Upcycled “CO$_2$-negative” concrete for construction functions

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Presentation outline

- Background
- Project objectives
- Team
- Scope of work (Tasks)
- Risks
- Project timeline
- Milestones
- Success criteria and decision points
- Budget

Background

- Electricity generation from coal-fired power plants represents 25% of total CO2 emissions in U.S. (1.4 B tons CO_2 in 2015)
- Identify routes for large-scale utilization of CO_2 as a precursor in beneficial products and processes, while yielding a carbon capture and storage (CCS) solution of permanence
- Utilize CO_2 by mineralizing stable carbonate compound with cementitious character
- Rapidly source light metal cations, and accomplish material processing without generating additional CO_2 emissions

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

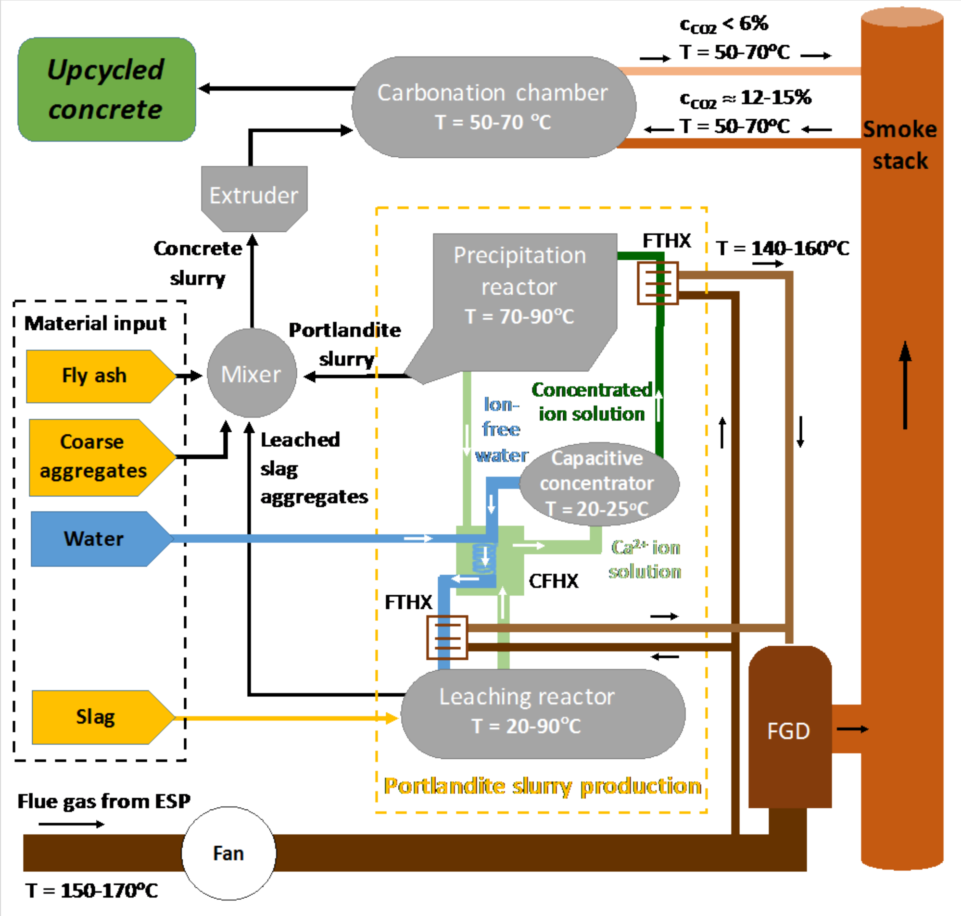
- To develop an integrated, ‘bolt-on’ technology/process solution for upcycled concrete production incorporating aspects of *Ca-leaching*, *$Ca(OH)_2$ precipitation*, *mixture formulation*, and *structural shape-stabilization*, while maximizing CO_2 uptake

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

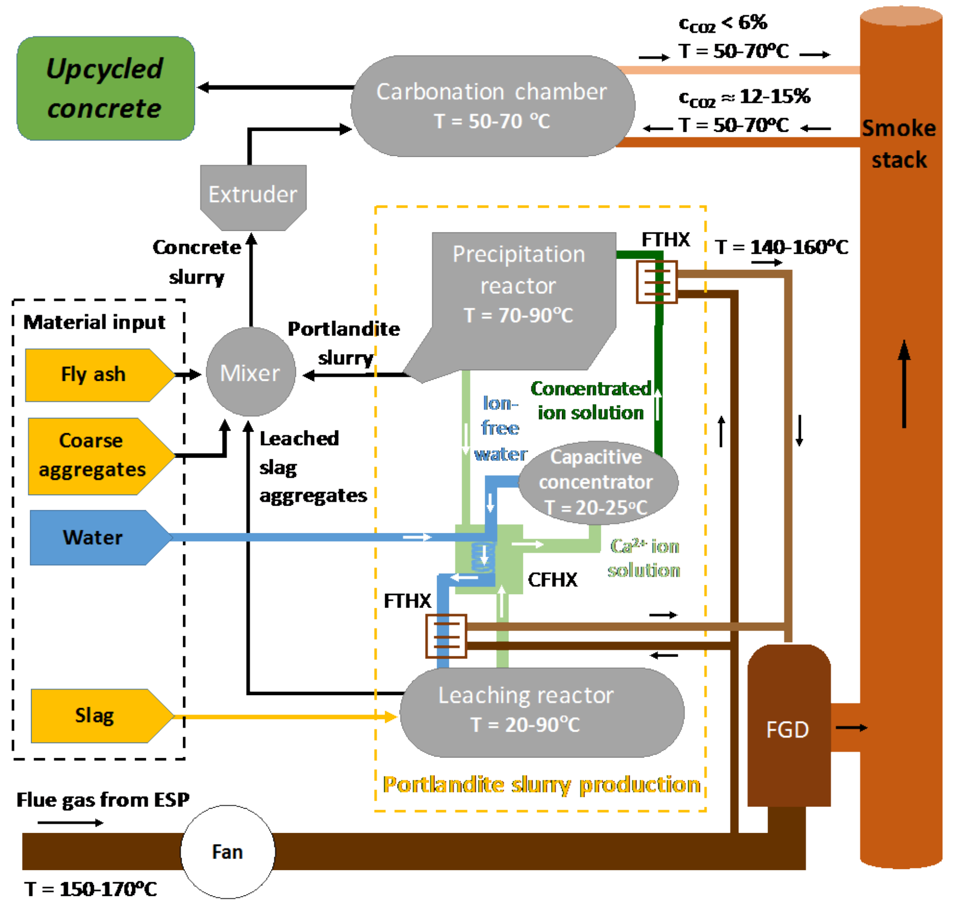
Process diagram

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

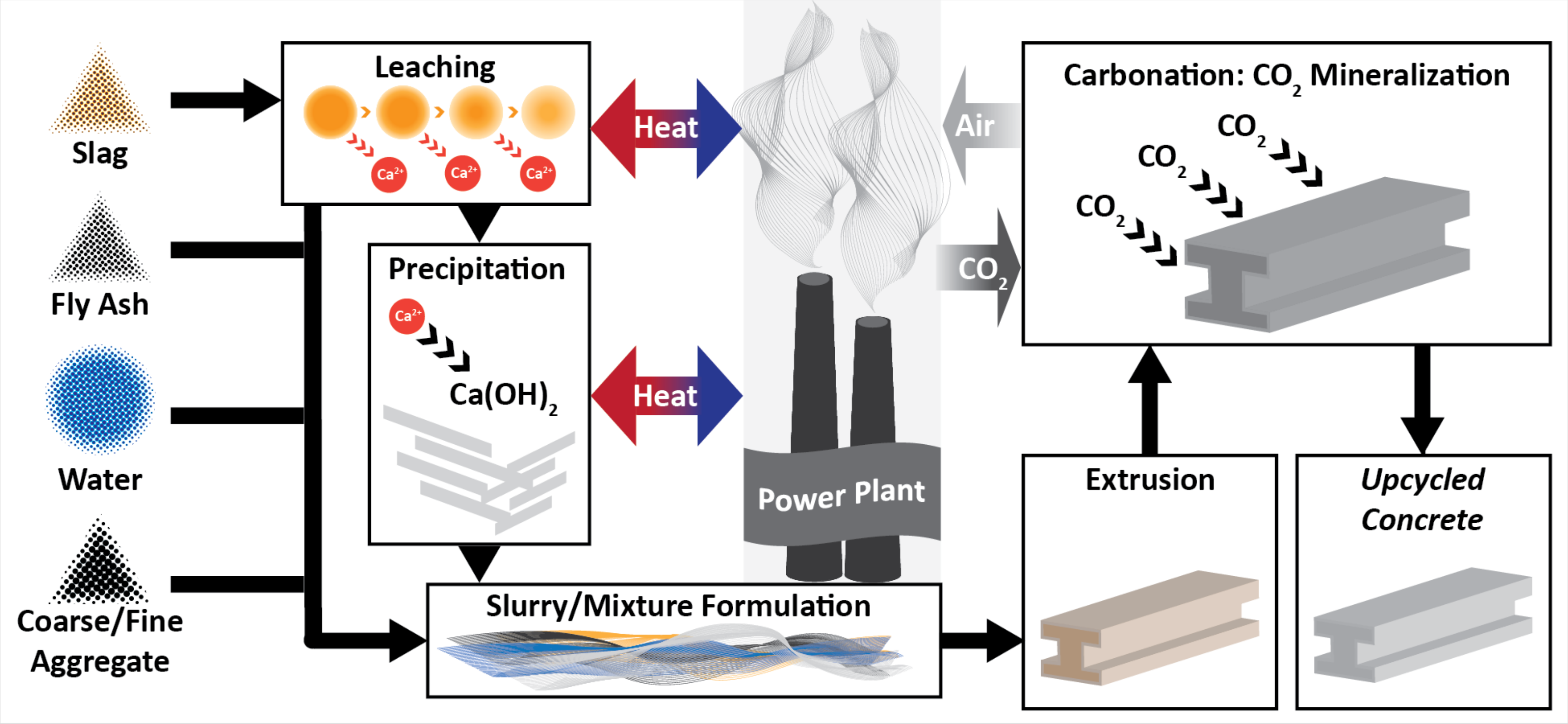


Process diagram

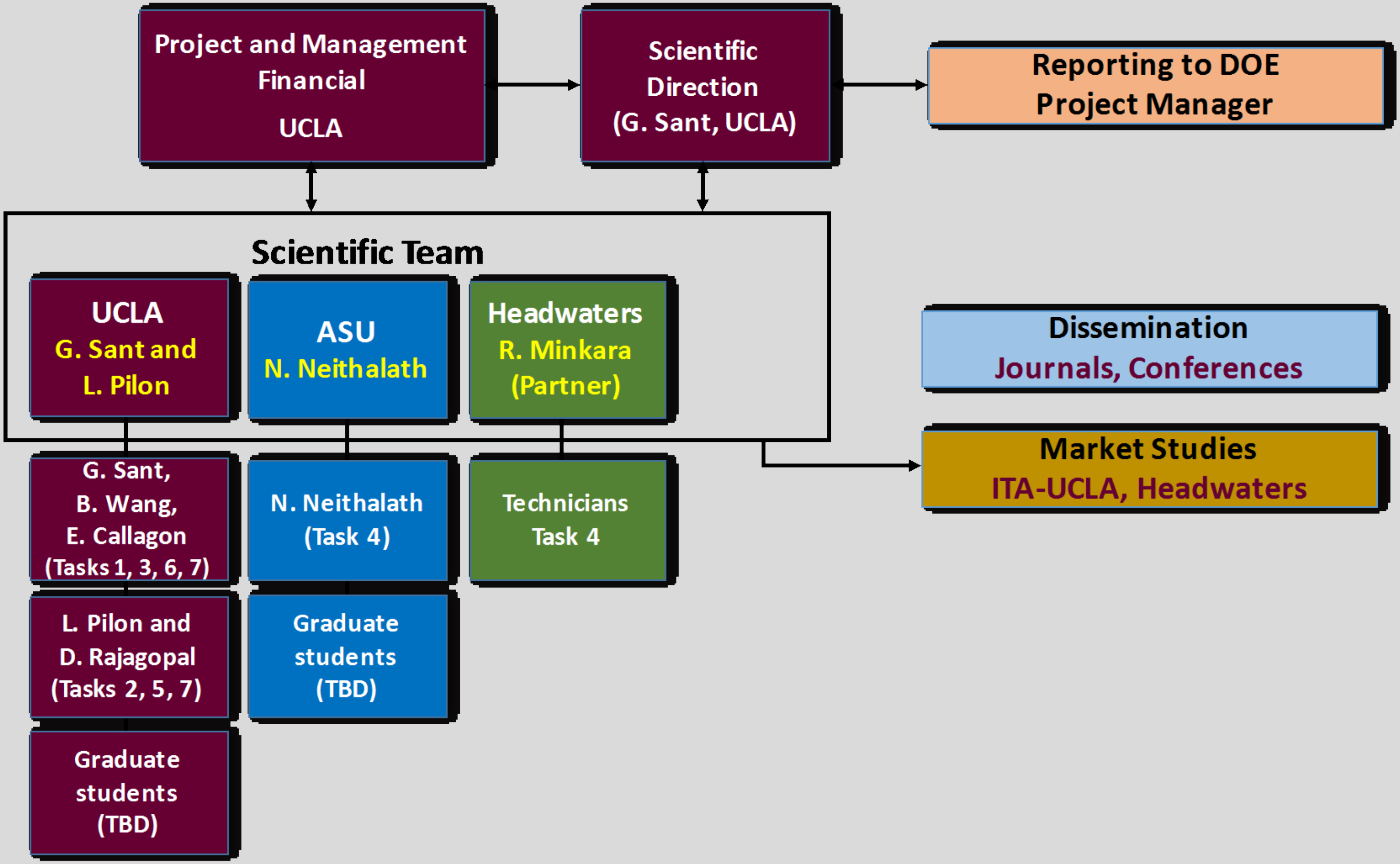
- Shape-stabilization of slurry into the form of a structural section (beam, column, etc.)
- Contacting structural section with flue-gas borne CO_2 within a carbonation chamber → *"upcycled concrete"* section
- Low-grade heat sourced from flue gas prior to, and following, desulfurization to optimize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



Upcycled concrete production process



Team structure and management



Project and Management
Financial
UCLA

Scientific
Direction
(G. Sant, UCLA)

Reporting to DOE
Project Manager

Scientific Team

UCLA
G. Sant and
L. Pilon

ASU
N. Neithalath

Headwaters
R. Minkara
(Partner)

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

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

Graduate
students
(TBD)

N. Neithalath
(Task 4)

Graduate
students
(TBD)

Technicians
Task 4

Dissemination
Journals, Conferences

Market Studies
ITA-UCLA, Headwaters

Team: Roles and responsibilities

Role	Responsibilities
PI: G. Sant	• Develop the project's risk register based on project time duration, complexity of the technical tasks, and milestones • Promote and ensure risk management for the project • Ensure proactive responses to all risks and opportunities to ensure beneficial outcomes of the project • Communicate risks and their management to the partners and DOE • Monitor and update risk/threat matrix • Track and monitor the effectiveness of risk response actions and retire risks
Faculty Co-PIs: L. Pilon, N. Neithalath D. Rajagopal	• Identify and assess risks • Develop response to risks • Communicate risks and response action to the PI, and contribute to the risk management plan
Project Scientist: B. Wang, E. Callagon	• Implement risk management activities • Look out for new risks and devise minimization strategies • Monitor and update risks for specific activities or milestones
Graduate Students: TBD	• Communicate issues in a timely manner to supervisors • Categorize risks and devise priorities for management • Report the mitigation strategies and document their effectiveness

Scope of work (Tasks)

- Budget Period 1
  - **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
  - **Task 4:** Upcycled concrete fabrication and properties
  - **Task 5:** Process design and scalability assessment
- Budget Period 3
  - **Task 6:** System evaluation
  - **Task 7:** Final technology assessment

Task 1: Project management and planning

- Periodic reports to DOE/NETL as well as manage informal correspondence and collaboration
- Technical briefings to DOE/NETL, and present project results jointly with other project partners at several industry- and DOE-sponsored conferences
- Monitor the project’s progress against plan, review and, if necessary, update the project management plan on a frequent basis and report on budget and schedule variances to DOE/NETL

Task 2: Portlandite production by leaching of crystalline iron and steel slags

- Setup a laboratory-scale leaching reactor and establish the leaching kinetics of air-cooled, crystalline slags under different conditions
- Construct and evaluate a capacitive concentrator
- Deliver compiled data on leaching characteristics of the crystalline slags, and process parameters and throughput of the portlandite production process

Subtask 2.1: Slag characterization

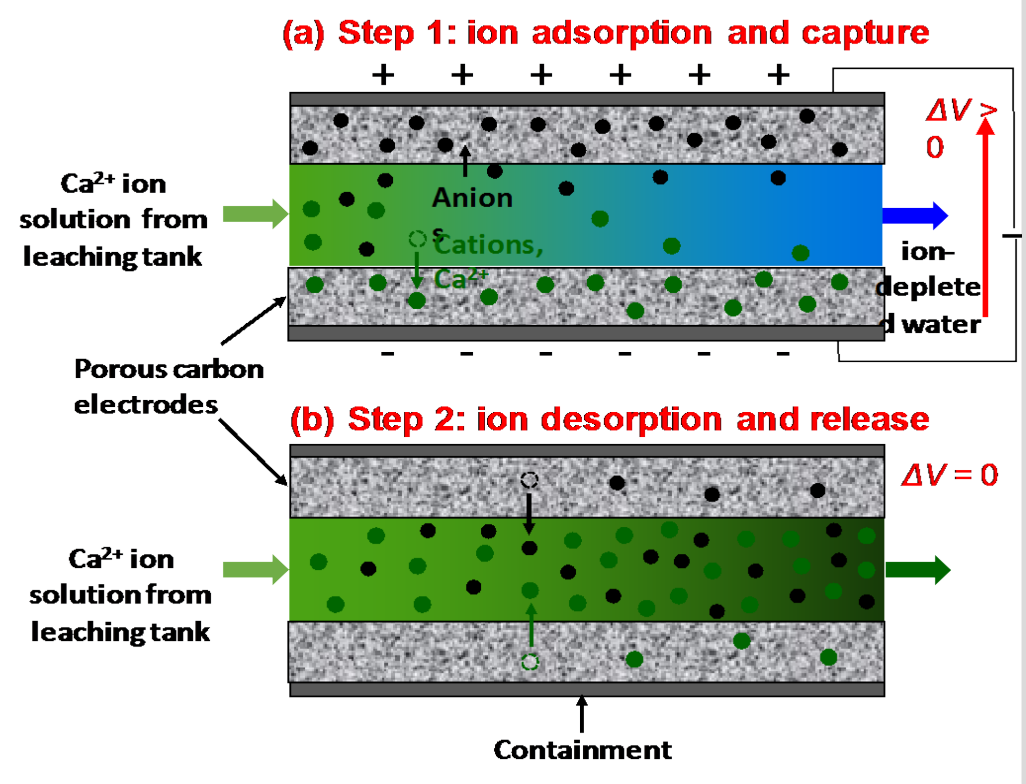
- Chemical and mineralogical characterizations (e.g., using XRF, SEM-EDS, XRD) of the following slag types:
  - Crystalline iron
  - Carbon steel
  - Stainless steel
- Leachability and carbonation potential will be assessed based on total alkaline simples oxide contents (e.g., CaO, MgO, Na_2O, etc.)
- Surface area of the granulated slag particles will be measured by BET

Subtask 2.2: Slag leaching kinetics

- Slag leaching kinetics will be evaluated as a function of slag particle size and leaching temperature
- Leaching kinetics will be analyzed based on a diffusion-controlled model (from leachant analyses and surface area)
- Kinetics will be measured at 3 leaching temperature between 25 and 90 °C to establish an Arrhenius-type model

Subtask 2.3: Optimizing capacitive concentrator

- Fabricate porous carbon electrodes and characterize the capacitive concentrator with leachant solutions from **Subtask 2.2** at 20 to 40 °C.



Task 3: CO_2 mineralization by accelerated carbonation

- Construct custom-built carbonation reactors and identify the appropriate process parameters to maximize the throughput of the CO_2 mineralization process.
- Carbonation characteristics of relevant coal-derived fly ash and leached slag granules, as well as the process conditions for carbonation of the *upcycled concrete* mortar will be delivered as a compiled dataset.

Task 3: CO_2 mineralization by accelerated carbonation

- **Subtask 3.1:** Fly ash particulates will be characterized using XRF and SEM-EDS (composition) and XRD (mineralogy), as in **Subtask 2.1**
- **Subtask 3.2:** Carbonation studies on blended fly ash, leached slag, and portlandite mixtures to assess their carbonation potential. Proportions may be adjusted by increasing precipitated portlandite content

Task 3: CO_2 mineralization by accelerated carbonation

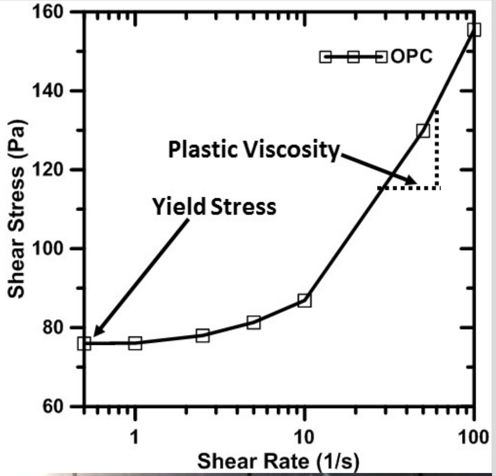
- **Subtask 3.3:** Custom-built carbonation reactors to establish the carbonation kinetics of fly ash, portlandite, and slag, as a function of temperature (45-90 °C) and CO_2 concentration (6-18%). Carbonation level will be determined by TGA.
- **Subtask 3.4:** Carbonation studies on *upcycled concrete* (equivalent mortars), with blend design and at carbonation conditions from **Subtasks 3.2 and 3.3**. Optimal proportions (i.e., from a carbonation perspective) will be established.

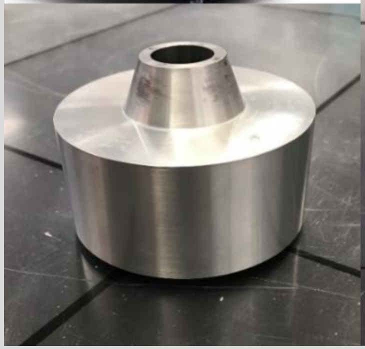
Task 4: Upcycled concrete fabrication and properties

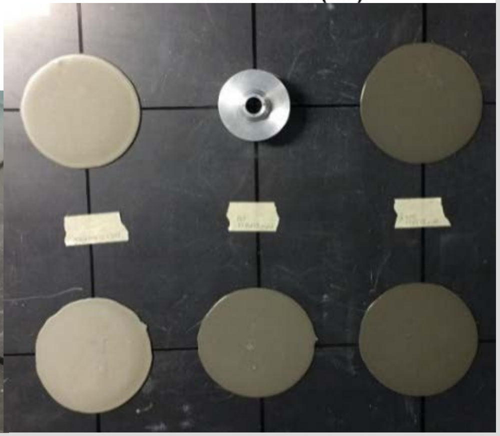
- Determine the mixture proportions that optimize the rheology and workability of fresh upcycled concrete formulations (i.e., “mixing ratios” between the fly ash-portlandite-slag particulate blends, additional fine aggregates, water and chemical admixtures (as needed)).
- Develop and identify and optimal shape stabilization process for fabrication of prismatic upcycled concrete geometries
- Mechanical performance of upcycled concrete will be evaluated using standard ASTM protocols

Subtask 4.1: Rheology characterization and optimization of upcycled concrete mortars

- Rheology of mortars from **Task 3** will be characterized in terms of yield stress, plastic viscosity, suspension stability
- Dispersants to ensure suitable workability and shape stability
- Suitable shape stabilization process (e.g., extrusion forming, molding, or pressing) will be selected







Rheology characterization and optimization of upcycled concrete mortars

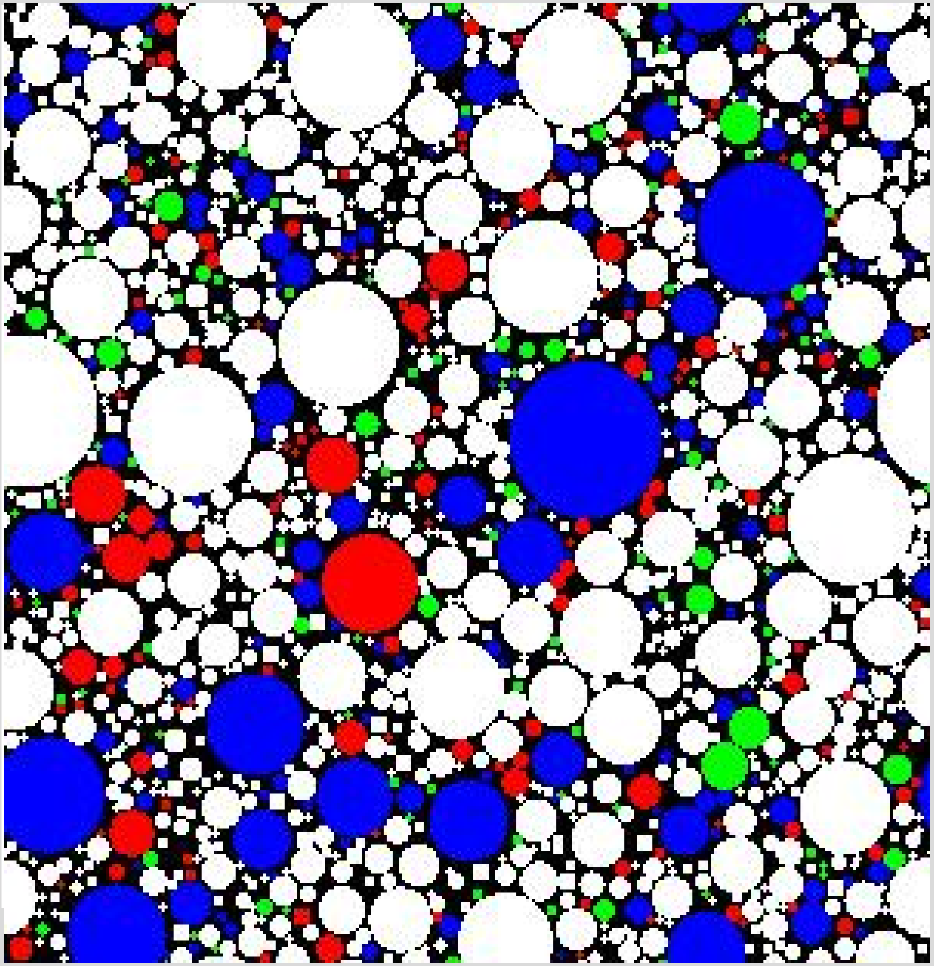
- Slurry rheology
  - On binder proportions designed to achieve target carbonation levels
  - Yield stress and plastic viscosity as the target parameters
  - Mini slump for rapid assessment

$$Flow\ Coefficient\ (\kappa) = \sqrt{\frac{A_{ms}}{\tau_y\ X\ \mu_p}}$$

$$\kappa_i\ \geq$$

Linking particle characteristics to rheology

- Suspensions at solid loadings close to maximum packing are very sensitive to operating conditions
- Packing of particles and packing characteristics (e.g., number density, SSA) related to rheology
- Provides a means to design particle characteristics (e.g., careful size distribution of components, grinding) for desired rheology that help form construction elements



Subtask 4.1: Rheology characterization and optimization of upcycled concrete mortars

- Low workability (stiff mixtures)
  - Stabilization by compaction/pressing into the molds (e.g., concrete blocks)
- Intermediate workability
  - Extrusion into structural shapes (e.g., beams, pipes, poles)
- Highly flowable mixtures
  - Casting
  - Rheology control to prevent segregation

Subtask 4.2: Concrete formulation, shape stabilization, property characterization

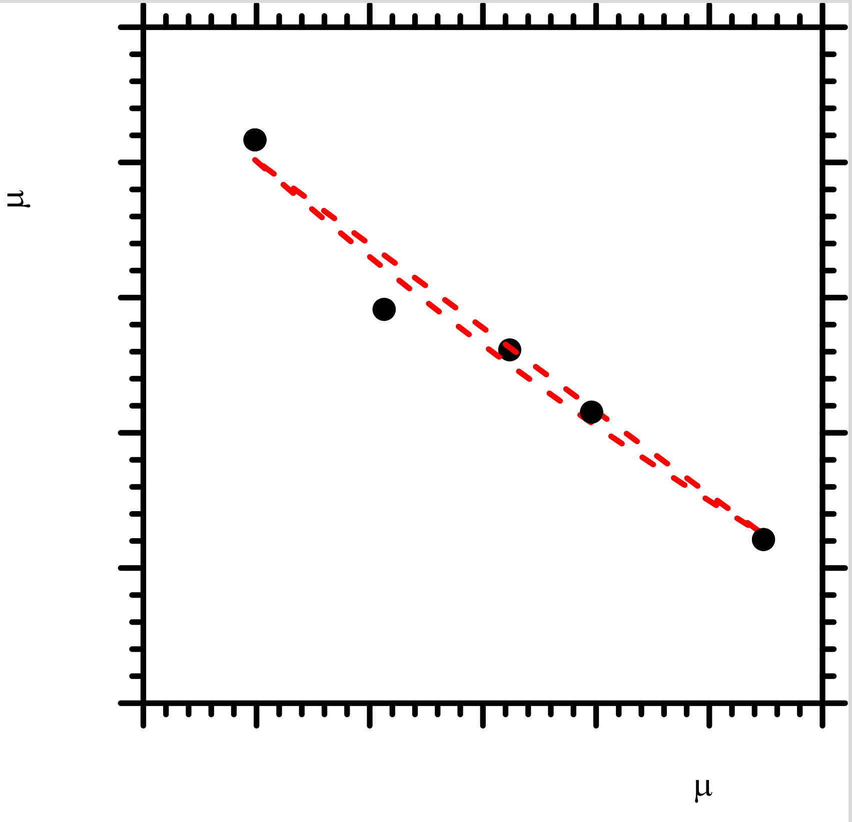
- Develop formulations and material proportions for optimal upcycled concrete mixtures
- Mortars will be formed into prismatic samples using shape stabilization method in **Subtask 4.1**

Laboratory tests

Shape stabilization based on application

Forming structural shapes using

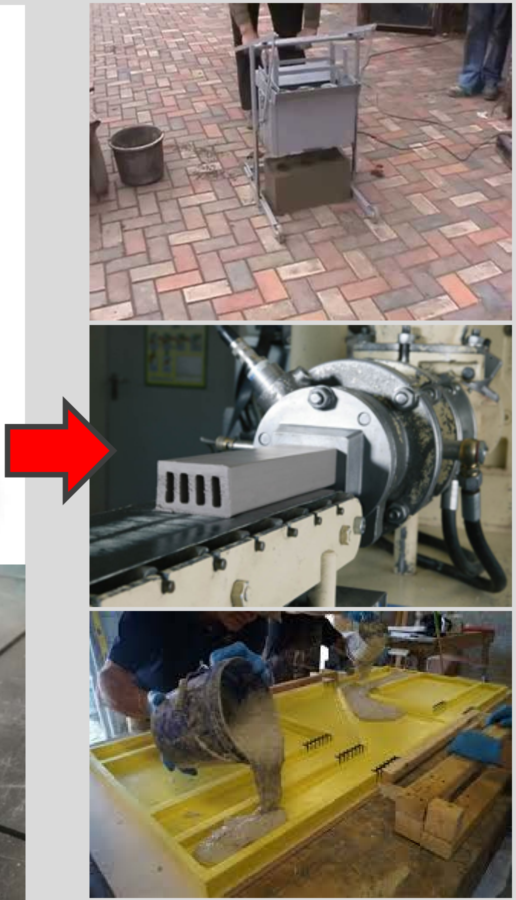
- Mixtures with desired rheology used as binders in the formation of structural shapes for carbonation
- Fine and coarse aggregates for volumetric stability
- Determination of adequate paste volume fraction (film thickness on particles) to ensure binding capacity
- Mixing procedure to ensure homogeneity and molding into structural shapes



Stabilizing structural shapes

- Rheology modification of binders so as to obtain desired workability
- Workability dictates the stabilization method
- Relating the flow coefficient to the method of shape stabilization

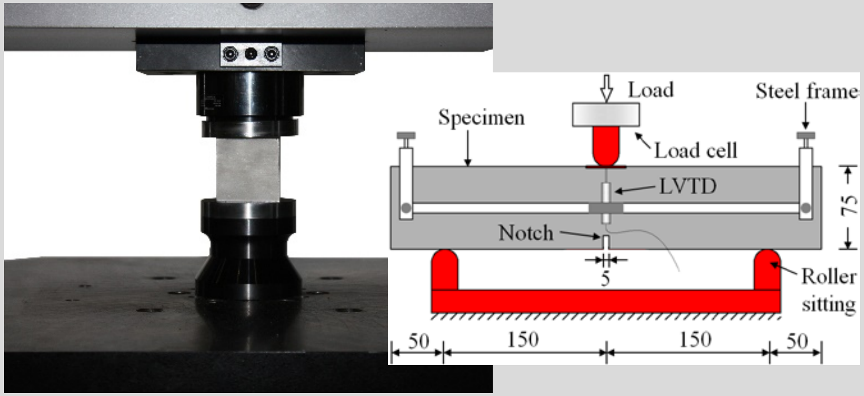
Laboratory tests

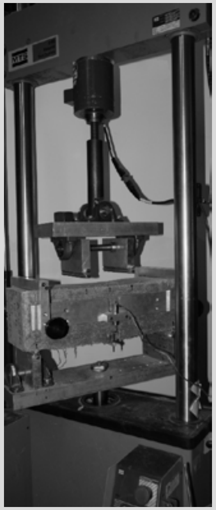


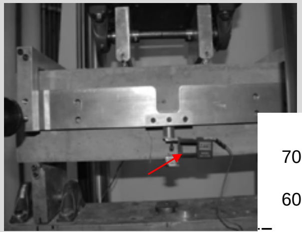
Shape stabilization method based on application

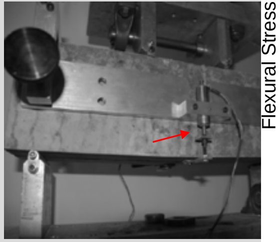
Subtask 4.2: Concrete formulation, shape stabilization, property characterization

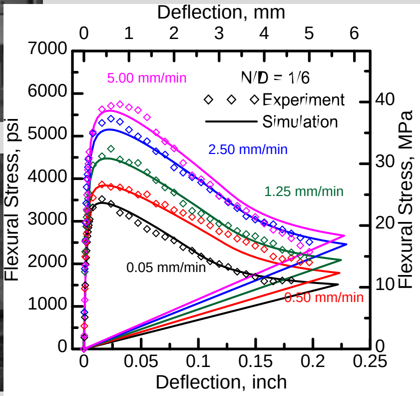
- Mechanical property analyses (e.g., flexural strength) following ASTM
- Engineering properties of upcycled concrete
  - Compressive strength
  - Flexural strength
  - Modulus of elasticity
  - Fracture properties











Mixture refinement and optimization

- Mechanical properties to refine the mixture
- A target flexural strength > 7 MPa for the carbonated pastes
- If needed, strength enhancement procedures will be employed
  - Better particle packing
  - Additives such as sodium silicate
  - Refining carbonation parameters to increase carbonation efficiency

Task 5: Process design and scalability assessment

- Establish process design for laboratory-scale, integrated *upcycled concrete* production system, and for its industrial scale-up
- Detailed design for the laboratory-scale demonstrated system to be constructed and tested in **Task 6** will be delivered

Task 5: Process design and scalability assessment

- **Subtask 5.1 (Component selection and design):** Identify the characteristics and specification of each component, with focus on the design and performance of capacitive concentrator and leaching reactor. Equipment required for assembling a laboratory-scale system is identified.
- **Subtask 5.2 (System design and process optimization):** Create a system design that integrated the individual components of the *upcycled concrete* process

Task 6: System evaluation

- Construct a laboratory-scale system to demonstrate the integrated *upcycled concrete* process.
- Report of all performance data collected during experimental test runs, including CO_2 uptake, mass flow rate, production throughput, energy consumption, etc. will be delivered.

Subtask 6.1: System procurement/construction

- Procure required equipment components from **Subtask 5.1**, and assemble a laboratory-scale test system from **Subtask 5.2**.
- Procure simulated coal-fired power plant flue gas.
- Establish operating procedures and test plan

Subtask 6.2: Integrated laboratory-scale tests

- Conduct test runs with the laboratory-scale system to evaluate the integrated *upcycled concrete* process
- Perform 3 test runs using simulated coal-fired power plant flue gas (e.g., typical concentration on the order of: 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) for a 12-24 h duration
- Produce upcycled concrete with 3 different (target) CO_2 uptake levels

Subtask 7.1: Scalability assessment and economic feasibility study

- Technical and economic feasibility study to provide detailed accounting of capital costs, operation and maintenance costs and RSP relative to existing markets for the scaled-up process
- Conceptual design for coupling the upcycled concrete production process with coal-fired power plant
- Market assessment, including all revenue streams, assumed unit costs, current and projected market volume and value, and estimated quantity of CO_2 utilized.
- Deliver compiled results of the techno-economic feasibility study, including a high-level, return-on-investment (ROI) analysis based on experimental and modeling results.

Subtask 7.2: Lifecycle analysis

- Lifecycle analysis (LCA) that considers both material and process aspects.
- System design from **Subtask 5.2** will be further optimized for minimizing the LCA impacts
- LCA considering both materials and processing aspects will be conducted to identify environmental benefits
- Quantify net CO_2 avoidance offered

Subtask 7.3: Technology gap analysis

- Technology Gap Analysis to review the state of upcycled concrete process development.
- Estimations of performance, cost, emission, market, safety metrics per NETL’s guidelines for carbon utilization and storage technologues
- Technology Readiness Level (TRL) of critical process components (portlandite production by leaching and precipitation, CO_2 mineralization), upcycled concrete fabrication)
- Summarize commercially-available equipment components and potential vendors

Risk management approach

- Close monitoring of scientific/financial aspects by PI and a project manager
- *Risk register* will help identification and mitigation of risks

Technical risks

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Slags show characteristics of slow leaching kinetics	Low	Moderate	Improve the kinetics by increasing interfacial surface area between slag particles and leachant, and dilution ratios, and slightly acidifying the leachant.
Unsatisfactory throughput or output concentration level from the capacitive concentrator	Moderate	Low	Construct a multi-concentrator system with concentrators in series (to improve concentration performance) or in parallel (to improve throughput). Further, use waste heat from power plant to accelerate precipitation by actively evaporating the concentrated solution.
Fly ash shows slow carbonation kinetics and/or low carbonation potential due to low calcium content	Moderate	Low	Increase the $Ca(OH)_2$/fly ash ratio, and/or secure calcium-rich fly ash (i.e., higher CaO content)

Technical risks (cont.)

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Concrete slurry shows unsatisfactory workability	Moderate	Moderate	Adjust workability with rheology modifiers (e.g., viscosity modifiers, and dispersants)
Carbonated concrete shows unsatisfactory strength	Low	Moderate	Enhance strength by pre-carbonation densification to reduce porosity reduction, and/or add inorganic binders to the formulation

Resource risks

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Budget shortfalls	Moderate	High	Closely monitor project costs and scope, and set spending priorities based on timelines and milestones.
Inexperienced staff	Low	Low	Schedule sufficient time for training of new staff and technicians
Losing critical staff at crucial point of the project	Low	Moderate	Training multi-skilled, cross-trained students and staff and establish clear standard operating procedures
Delayed delivery of supply	Moderate	Low	Anticipate supplies, front order, and plan for potential delays

Management risks

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Scope creep	Low	High	Set clear priorities and assign resources based on timelines and milestones defined in project management plan. Maintain clear communications between teams and DOE.
Intellectual property risks	Moderate	Moderate	Ensure that the project participants are knowledgeable of relevant IP agreements, and uniqueness of the research outcomes
Delayed finish of earlier activities	Moderate	Moderate	Closely track project progress and develop alternative pathways when delays emerge. Ensure timely delivery of independent research activities when delays emerge.

Project timeline

Tasks	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
Task 1.0 – Project Management and Planning	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Subtask 1.1 - Project management and planning	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Subtask 1.2 - Briefing and reports	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Task 2.0 – Portlandite production by leaching of crystalline iron and steel slags	🟧	🟧	🟧	🟧	🟧							
Subtask 2.1 - Slag characterization	🟧	🟧										
Subtask 2.2 - Slag leaching kinetics		🟧	🟧									
Subtask 2.3 - Optimizing capacitive concentrator			🟧	🟧								
Subtask 2.4 - Portlandite precipitation characteristics				🟧	🟧							

Project timeline (cont.)

Tasks	Budget Period 1					Budget Period 2				Budget Period 3		
	4/1/17 - 6/30/18					7/1/18 - 6/30/19				7/1/19 - 3/31/20		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 3.0 – CO_2 mineralization by accelerated carbonation	🟧	🟧	🟧	🟧	🟧							
Subtask 3.1 - Characterization and carbonation potential assessment of fly ash	🟧	🟧										
Subtask 3.2 - Carbonation potential of blended fly ash and portlandite		🟧	🟧									
Subtask 3.3 - Carbonation kinetics in simulated flue gas mixture			🟧	🟧								
Subtask 3.4 - Carbonation of upcycled concrete mortars (optimized blends)				🟧	🟧							

Project timeline (cont.)

Tasks	Budget Period 1					Budget Period 2				Budget Period 3		
	4/1/17 - 6/30/18					7/1/18 - 6/30/19				7/1/19 - 3/31/20		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 4.0 – Upcycled concrete fabrication and properties						🟧	🟧	🟧	🟧			
Subtask 4.1 - Rheology characterization and optimization of upcycled concrete mortars						🟧	🟧					
Subtask 4.2 - Concrete formulation, shape stabilization, property characterization								🟧	🟧			
Task 5.0 – Process design and scalability assessment						🟧	🟧	🟧	🟧			
Subtask 5.1 - Component selection and design/modifications						🟧	🟧					
Subtask 5.2 - System design and process optimization								🟧	🟧			

Project timeline (cont.)

Tasks	Budget Period 1					Budget Period 2				Budget Period 3		
	4/1/17 - 6/30/18					7/1/18 - 6/30/19				7/1/19 - 3/31/20		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 6.0 – System demonstration										🟧	🟧	🟧
Subtask 6.1 - Component procurement and system construction										🟧	🟧	
Subtask 6.2 - Integrated laboratory-scale testing											🟧	🟧
Task 7.0 – Final Technology Assessment											🟧	🟧
Subtask 7.1 - Scalability assessment and economic feasibility study											🟧	🟧
Subtask 7.2 - Lifecycle analysis											🟧	🟧
Subtask 7.3 - Technology Gap Analysis											🟧	🟧

Milestones

Milestones	Budget Period 1					Budget Period 2				Budget Period 3		
	4/1/17 - 6/30/18					7/1/18 - 6/30/19				7/1/19 - 3/31/20		
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
a. Updated Project Management Plan	🟧											
b. Kickoff meeting	🟧											
c. Establish the leaching characteristics (i.e., rate and extent) for 3 unique slag types				🟧								
d. Achieve 3 different CO_2 uptake levels (between 0.06-0.12 grams of CO_2 per gram of solid reactants) with blended fly ash and portlandite formulations					🟧							
e. Establish the rheology characteristics for upcycled concrete formulations with 3 different fly ash-portlandite blends								🟧				
f. Establish shape-stable, upcycled concrete formulation with compressive strength ≥ 15 MPa									🟧			

Milestones (cont.)

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
g. Establish process design for lab-scale test unit with production throughput between 10-to-100 kg of upcycled concrete per day									🟧			
h. Complete construction of lab-scale test unit with production throughput between 10-to-100 kg of upcycled concrete per day											🟧	
i. Achieve production throughput between 10-to-100 kg upcycled concrete per day, with CO_2 uptake between 0.06-0.12 grams of CO_2 per gram of reactants												🟧
j. Establish scalability, lifecycle CO_2 footprint and techno-economic feasibility												🟧
k. Technology Gap Analysis												🟧
QR. Quarterly RPPR report	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

Success criteria and decision points

Completion of BP 1

- Successful completion of all work proposed in Budget Period 1
- Carbonation characteristics of relevant coal-derived fly ash and leached slag granules, and the process conditions for carbonation of upcycled concrete mortar
- The critical steps (leaching, portlandite production, and carbonation) can be carried out such that the process can complete in 24-to-168 hours or less

Completion of BP 2

- Successful completion of all work proposed in Budget Period 2
- Achievement of a target upcycled concrete compressive strength of 15 MPa
- Resulting construction material has a 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 between 10-to-100 kg of upcycled concrete per day

Completion of BP 3

- Successful completion of all work proposed
- Real-time CO_2 uptake of the lab-scale test unit is accurate within 20% of the estimated “carbonation potential”
- Resulting construction material has a lifecycle footprint that is >75% smaller than OPC-concrete of equivalent performance grade (final assessment)
- Conceptual scaled-up process design and the completion of then required technical and economic feasibility study, market assessment, lifecycle analysis, and technology gap analysis

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%

Budget Period/Fiscal Year Project Costing Profile

Budget Period	Fiscal Year	Performing Organization	Planned Costs	
			Federal Share	Non-Federal Share
1	FY17	UCLA	$156,819	$56,382
1	FY18	UCLA	$187,618	$99,151
2	FY18	UCLA	$76,568	$20,492
2	FY19	UCLA	$197,574	$98,975
3	FY19	UCLA	$83,177	$-
3	FY20	UCLA	$98,244	$25,000
1	FY17	ASU	$30,062	$4,620
1	FY18	ASU	$45,093	$13,860
2	FY18	ASU	$16,635	$-
2	FY19	ASU	$49,906	$15,583
3	FY19	ASU	$19,435	$5,312
3	FY20	ASU	$38,869	$10,625