Upcycled ‘CO_2-negative’ concrete for construction functions

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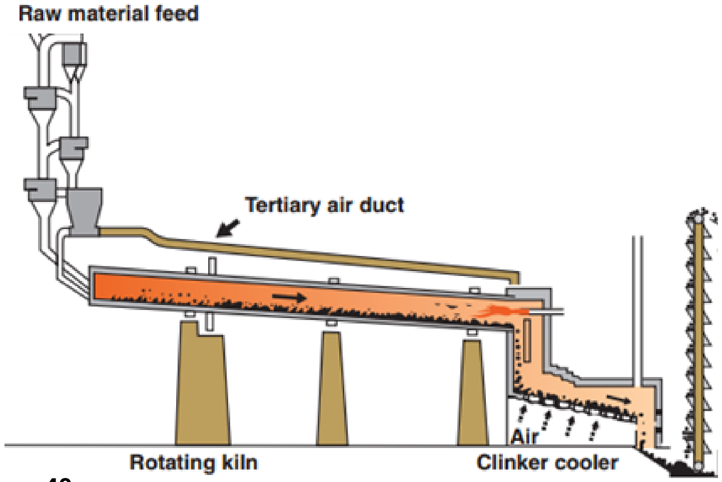
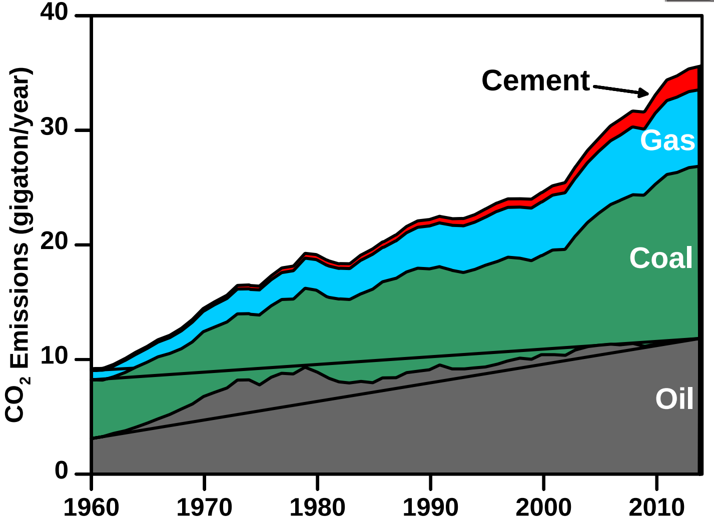
Presentation outline

- **Project Overview: Background, 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
- Progress and Current Status of Project
- Summary and future work

Upcycled ‘CO_2-negative’ concrete

- 33 billion tons of concrete, 4.5 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 T (~1600 °C) and CO_2 emitted during calcination
- Identify routes for large-scale utilization of CO_2 as a precursor in beneficial products and processes, by mineralization as stable carbonate compounds with cementitious properties



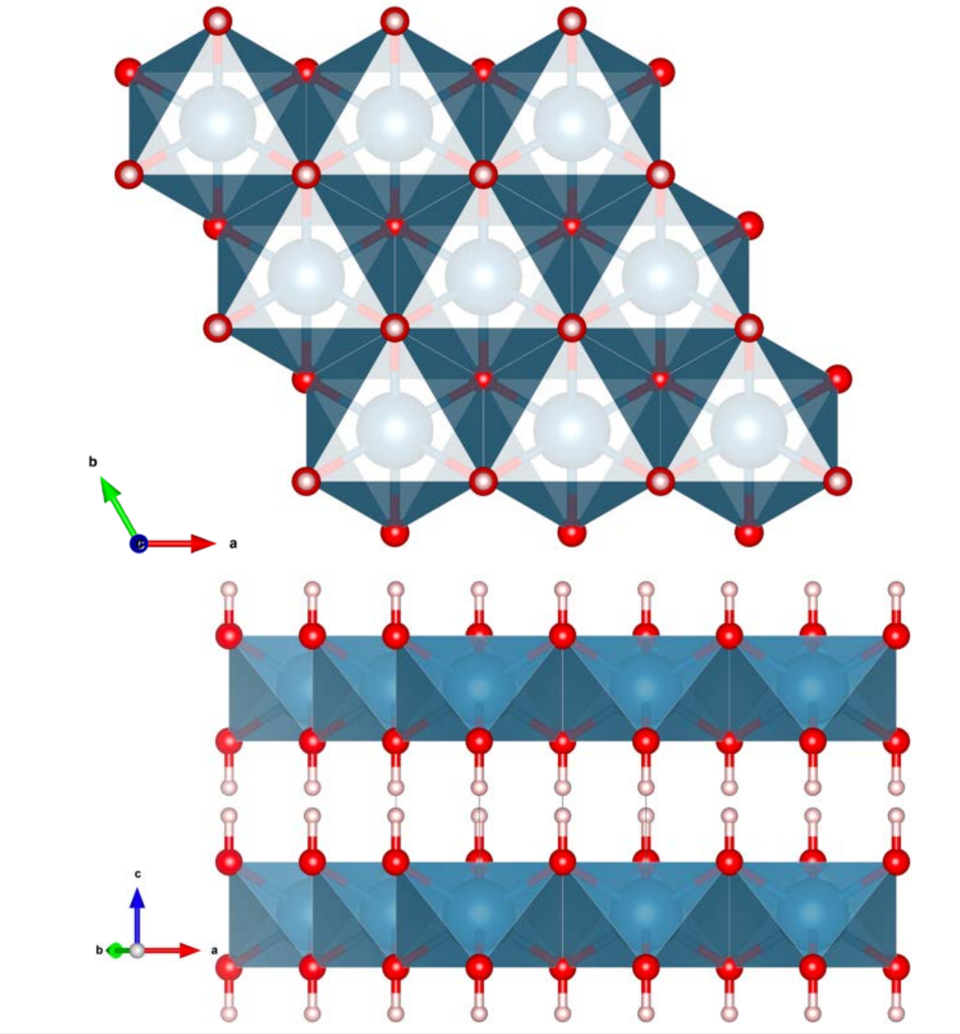


Low-temperature synthesis of portlandite

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

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

- Industrial methods of portlandite production require energy- and CO_2-intensive calcination of limestone
- Low-temperature synthesis of portlandite using industrial byproducts and waste heat



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

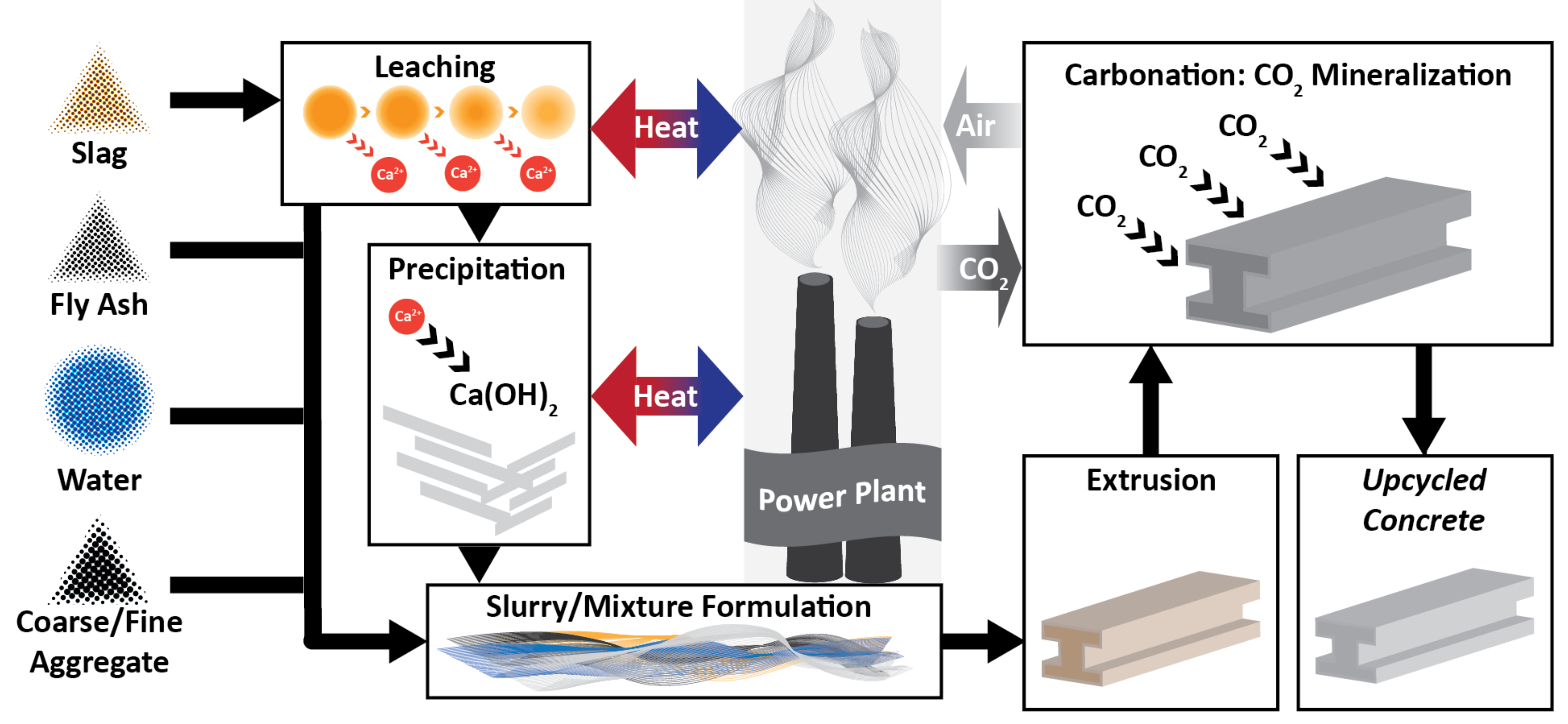
Process design

- 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



Project scope and current status

YEAR 1
04/01/17-06/30/18

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

YEAR 2
07/01/18-06/30/19

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

YEAR 3
07/01/19-03/31/20

- System evaluation
- Final technology assessment

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:

- University of California, Los Angeles (UCLA)
- Arizona State University (ASU)
- Boral North America

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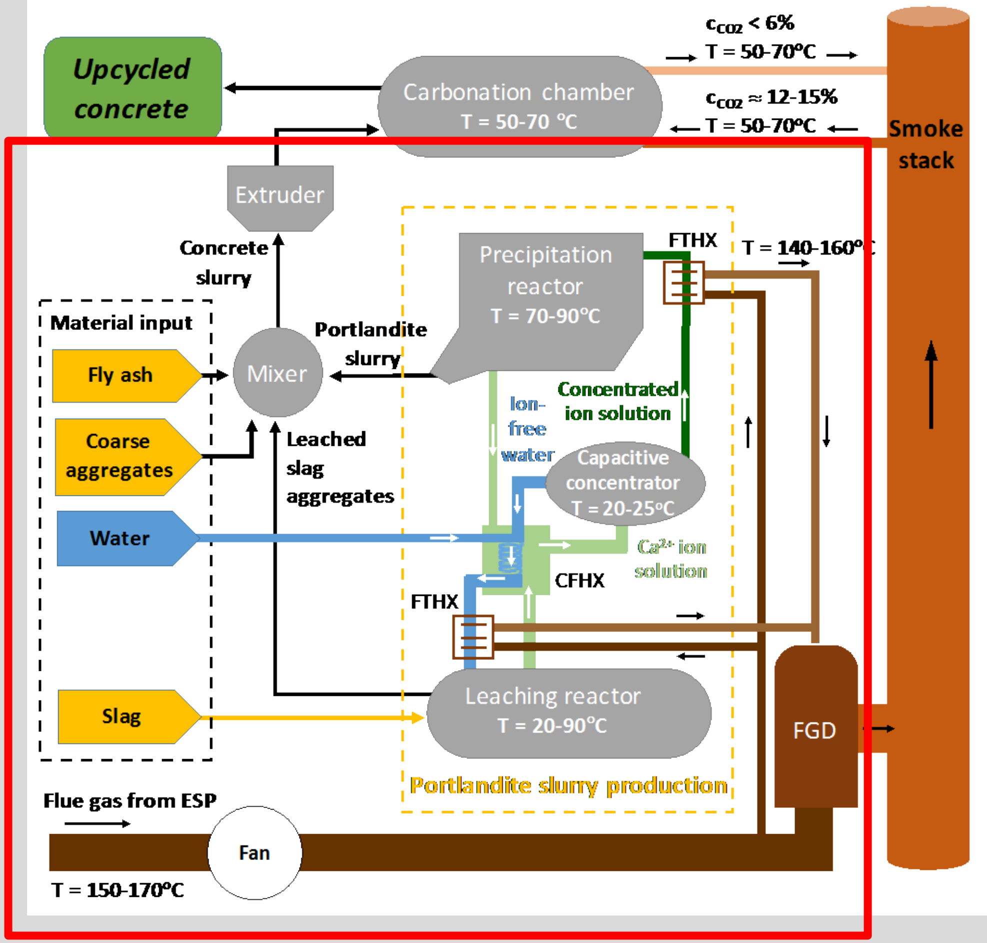
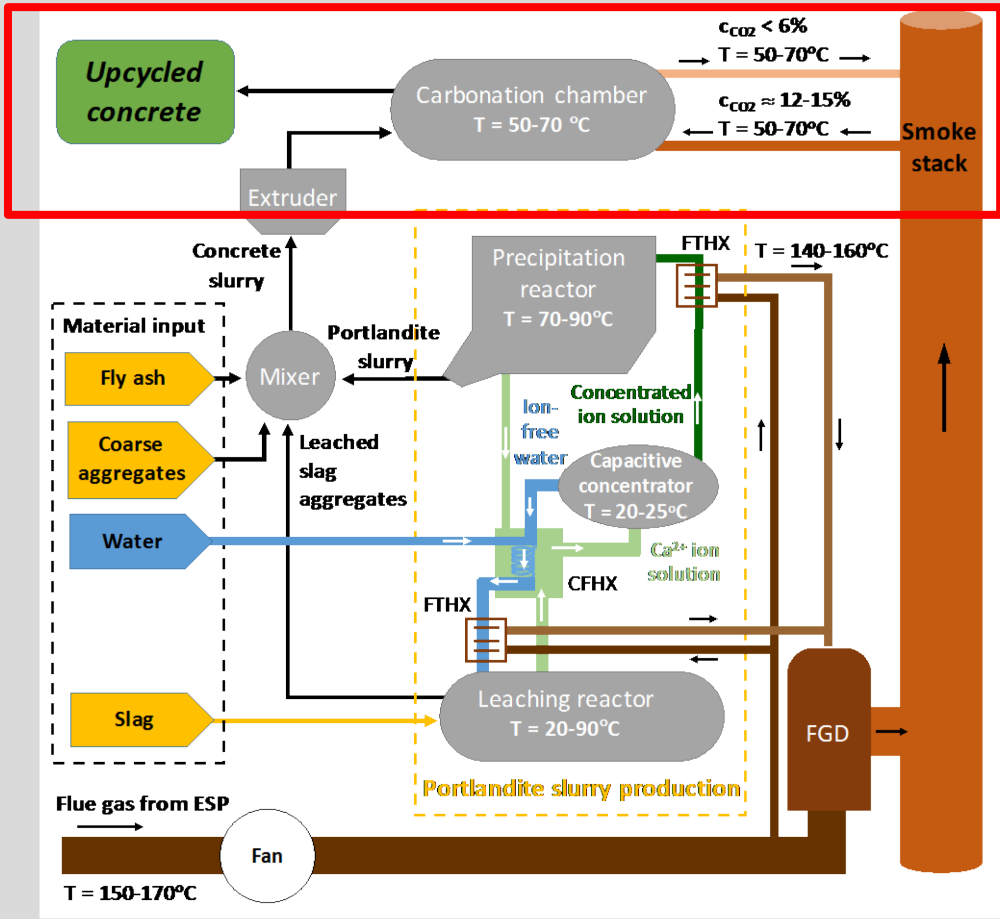
Process diagram for integrated production of *upcycled concrete*

- Securing reclaimed solid reactants
- Ca extraction (leaching) within the leaching reactor
- Concentration of leaching solution in Ca, followed by $Ca(OH)_2$ precipitation
- Formulation of a rheology-optimized slurry



Process diagram for integrated production of *upcycled concrete*

- Shape-stabilization of slurry into the form of a structural section (beam, column, etc.)
- Contacting structural section with flue-gas borne CO_2 within a carbonation chamber – *"upcycled concrete"* section
- Low-grade heat sourced from flue gas prior to, and following, desulfurization to optimize kinetics



Advantages of *upcycled concrete* technology and practical 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 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 through the production of hydrated lime, $Ca(OH)_2$
- Considerations on (1) compositional heterogeneity (leaching/carbonation potential) of fly ash and slag, (2) carbonation kinetics, (2) concrete workability and (3) mechanical properties

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Experimental design and work plan

1. Portlandite production by leaching of crystalline slags
2. CO_2 mineralization by accelerated carbonation
3. Upcycled concrete fabrication and properties
4. Process design and scalability assessment
5. System evaluation
    - System procurement and construction
    - Integrated laboratory-scale testing using simulated flue gas
6. Final technology assessment
    - Scalability assessment and economic feasibility study
    - Lifecycle and technology gap analyses

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				■								
3 different CO_2 uptake levels (0.06-0.12 g CO_2/g solid) with blended fly ash and $Ca(OH)_2$					■							
Rheology characteristics for upcycled concrete (UC) with 3 fly ash-$Ca(OH)_2$ blends								■				
Shape-stable upcycled concrete 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 above											■	
Production throughput of 10-100 kg/d 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												■

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 (preliminary assessment)
- Design of laboratory-scale, integrated concrete production system with production throughput of 10-100 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 “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

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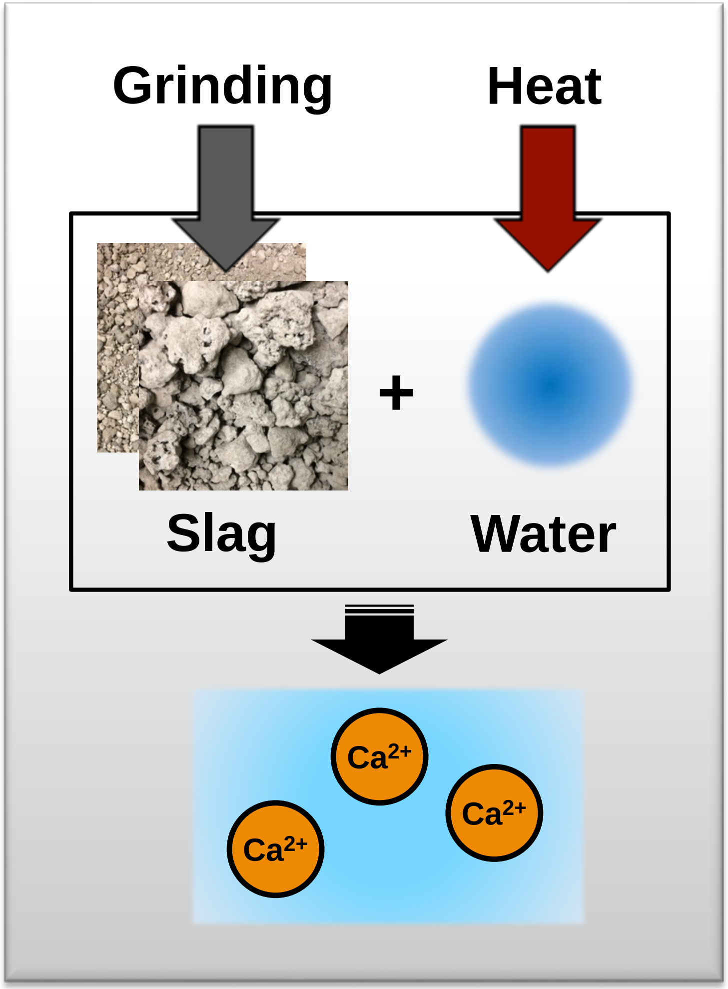
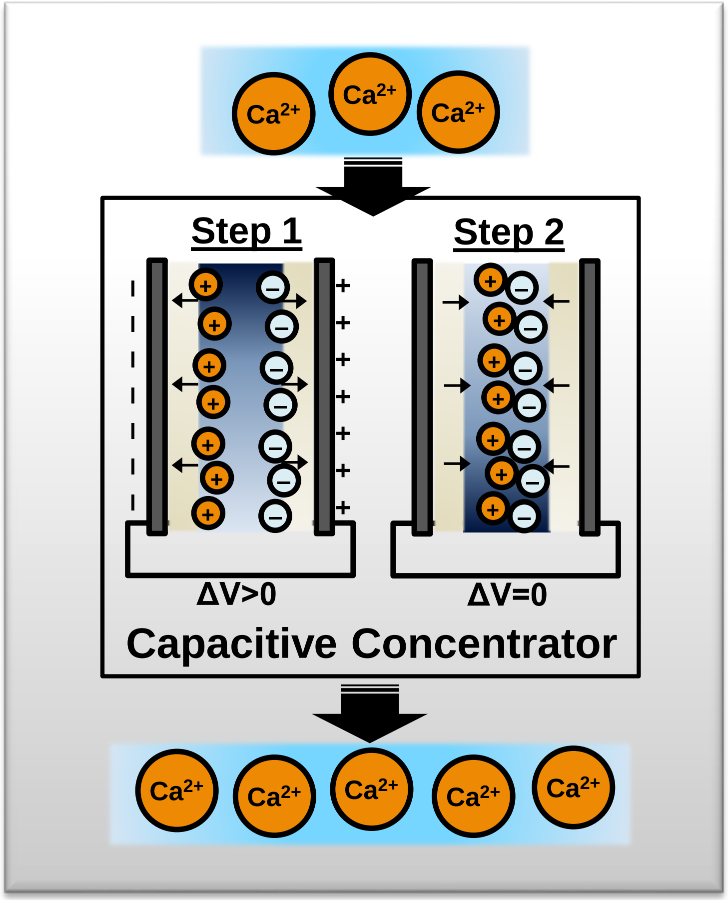
Sourcing of Ca from slags

- Slags contain about 30-50% CaO by mass – Ca leaching potential of ~0.2–0.3 g per g slag
- Crystalline slags, which are used as low-value aggregates, are the focus of our process
- Up to 10 mM (400 ppm) Ca leached in water after 24 hours
- Rapidly evolves to a highly alkaline solution amenable to portlandite precipitation (final step)



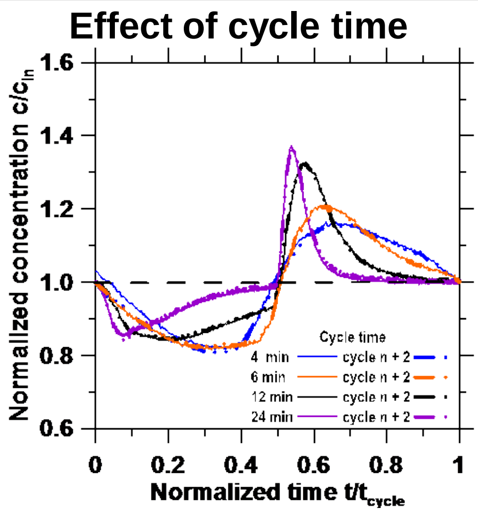
Enhancing Ca concentrations to reach $Ca(OH)_2$ (portlandite) saturation

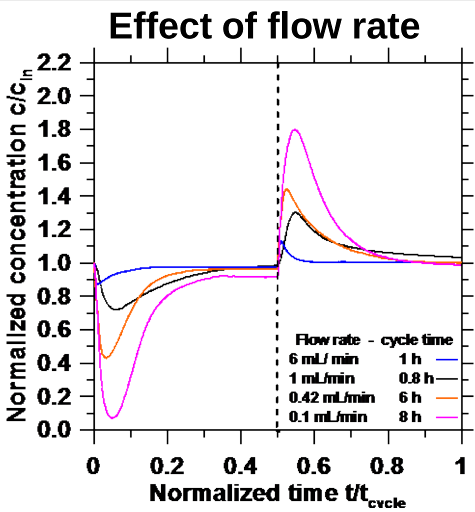
- Next step involves increasing Ca concentrations in the leachate to reach $Ca(OH)_2$ saturation
- Capacitive concentration cell with activated carbon or stainless steel electrodes
- As voltage is applied, ions migrate and adsorb on electrode surfaces; when voltage is reversed (or changed to zero), ions desorb, concentrating the flowing solution

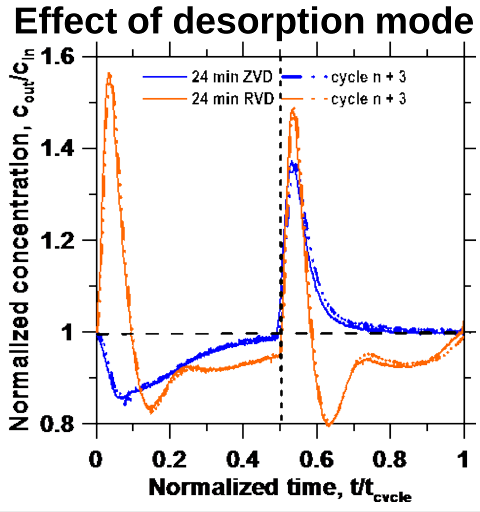


Capacitive concentration of $CaCl_2$ solutions

- Initial experiments used 10 mM $CaCl_2$ as inlet solution – easily handled, high solubility of $CaCl_2$ in water, and represents a solution rich in Ca^{2+} ions
- Concentration factor increases with decreasing flow rate and increasing cycle time, up to a value of 1.8x
- Slag leachates are highly alkaline – substantial decrease in extent of desorption (and concentration factor) for $Ca(OH)_2$ solutions







Applied potential ≤ 1 V during adsorption, -1 V (RVD) or 0 V (ZVD) during desorption

Normalized concentration, c/c_{in}, is the ratio of the outlet to the inlet Ca concentration

Alternative routes to concentration of alkaline Ca-containing solutions

- Capacitive concentration is not appropriate for alkaline solutions containing high [Ca]
- Stainless steel and nickel are electrochemically more inert than carbon under the relevant solution conditions, but their performance is limited by low SA
- Activated carbon electrodes have superior SA, but unstable in the presence of Ca

Membrane filtration which operates based on size exclusion and/or electrostatic repulsion is an alternative process to concentrate Ca^{2+} ions

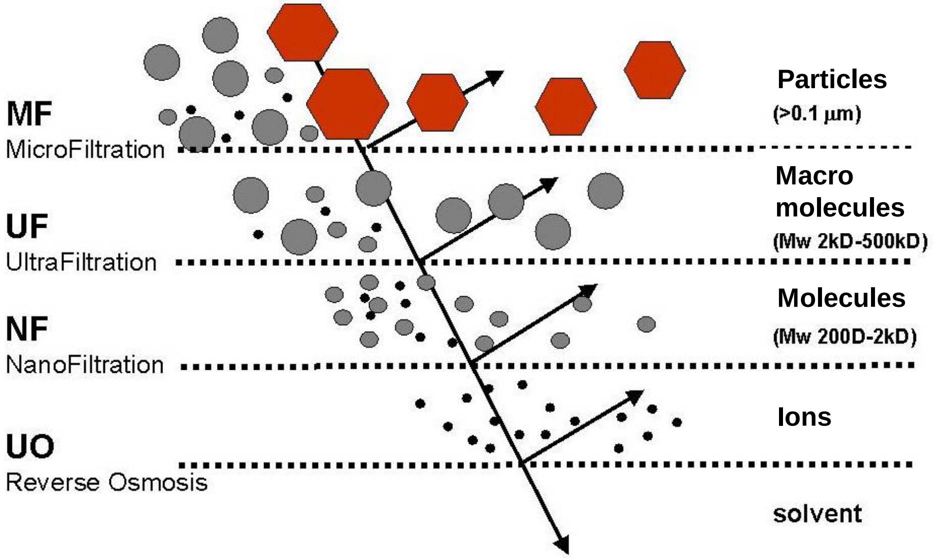
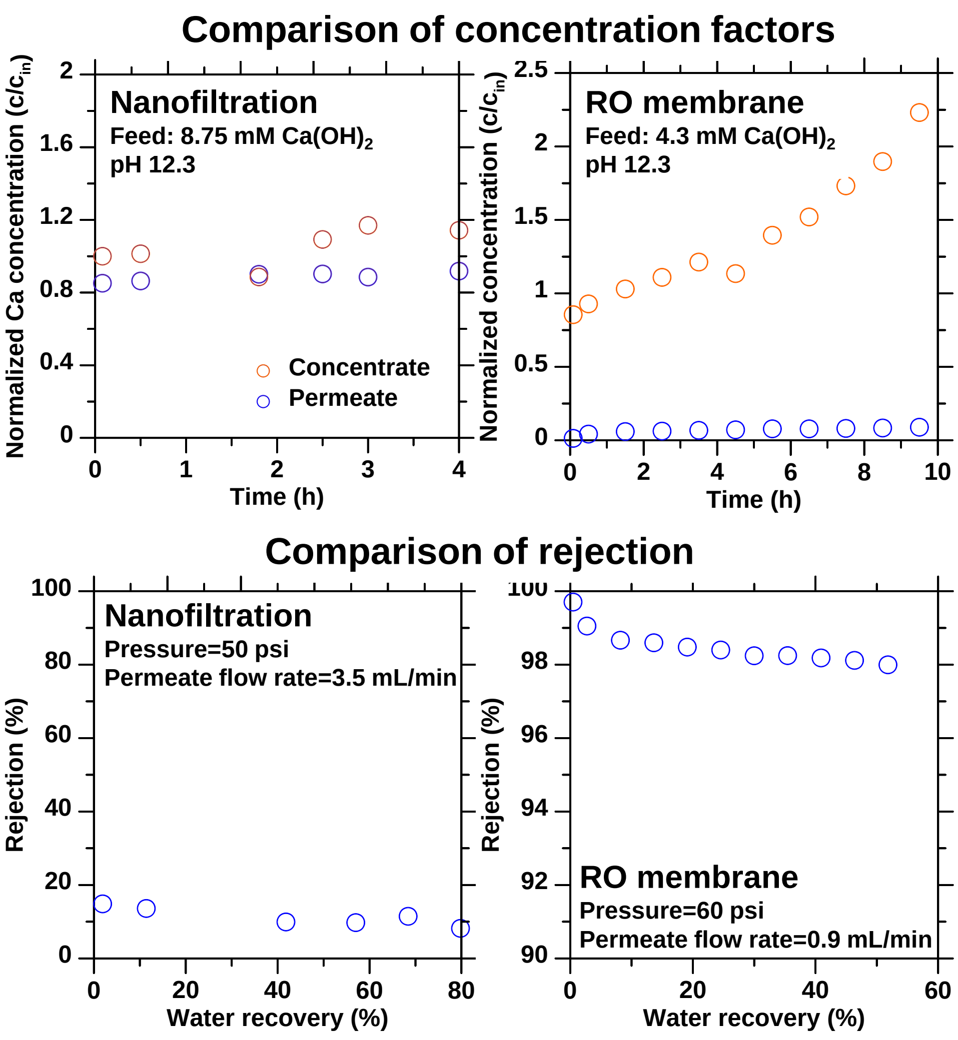


Image source: http://ps-prozesstechnik.com

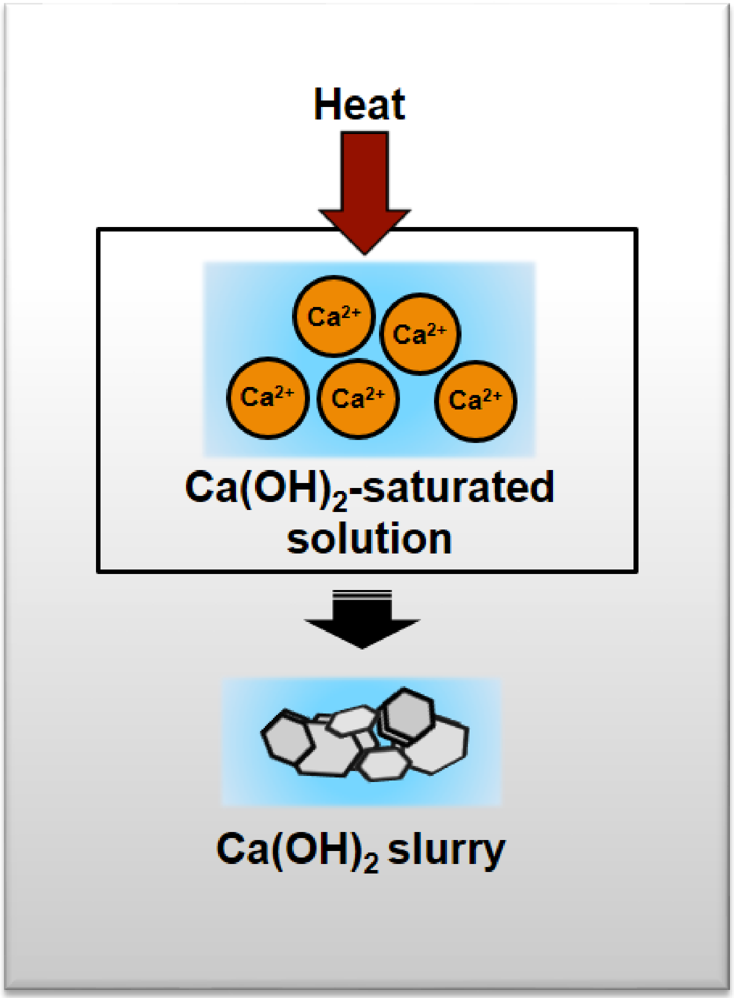
Concentration of $Ca(OH)_2$ solutions

- Ca concentration factor for $Ca(OH)_2$ solutions reached up to >2x using reverse osmosis membrane (vs. <1.2x using nanofiltration)
- RO membrane showed greater Ca rejection (>98%) than nanofiltration (<20%)
- RO membrane filtration suitable for concentration of alkaline Ca-rich solutions



Temperature ramping to induce precipitation

- Portlandite solubility decreases with increasing temperature
- Up to 500 ppm of portlandite can be precipitated from a saturated solution by temperature ramping
- pH adjustment is not necessary because of the alkaline nature of the slag leachate
- Precipitated portlandite is added to *upcycled concrete* formulation for subsequent carbonation



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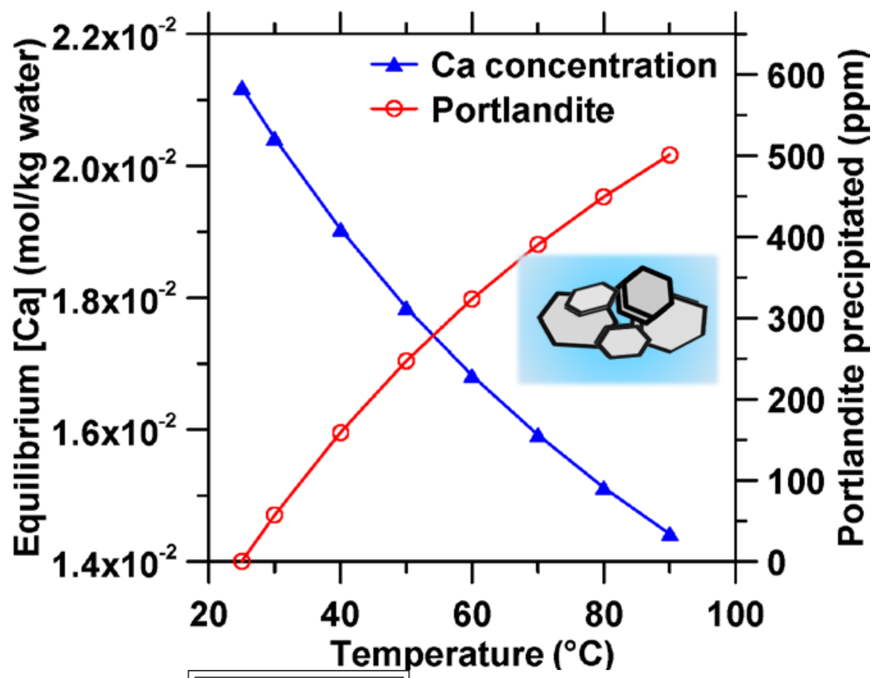
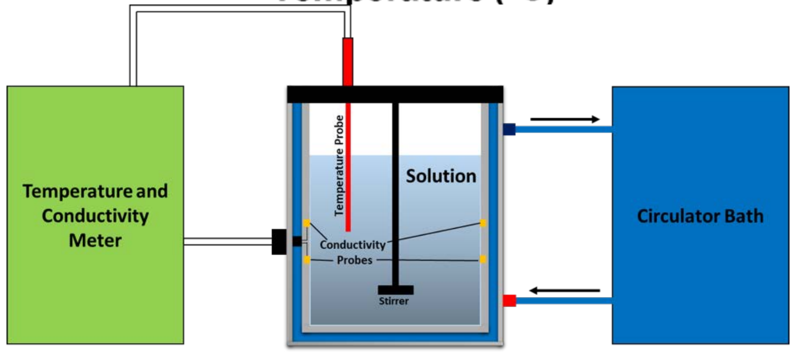
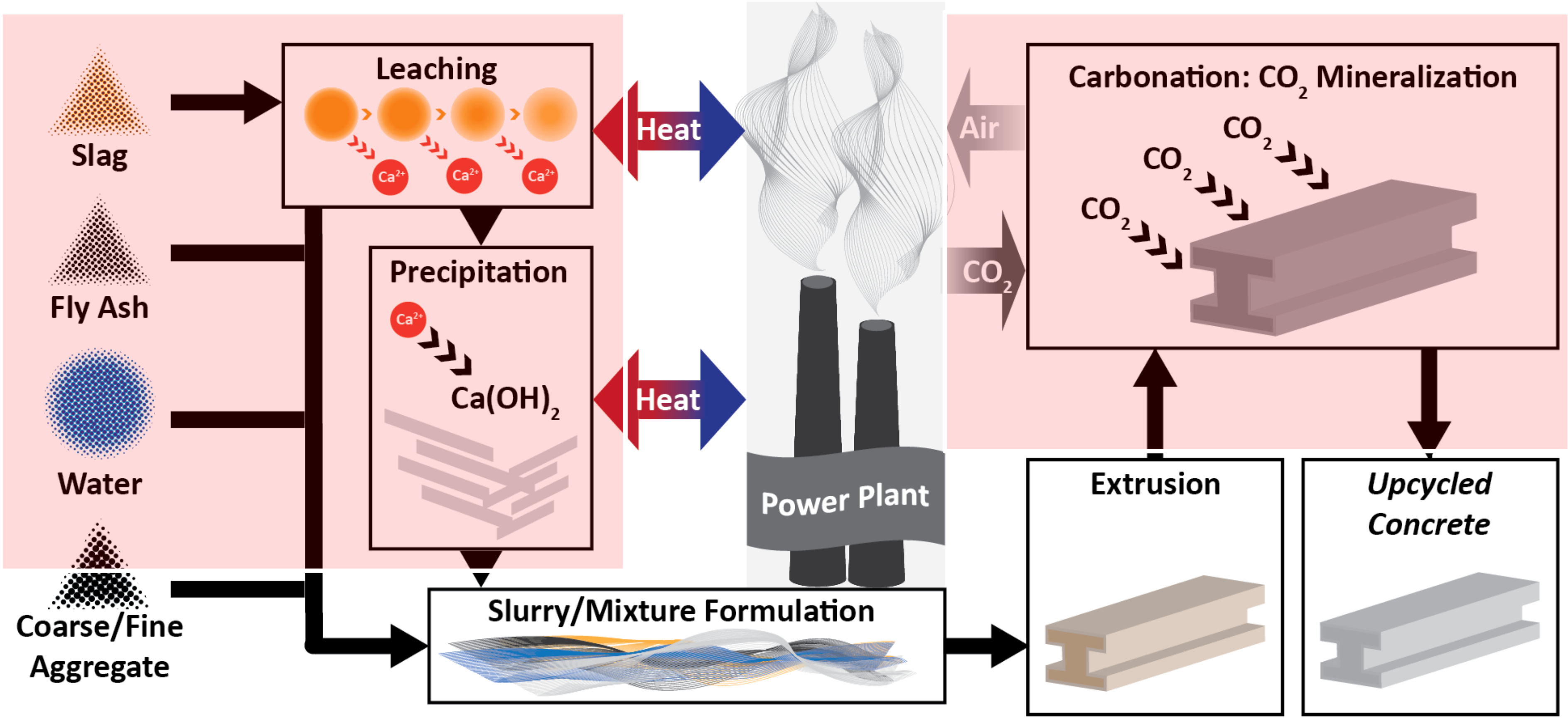


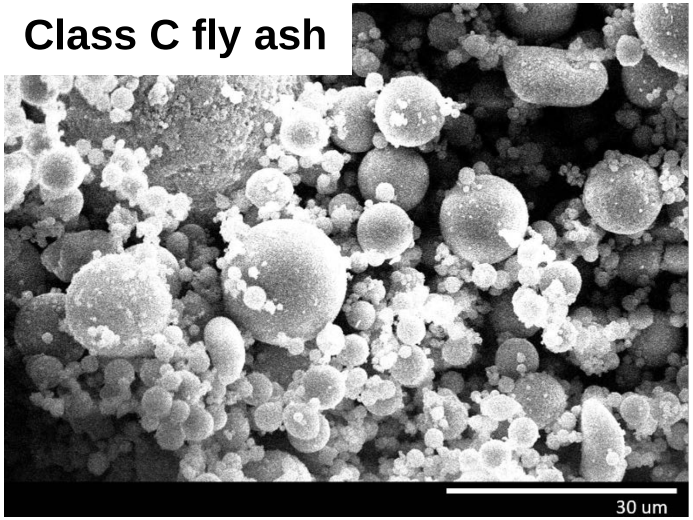


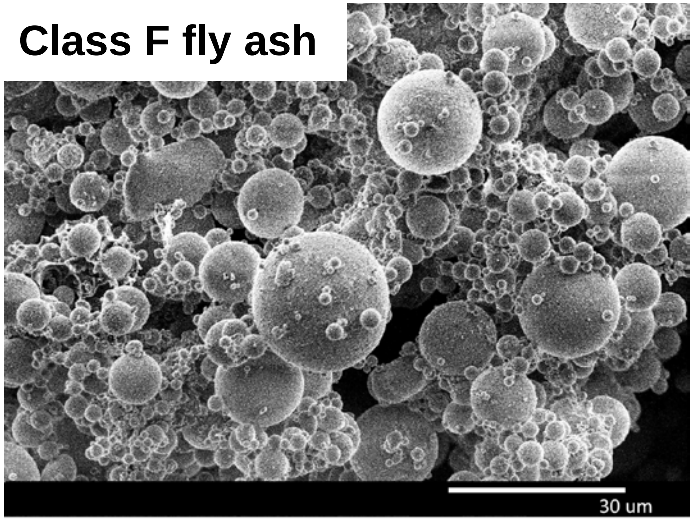
Carbonation of *upcycled concrete* mortars



Carbonation of fly ash and portlandite

- Fly ash is a coal combustion byproduct which has cementitious properties and potential for CO_2 uptake
- Depending on type, can sequester up to 0.05–0.3 g CO_2/g (0.59 for portlandite, CH)
- Carbonation of *suspensions* of CH–FA blends showed linear scaling of CO_2 uptake with CH
- Mortar samples prepared to represent *upcycled concrete*

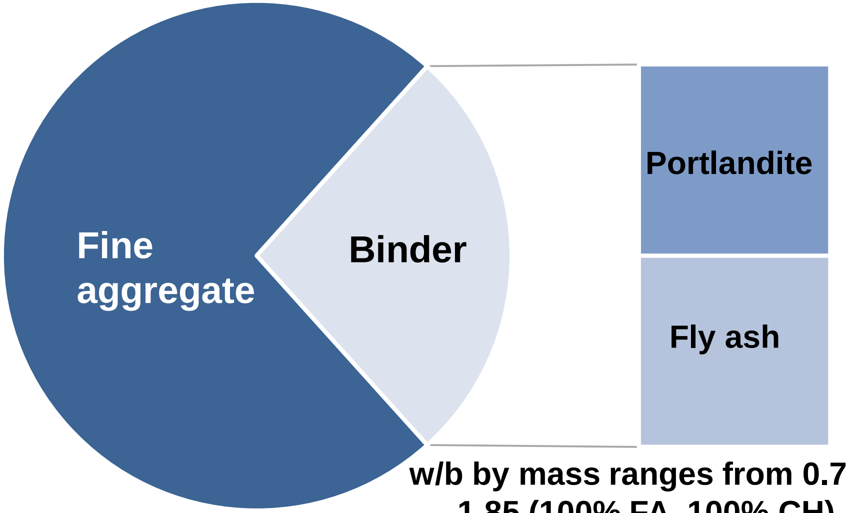

Class C fly ash


Class F fly ash

Carbonation of *upcycled concrete* mortars

- Mortars cured at 45 °C for 5 h, then removed from molds prior to carbonation
- Carbonation carried out in reactors by flowing a gas mixture containing 12% CO_2 (v/v) at a rate of 1 slpm
- TGA carried out on powder samples (extracted using a drill) to evaluate temporally evolving CO_2 uptake for the different mortar compositions

Upcycled concrete mixture proportions (mass basis)

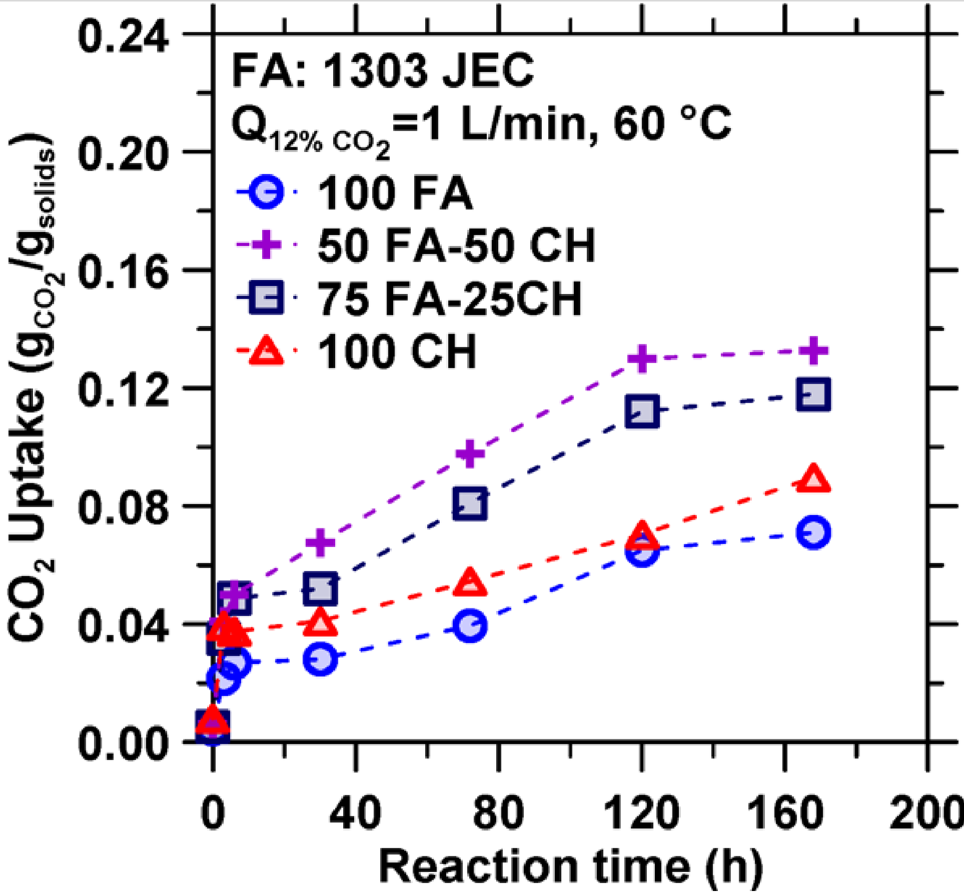


w/b by mass ranges from 0.70–1.85 (100% FA–100% CH)

Cylindrical mortars having dimensions of 50 mm × 100 mm (d × h)

Carbonation of *upcycled concrete* mortars

- CO_2 uptake increased with CH content, up to a point–not a simple linear scaling
- Optimum carbonation levels obtained for moderate dosages of CH (~50% by mass)
- Microstructure effects revealed and can be explained by (1) higher water content in CH-rich mixtures and/or (2) rapid carbonation of CH-rich mixtures, forming an outer carbonate layer having low porosity



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

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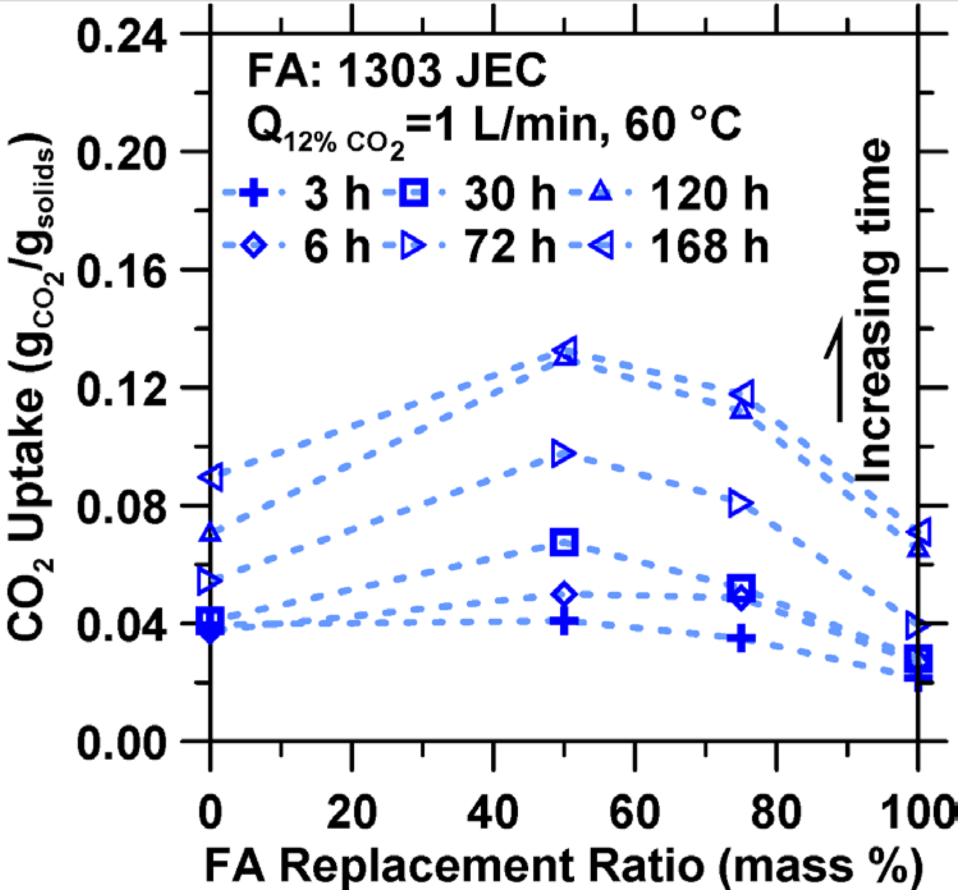

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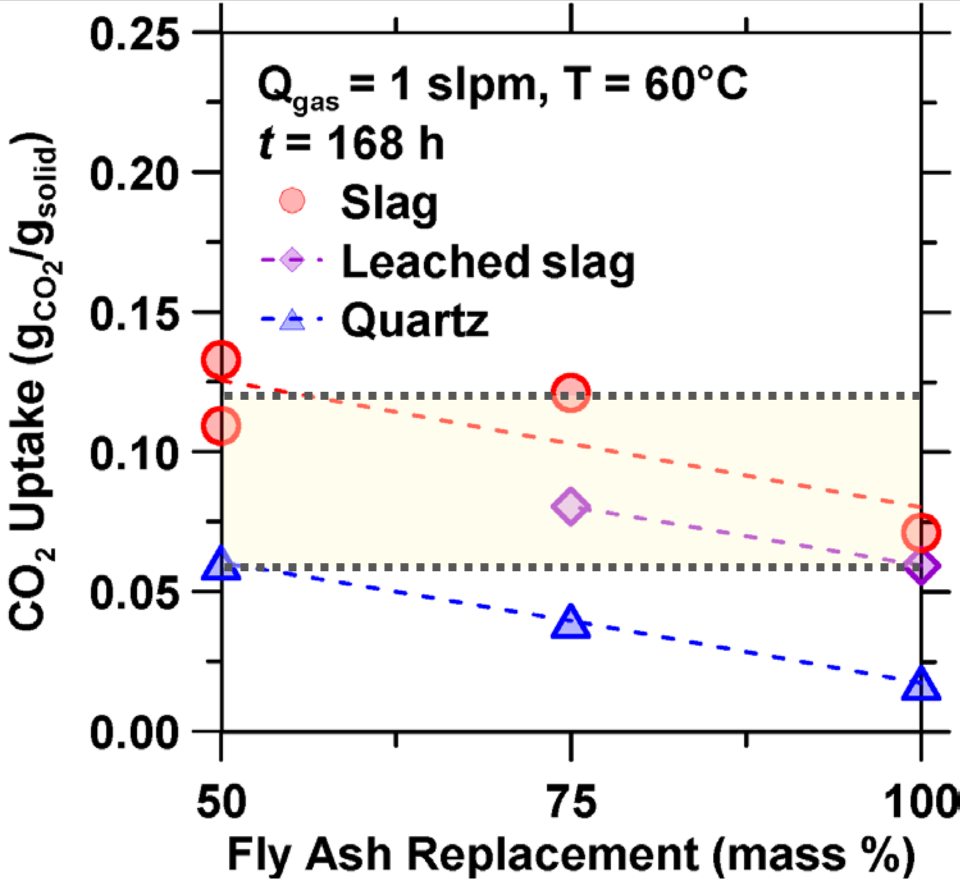
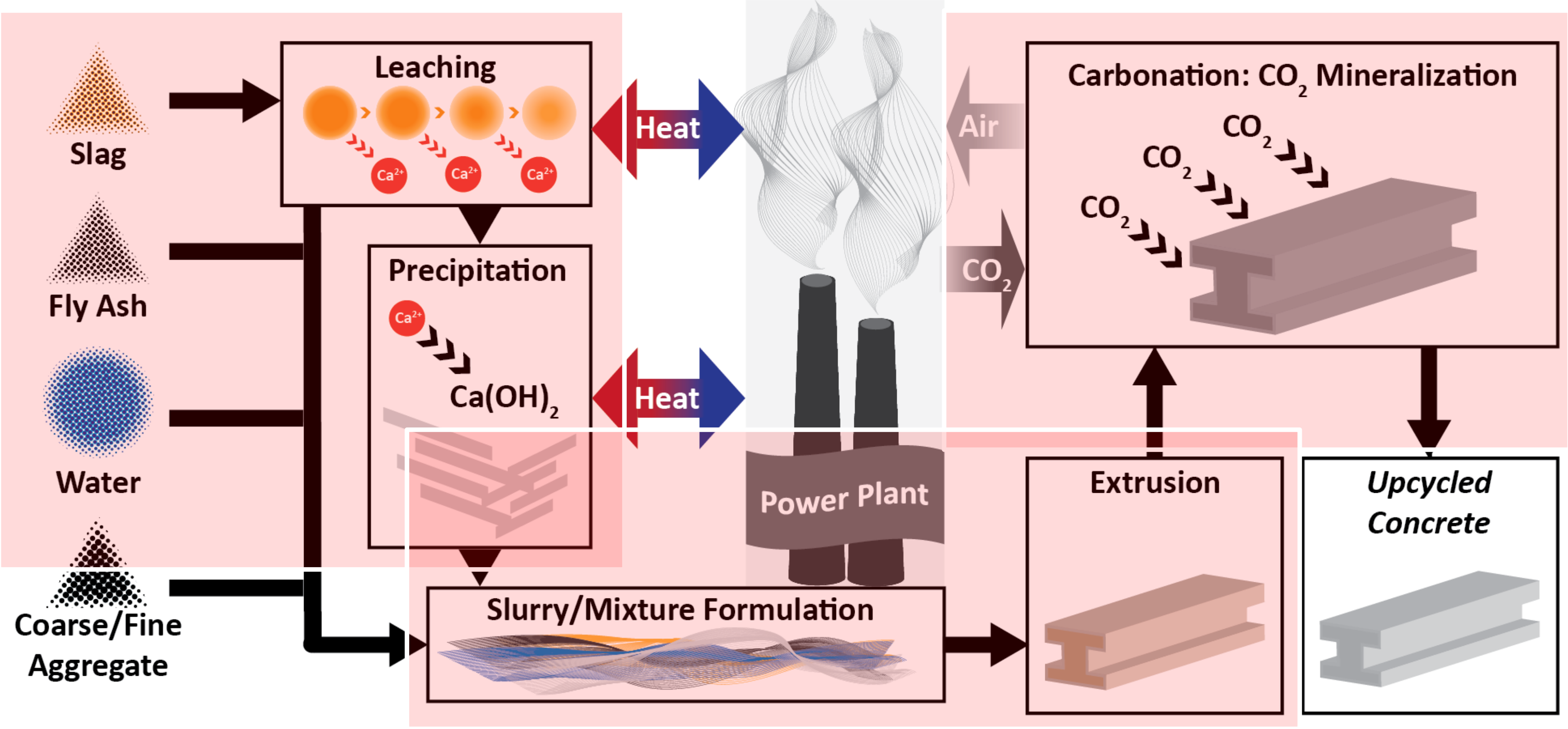
CO_2 uptake in portlandite-fly ash mortars

- Type of aggregate influenced CO_2 uptake – slag contributed significantly to carbonation
- Target CO_2 uptake of 6–12% achieved using ground as-received and leached slag
- Carbonation rates decreased over time – significant uptake at *t* ≤24 h
- Weak dependence on temperature over the range 45–85 °C



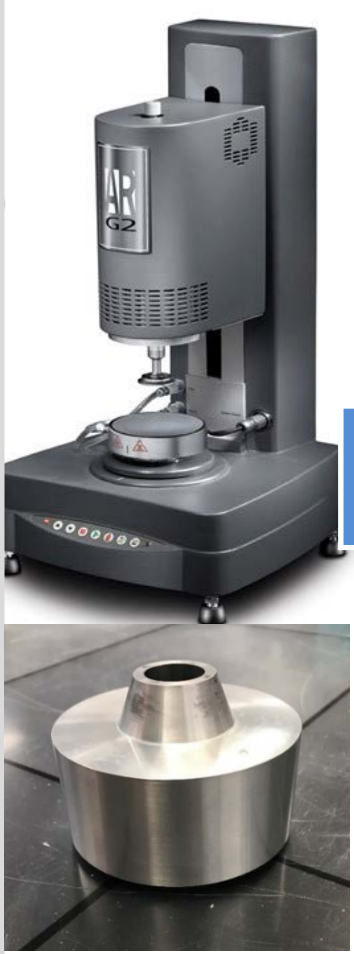
Target CO_2 uptake of 6–12% reached at 168 h for slag-containing mixtures having ≤50% CH

Fabrication of *upcycled concrete* mortars for carbonation

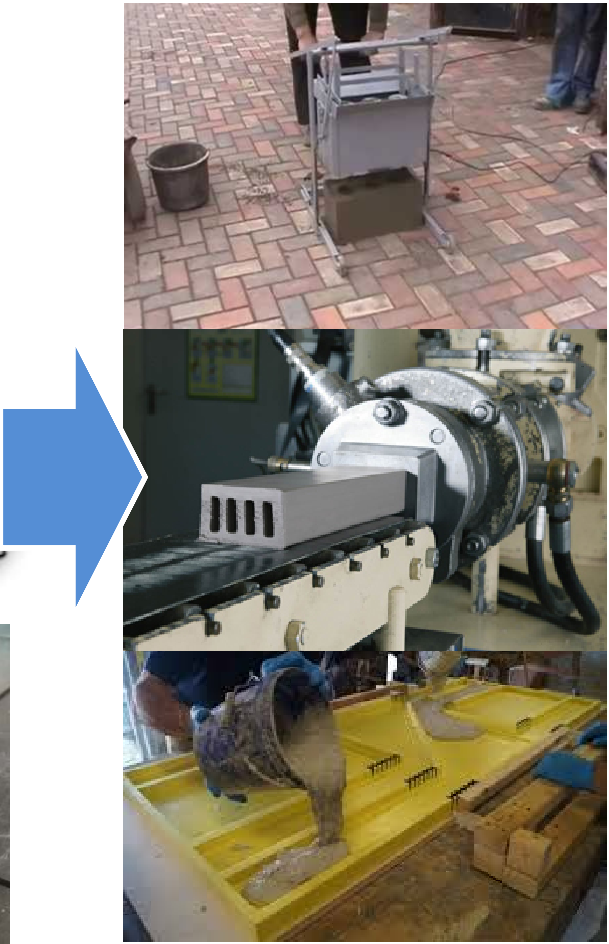


Upcycled concrete fabrication and properties

- Determine mixture proportions to optimize rheology (yield stress, plastic viscosity, suspension stability), workability
- Mixing ratios between the fly ash-portlandite-slag particulate blends, fine aggregates, water and chemical admixtures
- Select suitable shape stabilization process
- Optimize mechanical properties (compressive, flexural strength, fracture properties, etc.)



Laboratory tests



Shape stabilization method based on application

Process design and system evaluation

- Establish process design for laboratory-scale demonstration of integrated *upcycled concrete* production system
  - 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
- Performance data from experimental test runs: CO_2 uptake, mass flow rate, production throughput, energy consumption, etc.

Summary

- **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 the first year, we have demonstrated portlandite synthesis from crystalline slags and CO_2 uptake levels of 6–12% by mass of solid reactants
- Ongoing work includes the rheological characterization of upcycled concrete formulations and process design, including component selection for the laboratory scale upcycled concrete reactor

Acknowledgments

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- Project Manager: Andrew Jones

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