Upcycled ‘CO_2-negative’ concrete for construction functions

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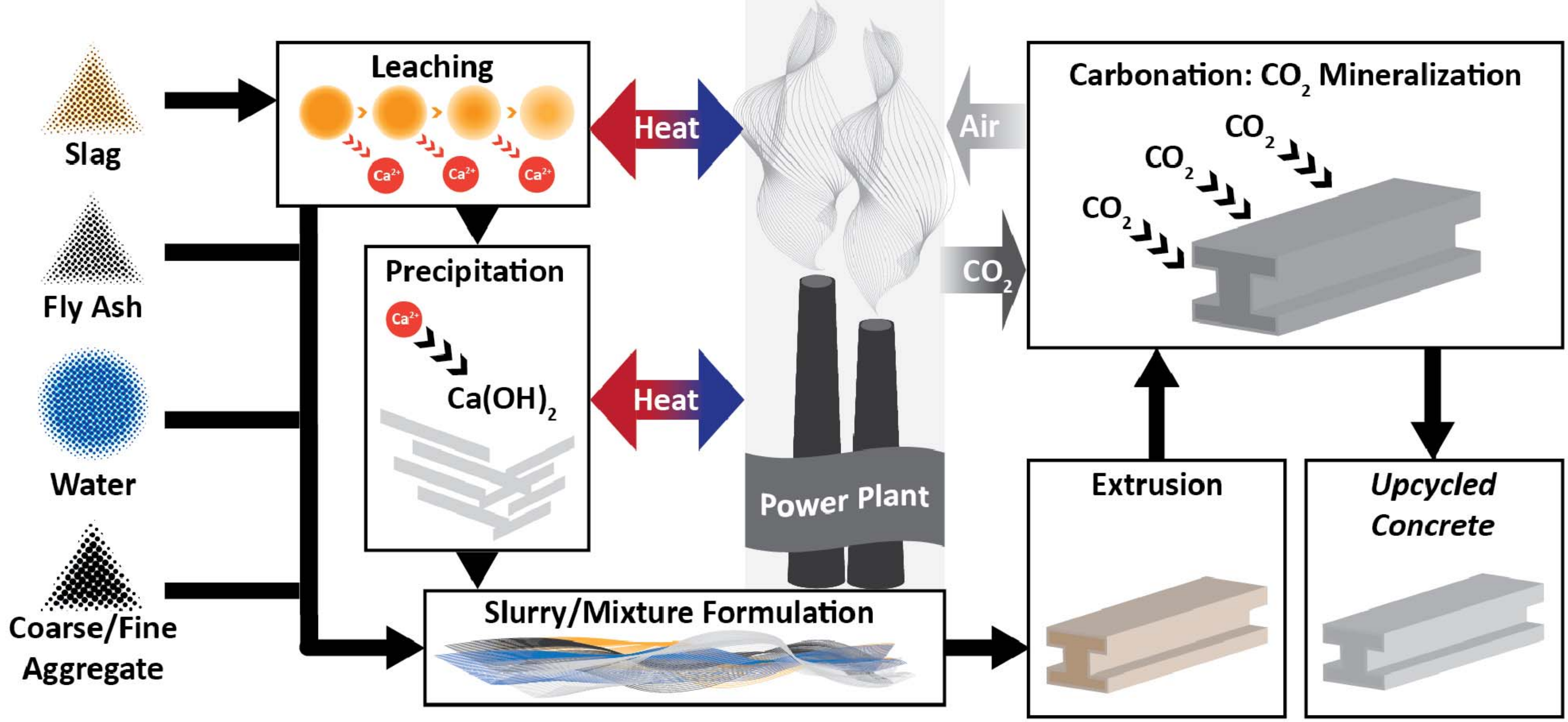
Presentation outline

- **Project Overview:** Motivation, overall project objectives and timeline, funding, participants
- **Technology Background:** Upcycled concrete production process, advantages and challenges
- **Technical Approach/Project Scope:** Experimental design and work plan, key milestones, success criteria, risks and mitigation strategies
- **Progress and Current Status of Project:** Production of portlandite from crystalline slags
- Summary and future work

Motivation for Upcycled *CO_2-negative* concrete

- Identify routes for large-scale utilization of CO_2 as a precursor in beneficial products and processes
- Focus on approaches which can utilize dilute CO2 streams, as is, while also utilizing coal combustion residuals (solid wastes)
- Rapidly source light metal (Ca, Mg) cations, and accomplish material processing without generating additional CO_2 emissions
- Mineralize stable carbonates compound with cementitious properties
- Thereby, develop an alternate to traditional ordinary Portland cement (OPC) based concrete as a construction material

Overview of CO_2-negative upcycled concrete production process



Project objectives

Upcycling industrial wastes and CO_2

- To utilize coal combustion and iron/steel processing wastes as precursors/reactant for scalable CO_2 mineralization

Process design

- To develop an integrated, 'bolt-on' technology/process 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

- To develop a novel CO_2-negative *upcycled concrete* that is performance-equivalent or superior to OPC-based concrete while maintaining functional and utility equivalence

UCLA Engineering

Civil and Environmental Engineering

Scope of work and project timeline

Budget Period 1
April'17-June'18

- **Task 1:** Project management and planning
- **Task 2:** Portlandite production by leaching of crystalline iron and steel slags
- **Task 3:** CO_2 mineralization by accelerated carbonation

Budget Period 2
July'18-June'19

- **Task 4:** Upcycled concrete fabrication and properties
- **Task 5:** Process design and scalability assessment

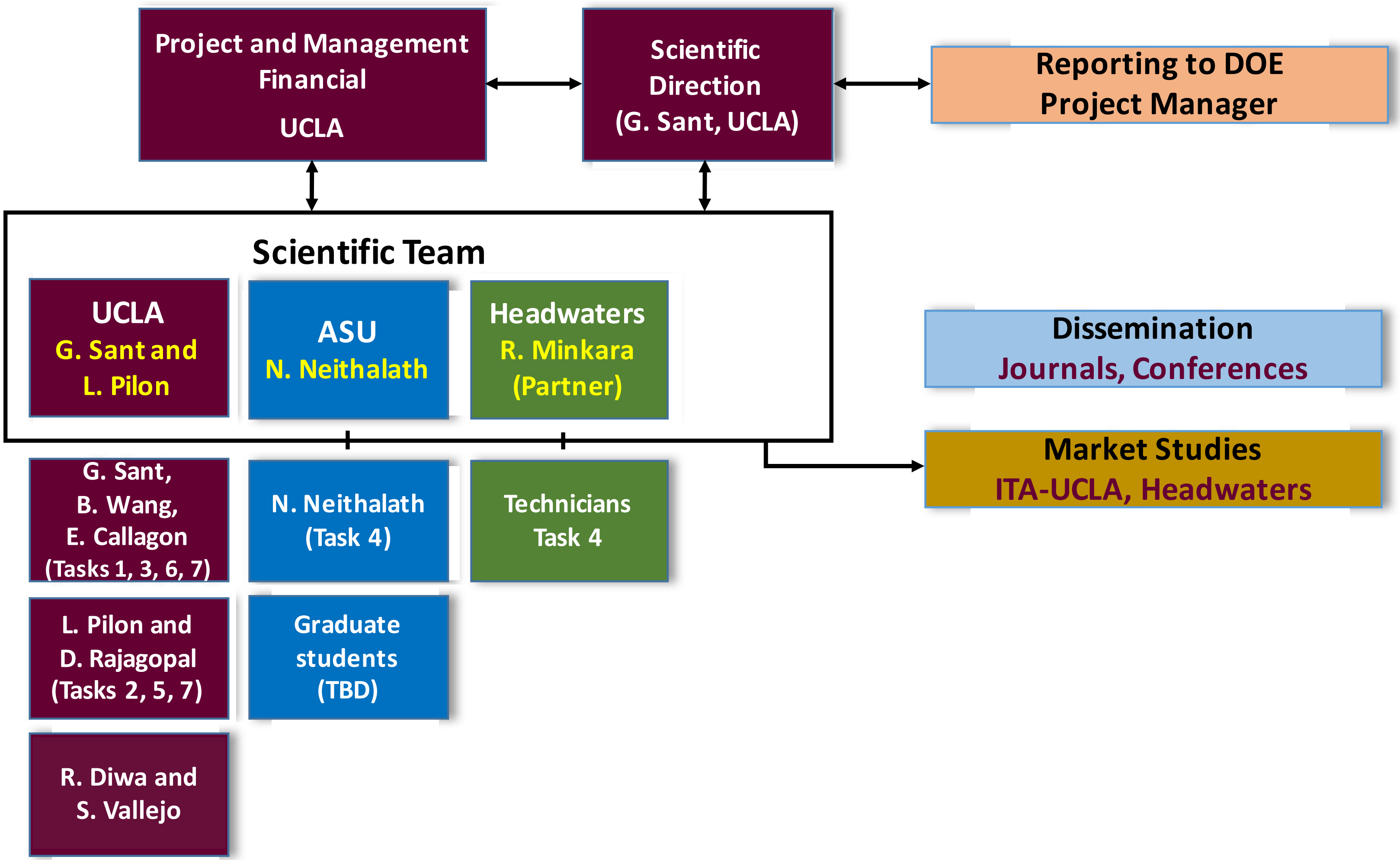
Budget Period 3
July'19-March'20

- **Task 6:** System evaluation
- **Task 7:** Final technology assessment

Overview: Project funding profile

	Budget Period 1		Budget Period 2		Budget Period 3		Total Project	
	04/01/17-06/30/18		07/01/18-06/30/19		07/01/19-03/31/20			
	Gov't Share	Cost Share	Gov't Share	Cost Share	Gov't Share	Cost Share	Gov't Share	Cost Share
UCLA	$344,436	$155,533	$274,142	$119,467	$181,421	$25,000	$799,999	$300,000
ASU	$75,155	$18,480	$66,541	$15,583	$58,304	$15,937	$200,000	$50,000
Total	$419,591	$174,013	$340,683	$135,050	$239,725	$40,937	$999,999	$350,000
Cost Share	71%	29%	72%	28%	85%	15%	74%	26%

Project participants



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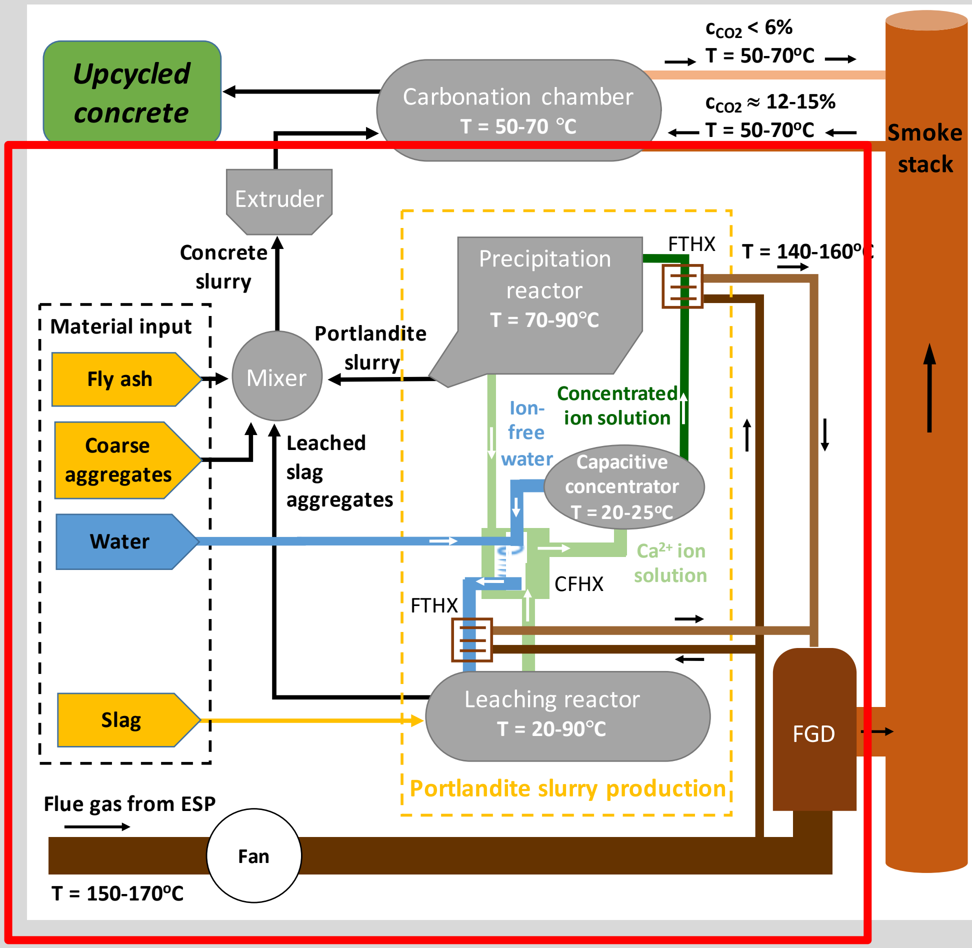
Process diagram for integrated production of *upcycled concrete*

- Securing reclaimed solid wastes reactants of an alkaline nature
- Ca-extraction (leaching) within leaching reactor
- Allow concentration of leaching solution by capacitive action to enable $Ca(OH)_2$ precipitation
- Formulation of a rheology-optimized slurry which can be formed into concrete products
- Contact with flue-gas borne CO_2

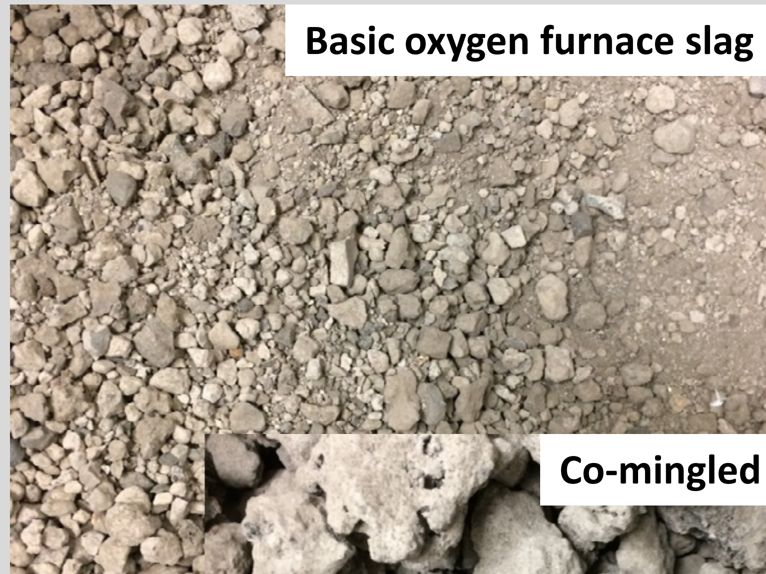


Advantages of *upcycled concrete* technology and practical considerations

- Utilize CO_2 and waste heat carried by the flue gas in a typical coal-fired power plant, and reject waste streams (e.g., crystalline slags, non-compliant fly ash in landfills and ash ponds)
- Path to carbon neutral/negative cementation by rapid production of hydrated lime, $Ca(OH)_2$ by capacitive concentration
- Considerations of: (1) compositional heterogeneity (i.e., for leaching and carbonation potential) of fly ash and slag, (2) carbonation kinetics, (2) concrete workability and mechanical properties

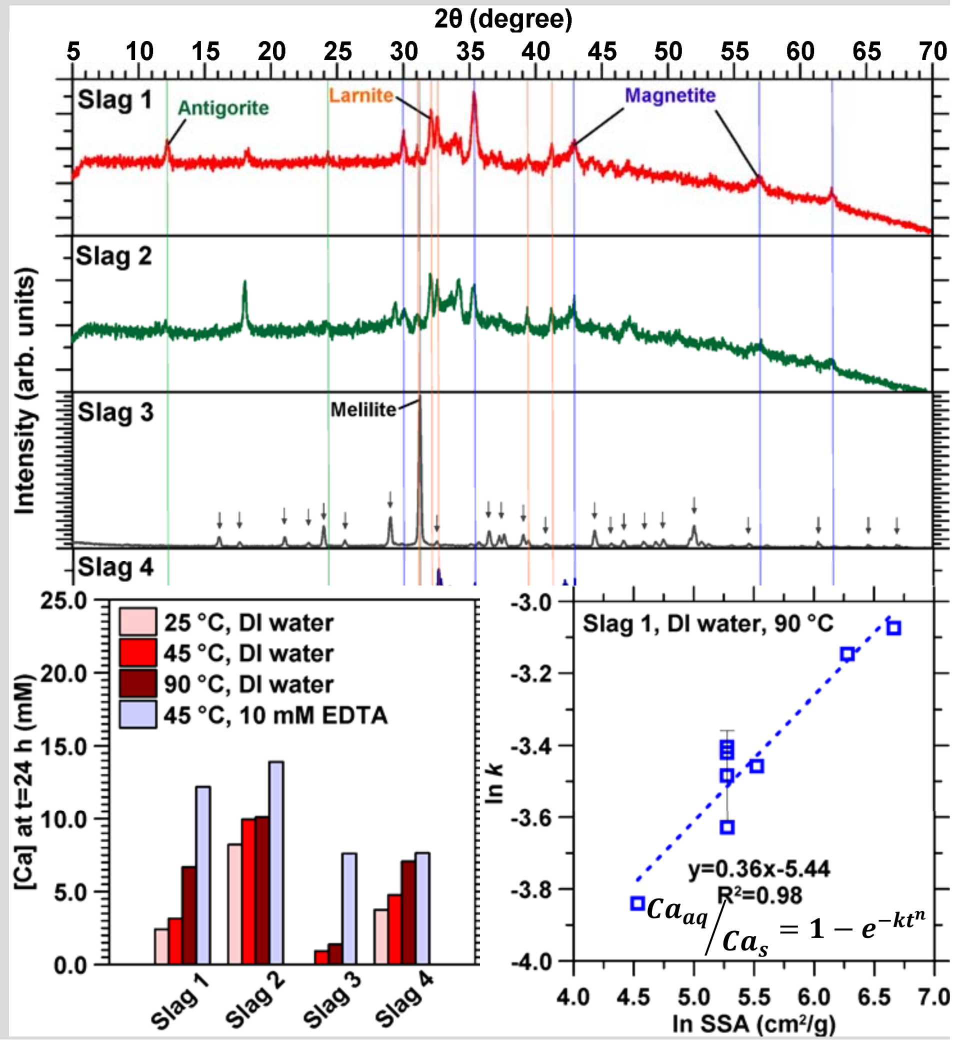
$Ca(OH)_2$ production by leaching, concentration

- Ca needed for production of $Ca(OH)_2$ (portlandite) can be leached from slag and (fly ash)
- Establish leaching kinetics of crystalline slags under different conditions
  - Chemical (SEM-EDS, XRF) and mineralogical (XRD) characterization of slags, surface area measurements
  - Slag leaching rate and extent as a function of slag type, solution composition, temperature, and particle size



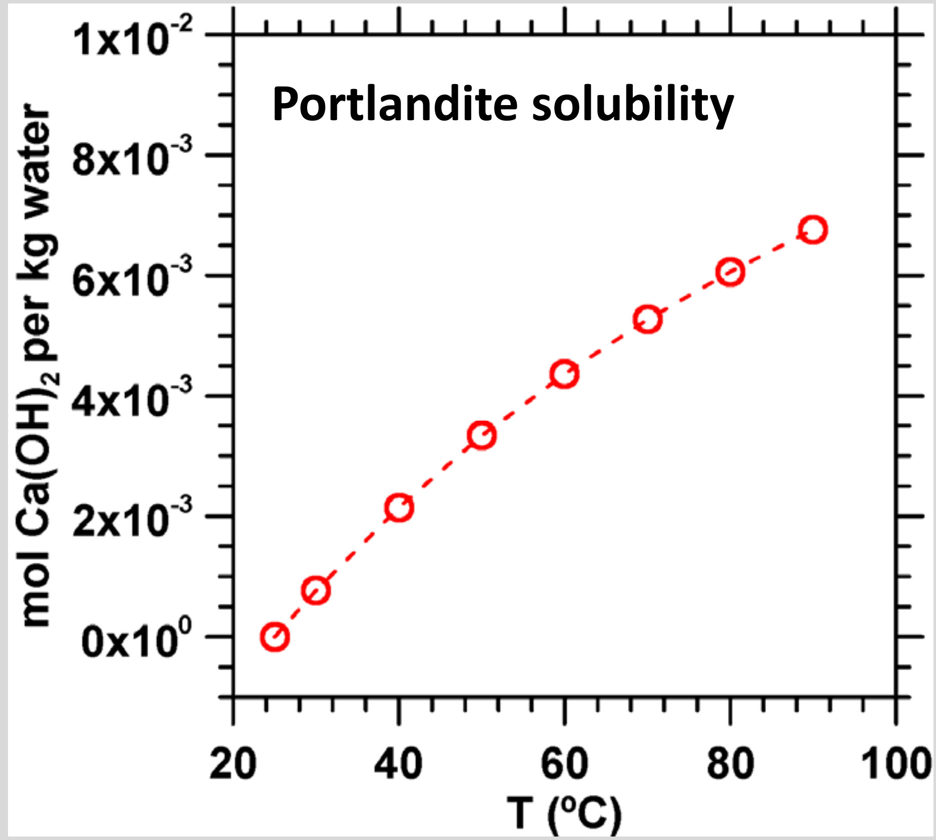
Ca-extraction from (U.S.) crystalline slags

- Characterization by XRF, and XRD reveals CaO > 35%, and presence of Ca- and Mg-silicate phases
- Ca release as a function of time up to 7 days measured by ICP-OES as measure of "leachability"
- Rates and final Ca-content vary with slag type, and additives
- Expectedly, leaching rates can increase with surface area, temperature, and presence of complexing agent and acid(s)



Capacitive concentration of leachate and precipitation of portlandite

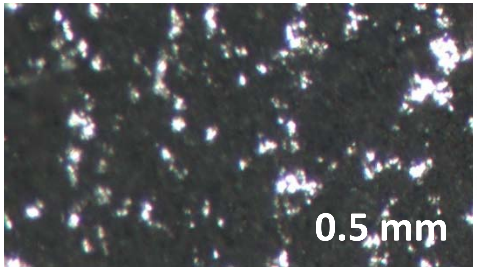
- Fabricate novel C-electrodes and characterize extent of capacitive concentration of the slag leachate, between 20-45 °C
- Exploit the idea that solubility of portlandite decreases with increasing temperature
- Therefore, portlandite-saturated solutions can be heated to up to 90 °C to induce precipitation (using waste heat for process)

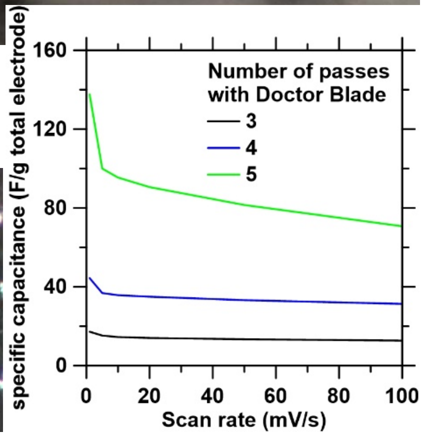


Design, fabrication, and characterization of capacitive concentration module

- The electrodes are composed of reduced graphite oxide 85%, PVDF (binder) 10%, and carbon black 5% (high conductivity)
- Fabrication using Doctor Blade method: increasing number of passes increases level of surface coverage/specific capacitance
- The designed cell has now been assembled, and will be tested using solutions similar to slag leachate (expected 1-2 passes)

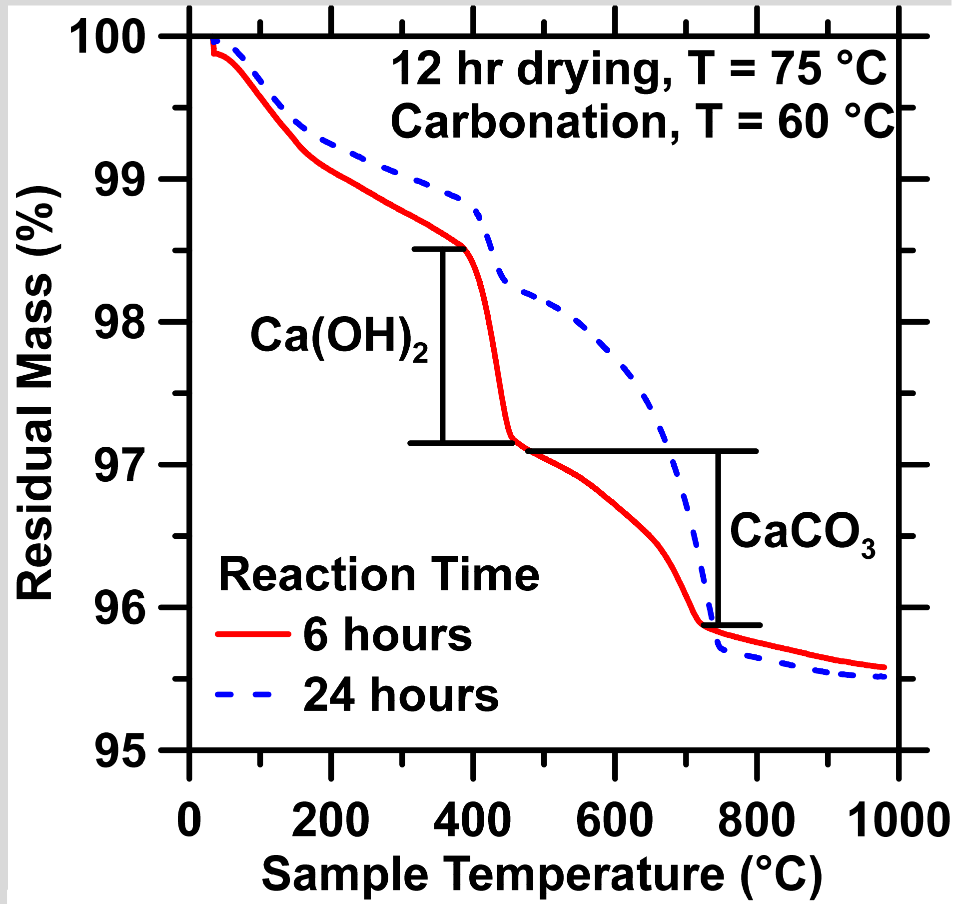
Electrode casting using Doctor Blade





CO_2 mineralization by accelerated carbonation

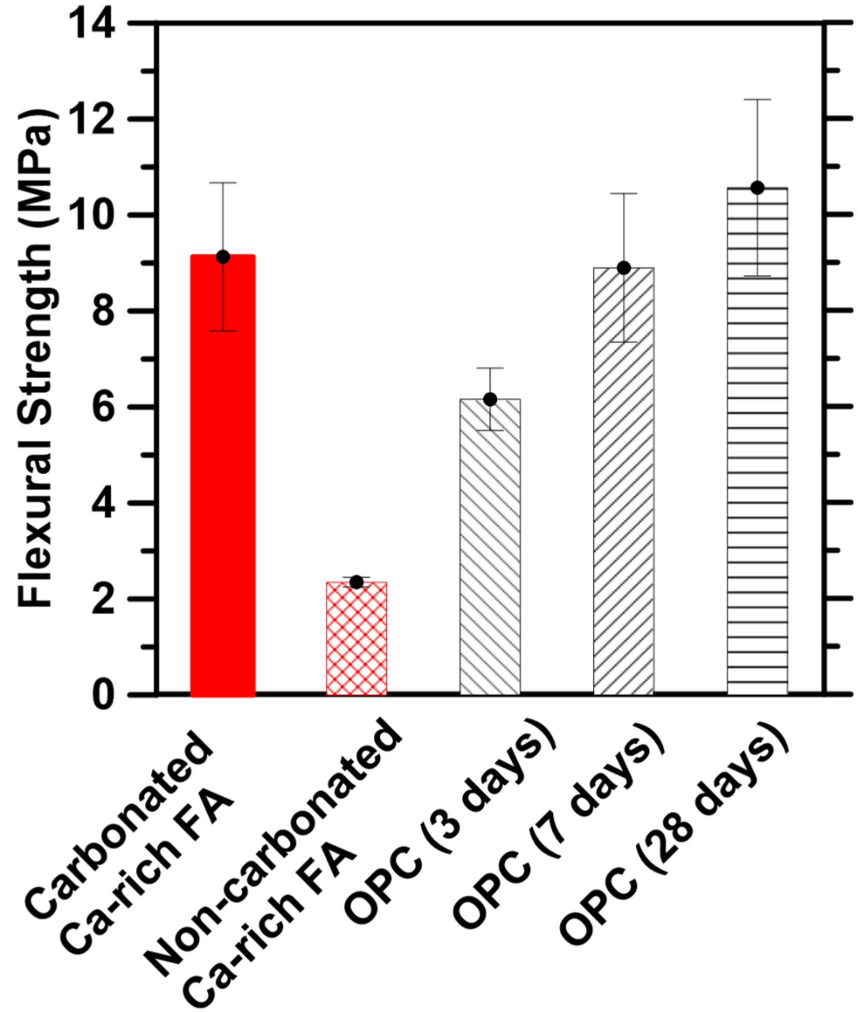
- Concrete slurry composed of $Ca(OH)_2$ slurry, fly ash, leached slag, coarse aggregates
- Build carbonation reactors and identify process parameters to maximize CO_2 mineralization, at 45-90 °C, and for CO_2 flue gas concentration of 6-18% CO_2 (v/v)
- Determine carbonation characteristics of fly ash and leached slag granules, and $Ca(OH)_2$ as well as the process conditions for carbonation



CO_2 uptake quantified by TGA based on the mass loss due to decarbonation

Upcycled concrete fabrication and properties

- Establish mixture proportions to optimize rheology, workability and shape stability of materials for extrusion, or cold-forming
- Mixing ratios between the fly ash-portlandite-slag particulate blends, fine aggregates, water and chemical additives provide levers for "rheology control"
- Establish mechanical properties and methods for strengthening. Preliminary data is promising and shows "CO_2 strengthening"



Process design and system evaluation

- Establish process design for lab-scale demonstration of integrated *upcycled concrete* production system, and its industrial scale-up
  - Component selection and design
  - System design and process optimization
  - Operating procedures and test plan
- Perform test runs using simulated coal-fired power plant flue gas
- Produce upcycled concrete with different CO_2 uptake levels
- Report performance data from experimental test runs: CO_2 uptake, mass flow rate, production throughput, energy consumption, etc.

Scalability assessment and economic feasibility

- Technical and economic feasibility study for detailed accounting of capital costs, operation and maintenance costs and required selling price relative to existing markets for the scaled-up process
- Conceptual design for coupling the upcycled concrete production process with coal-fired power plant (i.e., for “co-location”)
- Market assessment, including all revenue streams, assumed unit costs, current and projected market volume and value, and estimated quantity of CO_2 that can be utilized
- High-level, return-on-investment (ROI) analysis based on the overall experimental and modeling results and analysis

Lifecycle and technology gap analyses

- Lifecycle analysis (LCA) that considers both materials and process
- System design further optimized to minimize the LCA impacts
- Identify environmental benefits and quantify net CO_2 avoidance
- Estimate performance, cost, emission, market, safety metrics per NETL's guidelines for carbon utilization and storage technologies
- Technology gap analysis to review the state of upcycled concrete process development.
- Technology readiness level of critical process components (e.g., $Ca(OH)_2$ production by leaching and capacitive concentration, CO_2 mineralization), and upcycled concrete fabrication

Success criteria and decision points

Completion of BP 1

- Carbonation characteristics of fly ash and leached slag, and the process conditions for carbonation of upcycled concrete mortar
- The critical steps (leaching, portlandite production, and carbonation) can be carried out in 24-to-168 hours or less

Completion of BP 2

- Compressive strength of ≥ 15 MPa
- Lifecycle footprint that is > 75% smaller than OPC-concrete of equivalent performance grade (based on our preliminary assessment)
- Design of laboratory-scale, integrated concrete production system with production throughput of 10-to-100 kg/day of upcycled concrete

Completion of BP 3

- Real-time CO_2 uptake of the lab-scale test unit within 20% of the estimated “accessible carbonation potential”
- Lifecycle footprint that is >75% smaller than OPC-concrete of equivalent performance grade (final assessment)
- Conceptual scaled-up process design and completion of technical and economic feasibility study, market assessment, lifecycle analysis, and technology gap analysis

Technical risks and mitigation strategies

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Slow leaching kinetics of slag	Low	Moderate	Increase surface area of slag particles, and dilution ratios, and slightly acidify the leachant
Unsatisfactory throughput or output concentration level from the CC	Moderate	Low	Construct concentrators in series (to improve concentration) or in parallel (to improve throughput). Use waste heat from power plant to accelerate precipitation by actively evaporating the concentrated solution.
Slow carbonation kinetics or low carbonation potential of fly ash	Moderate	Low	Increase the $Ca(OH)_2$/fly ash ratio, and/or secure Ca-rich fly ash
Concrete slurry shows unsatisfactory workability	Moderate	Moderate	Adjust workability with rheology modifiers (e.g., viscosity modifiers, and dispersants)
Carbonated concrete shows unsatisfactory strength development	Low	Moderate	Enhance strength by pre-carbonation densification to reduce porosity reduction, or add inorganic binders to the formulation

Summary and future work

- **Upcycled 'CO_2-negative' concrete** project utilizes coal combustion and metal processing wastes to develop an integrated technology solution for the production of OPC-concrete replacement, while maximizing CO_2 uptake
- Kinetic data on slag dissolution shows significant extractable Ca. The leachate will be concentrated to further increase [Ca] to achieve saturation with respect to $Ca(OH)_2$ at ambient/elevarted temperature
- Ongoing work also includes:
  - Precipitation of $Ca(OH)_2$ by heating $Ca(OH)_2$-saturated solutions
  - Assessment of carbonation potential of different fly ashes
  - Determination of carbonation kinetics of fly ashes and portlandite