2: System design using Aspen Plus – Power consumption

- Steady-state model developed based on mass and energy balances using Aspen Plus
- Leaching is considered as a batch process, NF/RO and precipitation are steady-state processes
- Slag conversion (8.5%) based on experimental data
- Pump efficiency: 15% (lab-scale) or 80% (industrial)
- For a fixed production throughput of 1 kg/day, with increasing precipitation T, precipitation power ($\dot{Q}_{pr}$) increases and NF/RO retentate flow rate ($\dot{V}_{sln,r}$) decreases
- Increasing [Ca] in retentate decreases both $\dot{Q}_{pr}$ and $\dot{V}_{sln,r}$; $\dot{Q}_{pr}$ dominates energy input

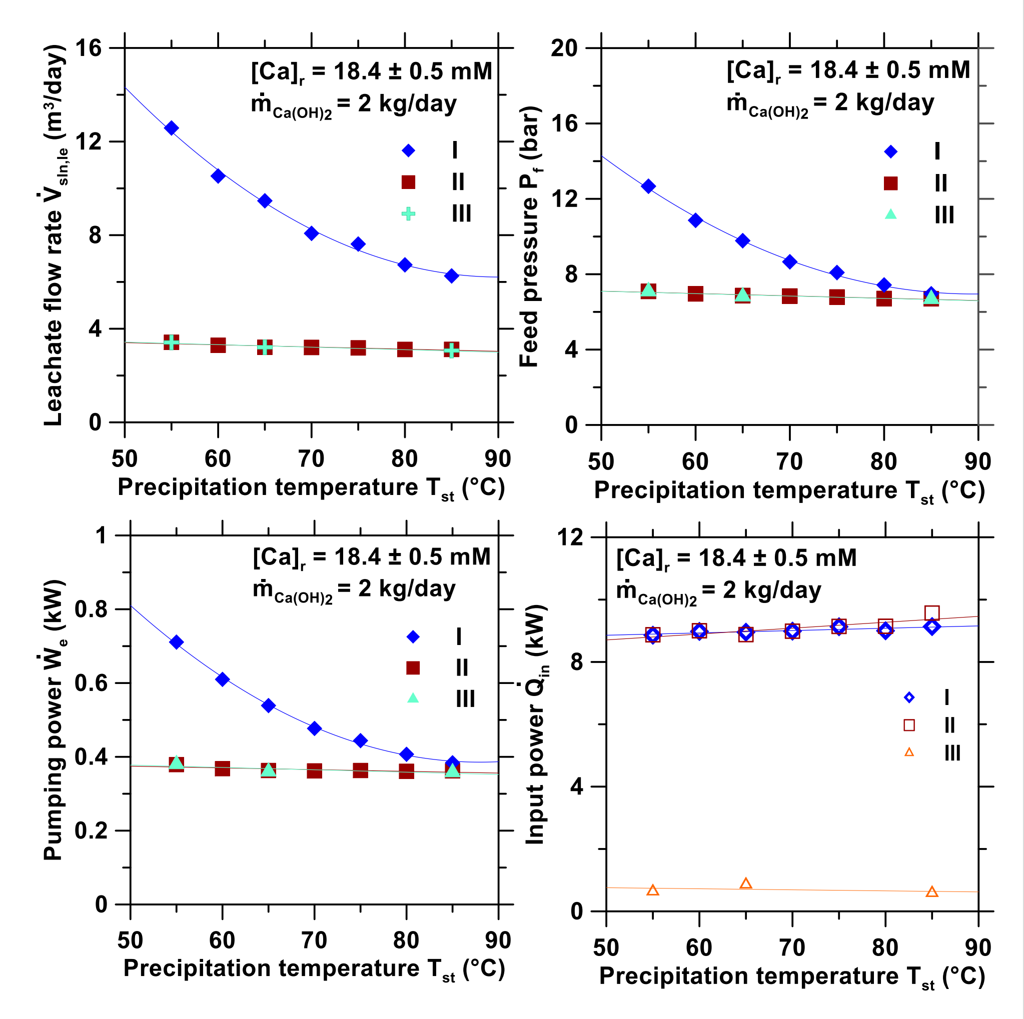


Total power consumption →

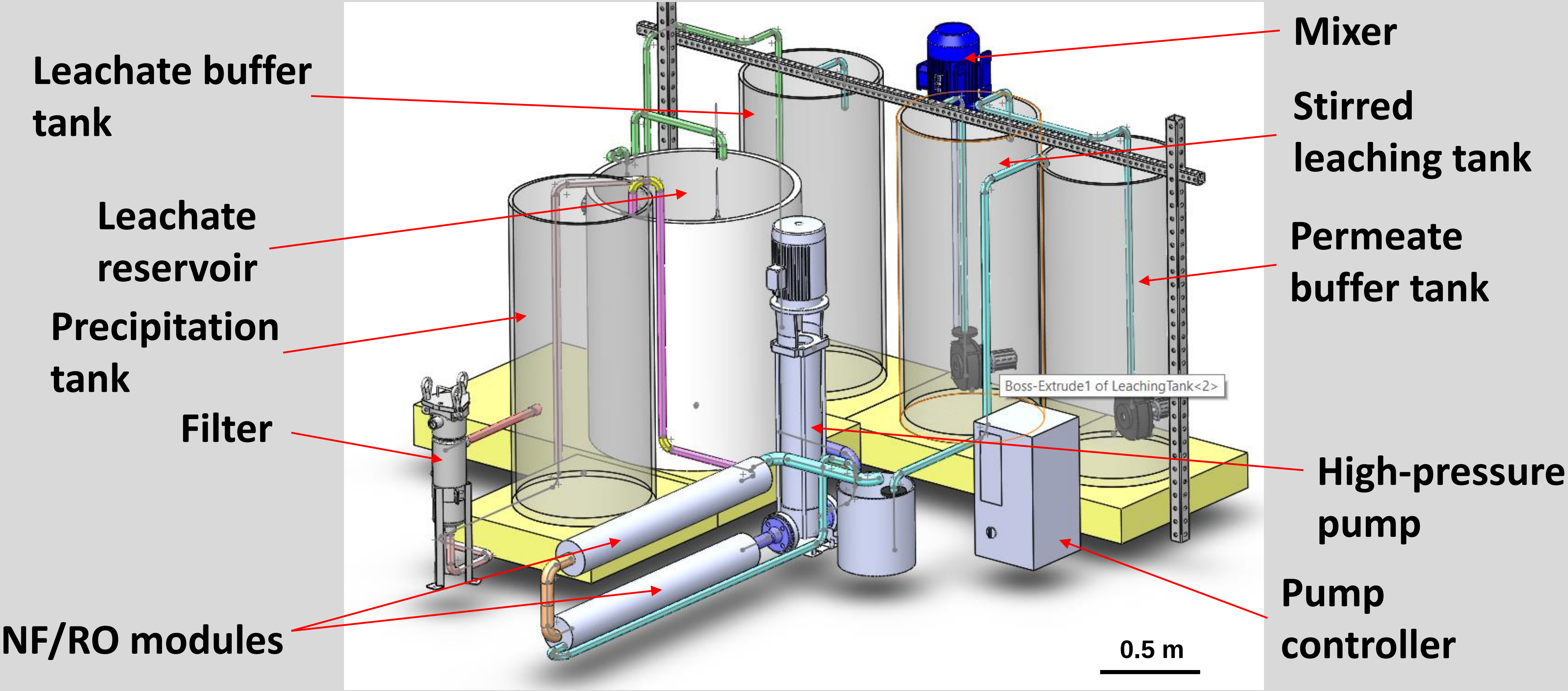


BP2: Process optimization by water recirculation and heat integration

- ***Case I:*** Minimize $\dot{Q}_{pr}$ and calculate $\dot{V}_{sln,le}$ at a fixed T_{st}
  - Increasing T_{st} to 85 °C decreased water consumption and pumping power, $\dot{W}_e$, by 50%; Total power, $\dot{E}_{tot} = \dot{Q}_{pr} + \dot{W}_e$ largely unaffected by T_{st}
  - Large volumes of water (5–12 m^3/day) for 2 kg $Ca(OH)_2$/day
- ***Case II:*** Filtrate after $Ca(OH)_2$ precipitation and separation ([Ca]>10 mM) recirculated to NF/RO feed
  - Reduced water consumption; $\dot{W}_e$ constant for variable T_{st} (lower T_{st} results in higher [Ca] in recirculated water)
- ***Case III:*** Heat exchanger for recirculated saturate
  - Precipitation power, $\dot{Q}_{pr} = \dot{Q}_{in} + \dot{Q}_{re}$, where $\dot{Q}_{in}$ is the input from a waste heat source and $\dot{Q}_{re}$ is from heat recovery
  - Significantly reduced $\dot{Q}_{in}$



Current status: Building of laboratory-scale system



Demonstration setup at UCLA – In progress…

- **General equipment**
  - Framing and tubing, safety drain pans
- **Leaching precursor:** 500 kg basic oxygen furnace slag
- **Leaching equipment**
  - 1 leaching tank: 45 gal (170 L), 2 buffer tanks: 45 gal, 1 mixer: 60–2000 rpm, 3 centrifugal pumps
- **Leaching instrumentation**
  - 2 conductivity meters, 2 pH meters, 2 float level switches, 1 data acquisition card, thermocouples
- **Membrane filtration equipment**
  - 1 reservoir tank: 80 gal (302 L), high pressure pump (up to 320 psi) and controller, variable speed drive

DOW FILMTEC™ BW30-2540 membrane module and housing

Vertical multistage centrifugal pump

BP3 Task: System construction and evaluation

– Procure required equipment components, and construct a laboratory-scale test system to produce **10–100 kg *upcycled concrete*/day**
– Procure simulated coal-fired power plant flue gas (e.g., 14 +/- 2% CO_2, 6.2 +/- 1% H_2O, 3.4 +/- 0.5% O_2, 20-120 ppm SO_2, 75-250 ppm NO_x, 74.5 +/- 2% N_2)
– Establish operating procedures and test plan
– Conduct 3 test runs using simulated coal-fired power plant flue gas over **12–24 h**
– Produce *upcycled concrete* with **0.06–0.12 g CO_2/g solids**, using the mixture designs and process conditions determined from previous tasks
– Collect and analyze key performance data, including production throughput, CO_2 uptake, mass flow rate, overall energy consumption

BP3 Task: Final technology assessment

- **Lifecycle Analysis (LCA)**
  - Complete an LCA that considers both material and processing aspects
  - Optimize the system design (if needed) for minimizing the LCA impacts
  - Identify the environmental benefits of *upcycled concrete* using LCA
  - Robustly quantify and deliver the net CO_2 avoidance by *upcycled concrete* (>75% smaller)
- **Technology Gap Analysis**
  - Complete a Technology Gap Analysis: Estimations of the performance, cost, emission, market and safety metrics per NETL's guidelines for carbon utilization and storage technologies
  - Establish TRL of critical process components, including portlandite production by leaching and precipitation, CO_2 mineralization, and fabrication
  - Analyze and summarize future R&D efforts to close the identified technology gap(s)

Summary and ongoing work

- **Upcycled 'CO_2-negative' concrete** project utilizes coal combustion and metal processing wastes to develop an integrated technology solution for the production of an OPC concrete replacement, while maximizing CO_2 uptake
- In Year 1, we have demonstrated portlandite synthesis from crystalline slags and CO_2 uptake levels of 6–12% by mass of solid reactants
- In Year 2, we performed rheological characterization of *upcycled concrete* formulations, and process design, including component selection for the laboratory scale demonstration system
- Ongoing work includes the construction of an integrated laboratory-scale *upcycled concrete* system, demonstration of an integrated process, technology gap analysis, and lifecycle analysis

Acknowledgements

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

UCLA Samueli School of Engineering

ASU Arizona State University