Upcycled ‘CO₂-negative’ concrete for construction functions

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**Developed for:** 2017 NETL CO₂ Capture Technology Project Review Meeting, Pittsburgh, PA, August 21-25, 2017
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

- Slag
- Fly Ash
- Water
- Coarse/Fine Aggregate

Leaching

Precipitation

Power Plant

Slurry/Mixture Formulation

Carbonation: CO$_2$ Mineralization

Extrusion

Upcycled Concrete
Project objectives

**Upcycling industrial wastes and CO₂**
- To utilize coal combustion and iron/steel processing wastes as precursors/reactant for scalable CO₂ 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 CO₂ uptake

**OPC concrete replacement**
- To develop a novel CO₂-negative upcycled concrete that is performance-equivalent or superior to OPC-based concrete while maintaining functional and utility equivalence
**Scope of work and project timeline**

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**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

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**Budget Period 2**
July’18-June’19

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

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**Budget Period 3**
July’19-March’20

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

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## Overview: Project funding profile

<table>
<thead>
<tr>
<th></th>
<th>Budget Period 1 (04/01/17-06/30/18)</th>
<th>Budget Period 2 (07/01/18-06/30/19)</th>
<th>Budget Period 3 (07/01/19-03/31/20)</th>
<th>Total Project</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gov't Share</td>
<td>Cost Share</td>
<td>Gov't Share</td>
<td>Cost Share</td>
</tr>
<tr>
<td>UCLA</td>
<td>$344,436</td>
<td>$155,533</td>
<td>$274,142</td>
<td>$119,467</td>
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<td>ASU</td>
<td>$75,155</td>
<td>$18,480</td>
<td>$66,541</td>
<td>$15,583</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$419,591</strong></td>
<td><strong>$174,013</strong></td>
<td><strong>$340,683</strong></td>
<td><strong>$135,050</strong></td>
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</table>

**Cost Share**

- UCLA: 71%
- ASU: 29%
- **Total**: 74%
Project participants

Scientific Team

Project and Management Financial
UCLA

Scientific Direction
(G. Sant, UCLA)

Reporting to DOE
Project Manager

Dissemination
Journals, Conferences

Market Studies
ITA-UCLA, Headwaters

UCLA
G. Sant and L. Pilon

ASU
N. Neithalath

Headwaters
R. Minkara (Partner)

G. Sant, B. Wang, E. Callagon
(Tasks 1, 3, 6, 7)

N. Neithalath
(Task 4)

Technicians
Task 4

L. Pilon and D. Rajagopal
(Tasks 2, 5, 7)

Graduate students
(TBD)

R. Diwa and S. Vallejo

Gaurav N. Sant 2017 NETL CO₂ Capture Technology Project Review Meeting
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• 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
• 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

Basic oxygen furnace slag

Co-mingled steel slag
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)
CO₂ 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 CO₂ mineralization, at 45-90 °C, and for CO₂ flue gas concentration of 6-18% CO₂ (v/v)
- Determine carbonation characteristics of fly ash and leached slag granules, and Ca(OH)₂ as well as the process conditions for carbonation

CO₂ 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 “CO₂ strengthening”.

![Graph showing flexural strength](image)
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 CO₂ uptake levels
- Report performance data from experimental test runs: CO₂ 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 CO₂ 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
<table>
<thead>
<tr>
<th>Completion of BP 1</th>
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<tbody>
<tr>
<td>• Carbonation characteristics of fly ash and leached slag, and the process conditions for carbonation of upcycled concrete mortar</td>
</tr>
<tr>
<td>• The critical steps (leaching, portlandite production, and carbonation) can be carried out in 24-to-168 hours or less</td>
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<table>
<thead>
<tr>
<th>Completion of BP 2</th>
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</thead>
<tbody>
<tr>
<td>• Compressive strength of ≥ 15 MPa</td>
</tr>
<tr>
<td>• Lifecycle footprint that is &gt; 75% smaller than OPC-concrete of equivalent performance grade (based on our preliminary assessment)</td>
</tr>
<tr>
<td>• Design of laboratory-scale, integrated concrete production system with production throughput of 10-to-100 kg/day of upcycled concrete</td>
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<thead>
<tr>
<th>Completion of BP 3</th>
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<tbody>
<tr>
<td>• Real-time CO₂ uptake of the lab-scale test unit within 20% of the estimated “accessible carbonation potential”</td>
</tr>
<tr>
<td>• Lifecycle footprint that is &gt;75% smaller than OPC-concrete of equivalent performance grade (final assessment)</td>
</tr>
<tr>
<td>• Conceptual scaled-up process design and completion of technical and economic feasibility study, market assessment, lifecycle analysis, and technology gap analysis</td>
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### Technical risks and mitigation strategies

<table>
<thead>
<tr>
<th>Description of Risk</th>
<th>Probability</th>
<th>Impact</th>
<th>Risk Management Mitigation and Response Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow leaching kinetics of slag</td>
<td>Low</td>
<td>Moderate</td>
<td>Increase surface area of slag particles, and dilution ratios, and slightly acidify the leachant</td>
</tr>
<tr>
<td>Unsatisfactory throughput or output concentration level from the CC</td>
<td>Moderate</td>
<td>Low</td>
<td>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.</td>
</tr>
<tr>
<td>Slow carbonation kinetics or low carbonation potential of fly ash</td>
<td>Moderate</td>
<td>Low</td>
<td>Increase the Ca(OH)₂/fly ash ratio, and/or secure Ca-rich fly ash</td>
</tr>
<tr>
<td>Concrete slurry shows unsatisfactory workability</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Adjust workability with rheology modifiers (e.g., viscosity modifiers, and dispersants)</td>
</tr>
<tr>
<td>Carbonated concrete shows unsatisfactory strength development</td>
<td>Low</td>
<td>Moderate</td>
<td>Enhance strength by pre-carbonation densification to reduce porosity reduction, or add inorganic binders to the formulation</td>
</tr>
</tbody>
</table>
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