STORING CO_2 IN BUILT INFRASTRUCTURE: CO_2 CARBONATION OF PRECAST CONCRETE PRODUCTS

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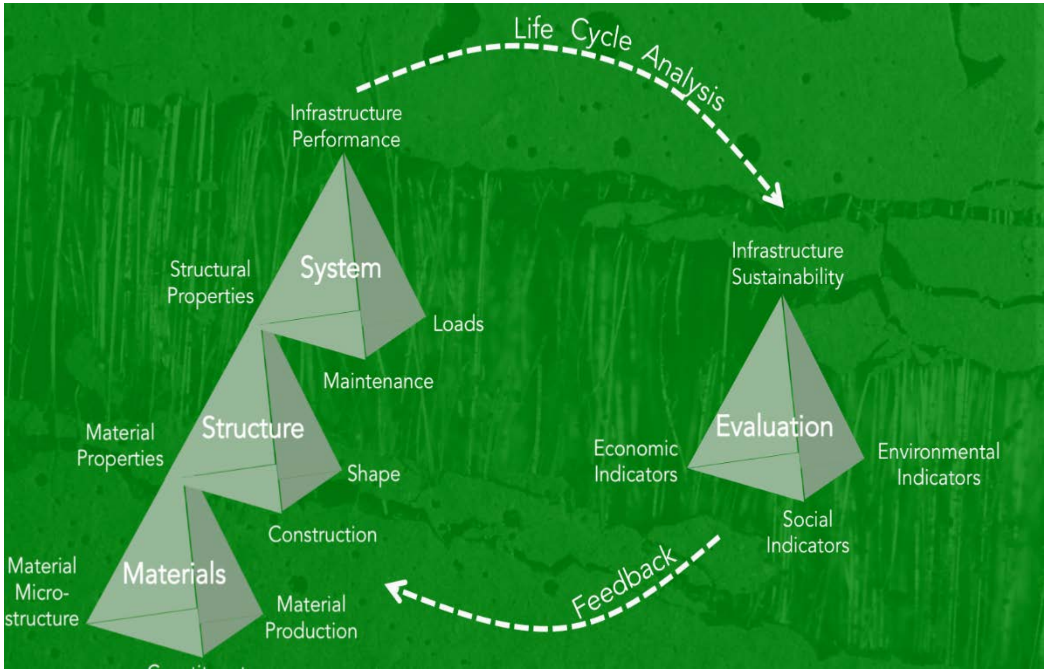
Award: DE FE0030684

Coupling CO_2 storage with novel cement materials to support sustainable infrastructure

GOAL: To advance the technical understanding of CO_2 incorporation into novel cementitious materials for the development of high value products that provide a net reduction in carbon emissions

Precast concrete elements, such as railroad ties, offer great potential to be a marketable product that is also a sink for coal-fired power plant CO_2 emissions via mineral carbonation



Enhanced Cementitious Composite (ECC)

Concrete Composition

Enhanced Cementitious Composite (ECC)

ECC Composition

+

+

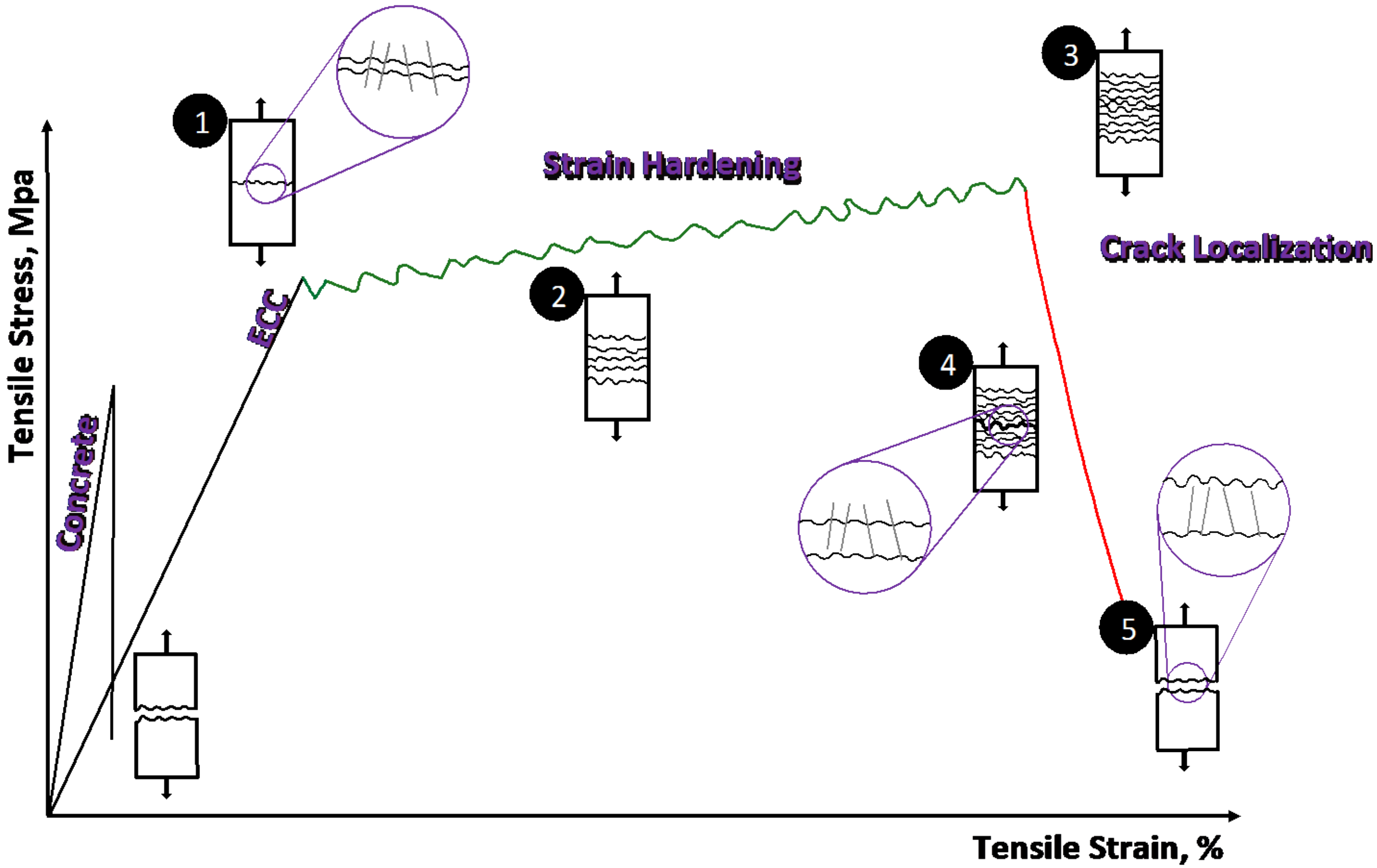
= ECC

+

+ **micromechanical design basis**

Enhanced Cementitious Composite (ECC)

ECC vs Concrete



Enhanced Cementitious Composite (ECC)

Ultra-ductile fiber-reinforced cementitious composites

(1). Improved tensile strength

(2). Limited crack width

(3). Potential for fracture healing

Enhanced Cementitious Composite (ECC) and Railroad Ties

ECC characteristics

- **Self-healing properties**
- **Controlled crack width < 50 µm**
- **'Bendable' concrete**
- **Offers improved durability, longer lifetime of precast concrete products**

Rail Ties as demonstration product

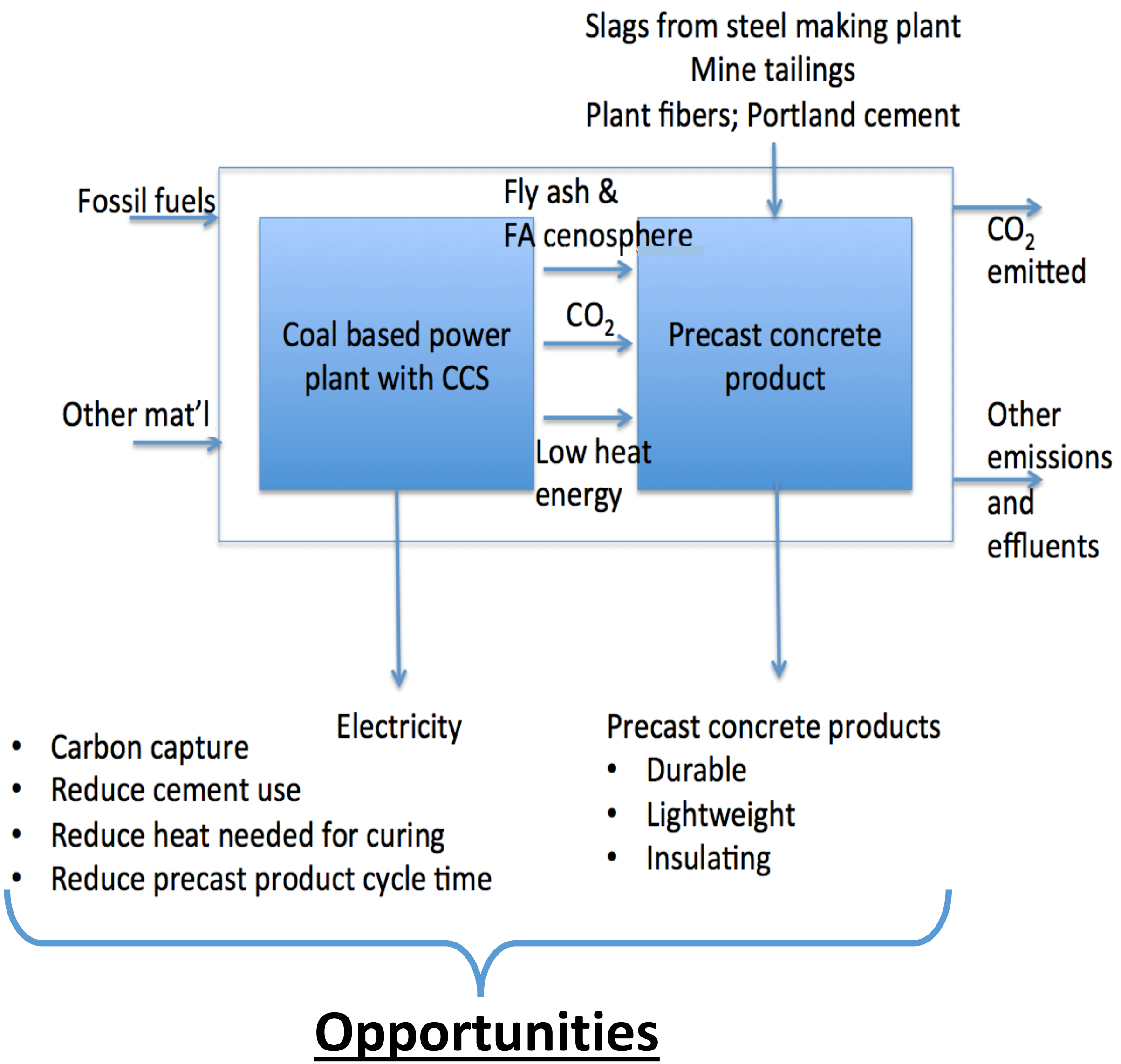
- **Improve product lifetime (~50yr)**
- **No need for pre-stressed steel reinforcement, which has benefits from both a cost and longevity perspective**

This project seeks to:

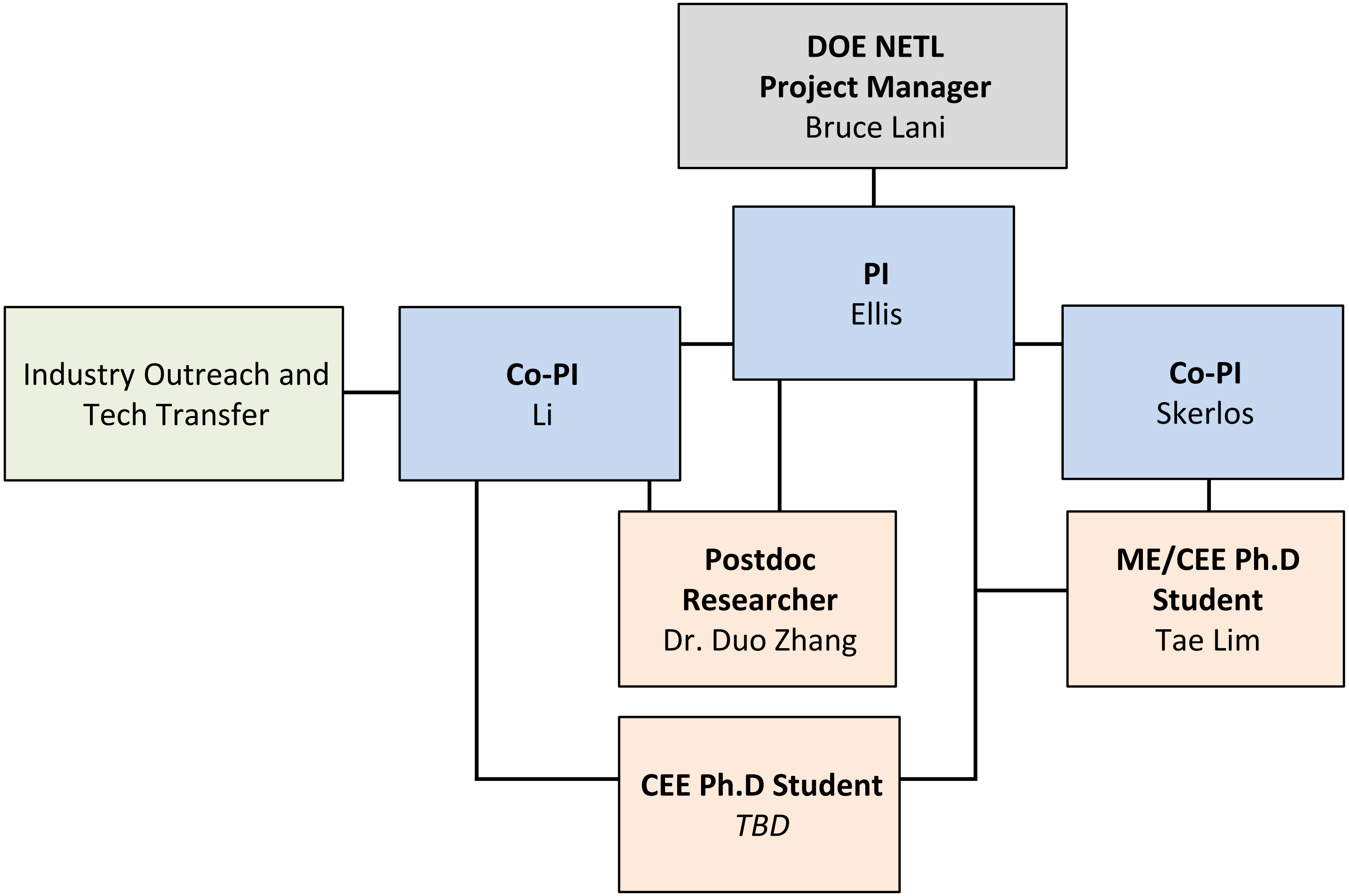
(1) optimize CO_2 carbonation of cementitious materials

(2) evaluate physical properties of novel carbonated materials

(3) assess the reductions in life cycle CO_2 emissions attributed to CO_2 carbonation of precast cementitious materials



Team Organization, Roles, and Responsibilities



Scope of Work

Budget Period 1
10/01/17 – 3/31/19

Budget Period 2
4/01/19 – 9/30/20

Task 1: Project Management and Planning

Task 2: CO_2 Carbonation of Engineered Cementitious Composites (ECC) and Caustic Solid Waste Materials

Task 3: Integrating carbonated materials into precast products

Task 4: Composite-Product (rail tie) integration and testing

Task 5: Evaluation of Life Cycle CO_2 Emissions Reduction

Task 1: *Project management and planning*

- ***Quarterly and Monthly Reporting***

UM will manage and report on all project activities as dictated in the PMP

- ***Reporting and Deliverables***

Project PIs will provide all reports and required deliverables in accordance with Section D of the statement of project objectives (SOPO)

- ***Monitor project progress and update PMP as needed in consultation with DOE/NETL Project Manager***

Task 2: *CO_2 Carbonation of engineered cementitious composites (ECC) and caustic solid waste materials*

Portland cement hydration

$3CaO \cdot SiO_2 + H_2O \rightarrow$ C-S-H + $Ca(OH)_2$

$2CaO \cdot SiO_2 + H_2O \rightarrow$ C-S-H + $Ca(OH)_2$

C-S-H → Provide binding property

$Ca(OH)_2$ → Provide alkaline environment

Introducing CO_2

$3CaO \cdot SiO_2 + CO_2 + H_2O \rightarrow$ C-S-H + $CaCO_3$

$2CaO \cdot SiO_2 + CO_2 + H_2O \rightarrow$ C-S-H + $CaCO_3$

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

C-S-H + $CO_2 \rightarrow CaCO_3 + SiO_2$

Store CO_2 gas as stable carbonate mineral precipitate

Subtasks 2.1 & 2.2: *CO_2 carbonation of ECC and caustic solid waste materials*

- ***Batch carbonation experiments***
  - Vary: P_{CO2}, relative humidity, water:cement ratio, ECC composition
  - Carbonation and high pressure CO_2 curing experiments of ECC and industrial aggregate materials, such as fly ash and steel slag

Initial ECC composition

Material	Cement	Sand	Fly Ash	HRWRA	Water	Fibers
Mix proportion (Kg/m3)	393	457	865	5	311	26

Note: HRWRA is high range water reducing agent; Fibers are from polyvinyl alcohol (PVA)

Subtasks 2.1 & 2.2: *CO_2 carbonation of ECC and caustic solid waste materials*

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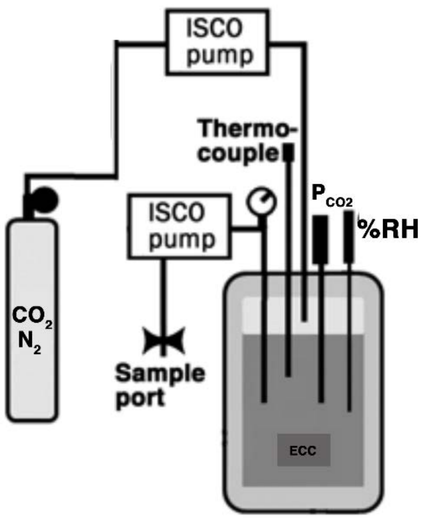
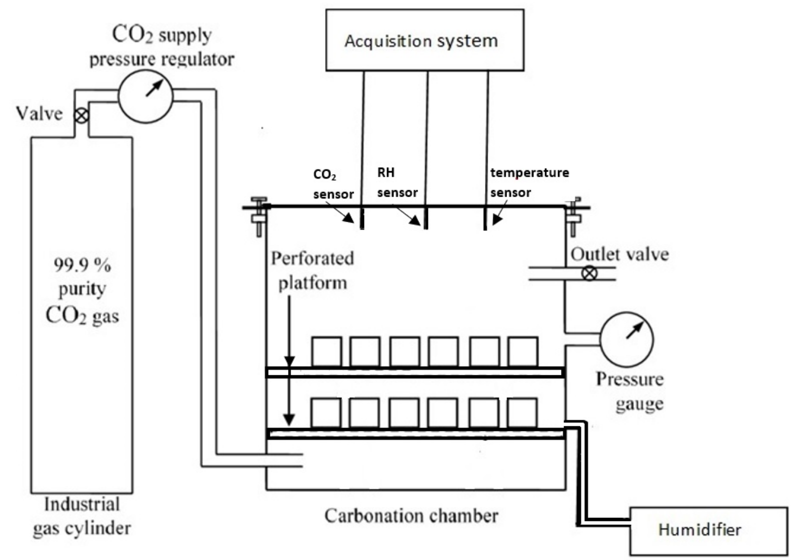
- ***Low and high pressure controlled carbonation***





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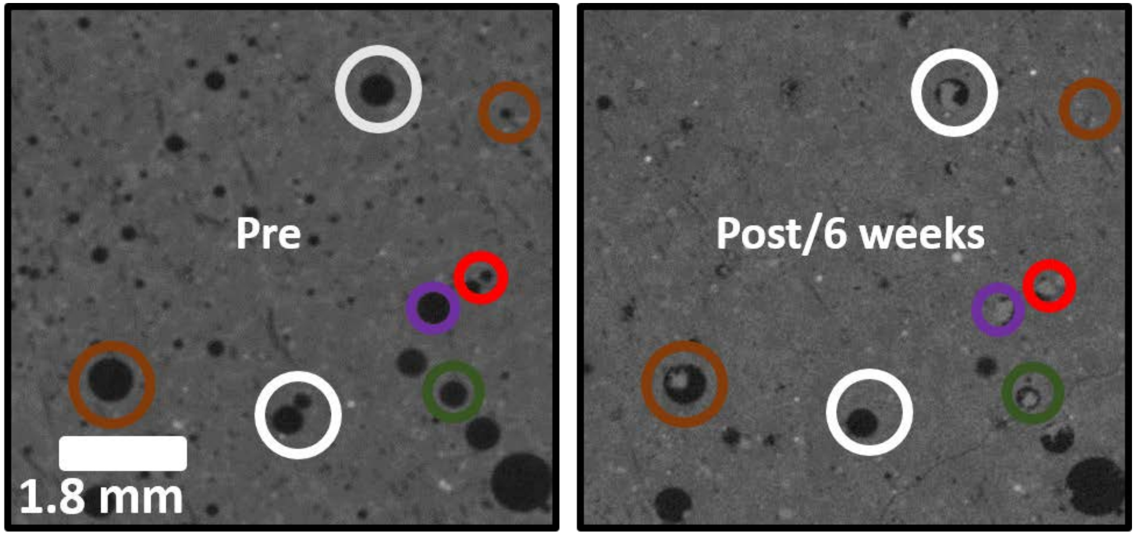


X-ray computed tomography data of ECC specimen showing calcite precipitation within macro-pores of cement matrix

Subtask 2.3: *Process optimization for maximal CO_2 storage*

Quantify the gains in CO_2 storage efficiency

- (*i*) precarbonation of cements and/or industrial waste aggregate prior to incorporation into the final precast concrete material
- (*ii*) direct injection of a CO_2-rich gas stream into wet cement and/or wet cement-aggregate mixtures prior to curing
- (*iii*) concrete curing under high P_{CO2} conditions.

Will address role of mass transport limitations in controlling carbonation efficiency (mass CO_2 stored / mass cement)

Subtask 2.4: *Geochemical modeling of CO_2 mineral sequestration in cementitious composites*

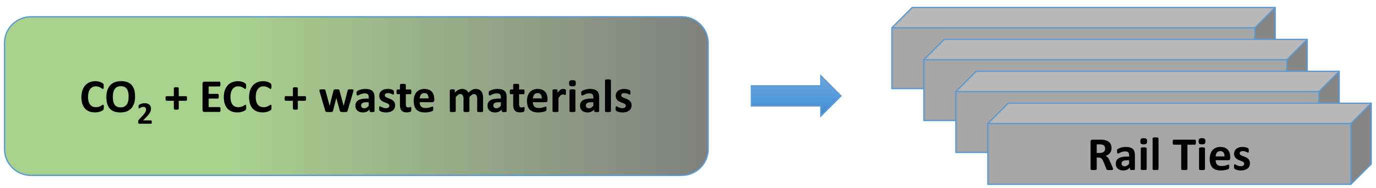
Batch geochemical modeling

- calibrated based on carbonation experiments
- will extend scope of investigation for optimizing carbonate mineral precipitation in cementitious composites

Reactive transport modeling

- evaluate how changes in cement matrix microstructure and permeability impact carbonation efficiency
- this transport model will further guide experimental efforts in *Subtasks 2.1* and *2.2* with a focus on tuning cement morphology to promote CO_2 sequestration in precast concrete products

Task 3: *Integrating carbonated materials into precast products*



The alteration of microstructure due to carbonation, the modification of hydration and pozzolanic activities, and the mechanical and durability performance of carbonated ECC needs to be experimentally assessed.

There is a need to evaluate how the mechanical properties of these new materials may evolve after contact with high P_{CO2} environments.

Subtask 3.1: *Matrix characterization*

This task will characterize the alterations to the ECC matrix associated with CO_2 carbonation and incorporation of carbonated industrial waste products.

<u>Approach:</u>

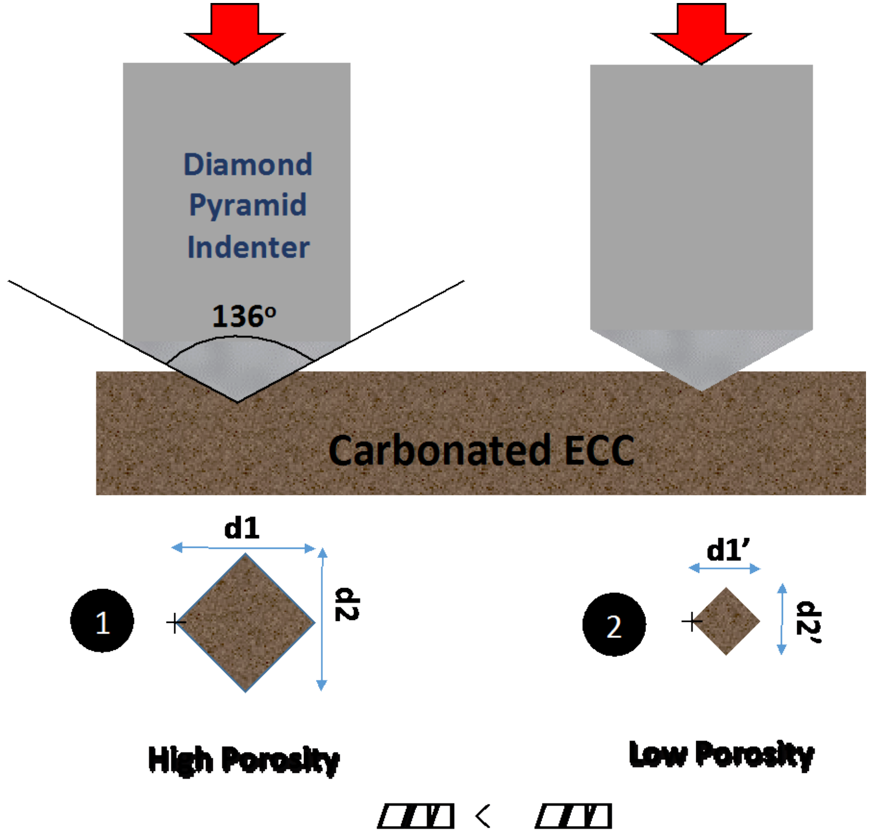
- Micro- and nanoscale indentation to characterize the hardness of various phases in ECC matrix.

HV = 1854*(F/d^2)

F = 500 g (variable)

d = average of d1 and d2 (µm)

Dwell time = 15 s (variable)

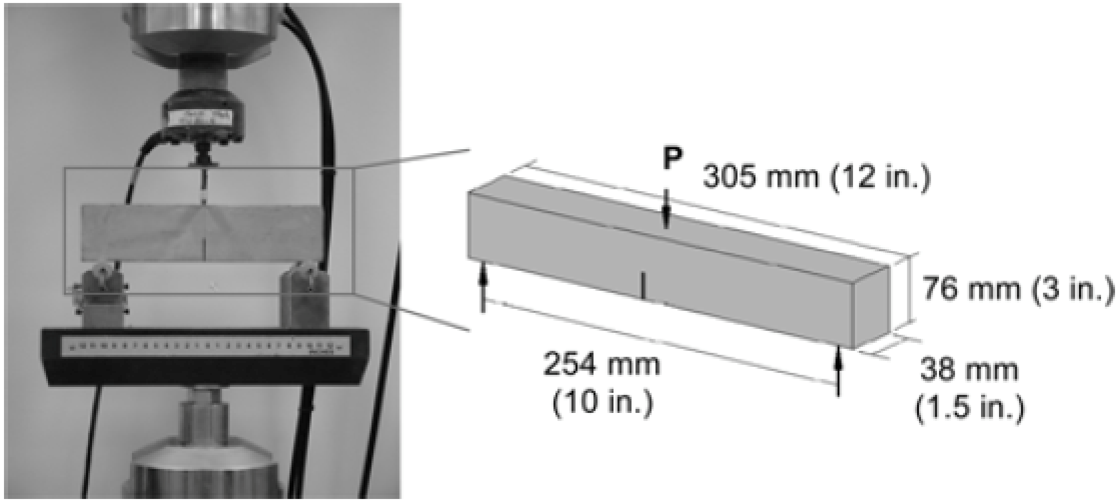


Subtask 3.1: *Matrix characterization*

This task will characterize the alterations to the ECC matrix associated with CO_2 carbonation and incorporation of carbonated industrial waste products.

Approach:

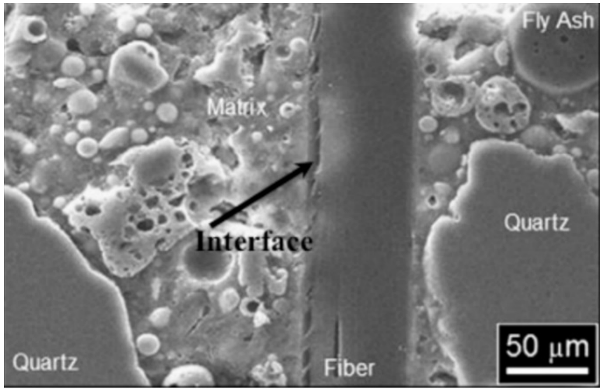
- Matrix fracture toughness will be experimentally determined using ASTM (E399)

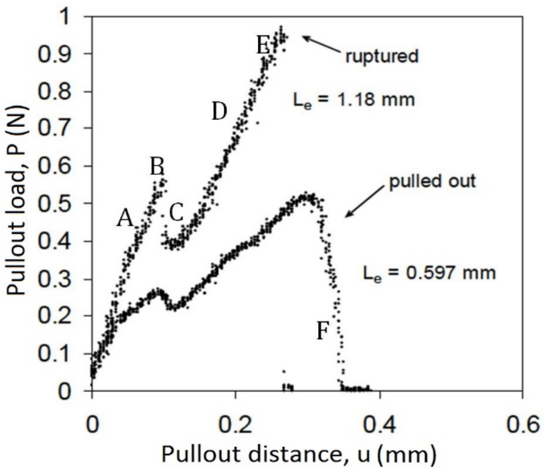


Fracture toughness testing of ECC matrix using ASTM standardized test method.

Subtask 3.2: *Fiber/matrix interface characterization*

The fiber/matrix interfacial chemical and frictional bonds will be determined using a single fiber pull-out test and extensive characterization via SEM and XCT

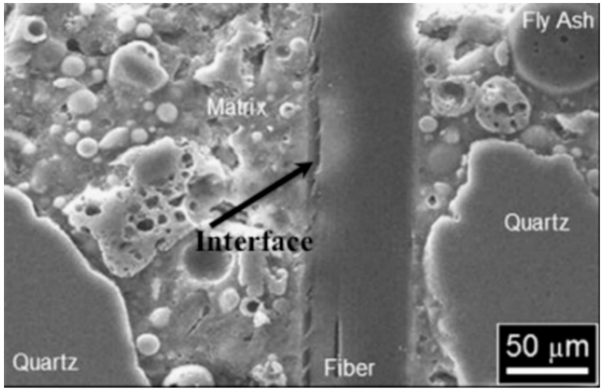


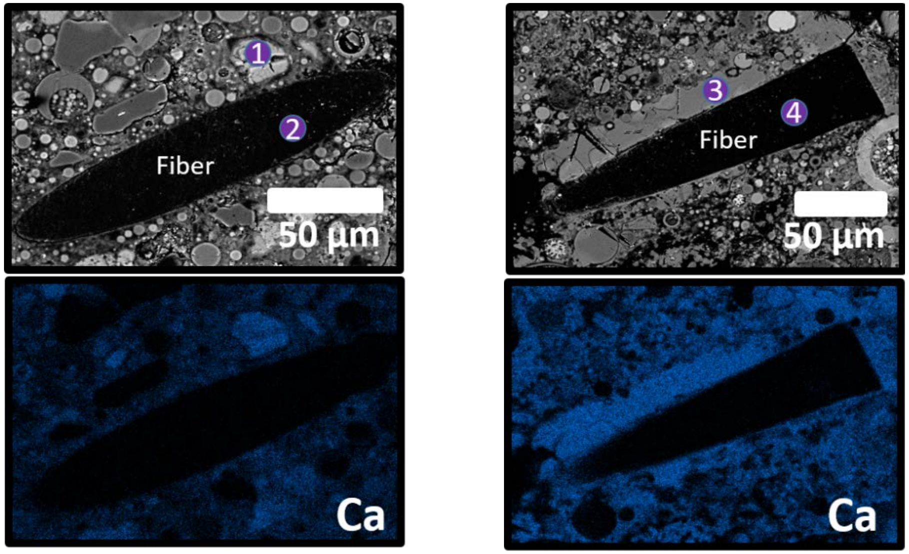


Single fiber pull-out test from which interfacial bond properties can be derived

Subtask 3.2: *Fiber/matrix interface characterization*

The fiber/matrix interfacial chemical and frictional bonds will be determined using a single fiber pull-out test and extensive characterization via SEM and XCT



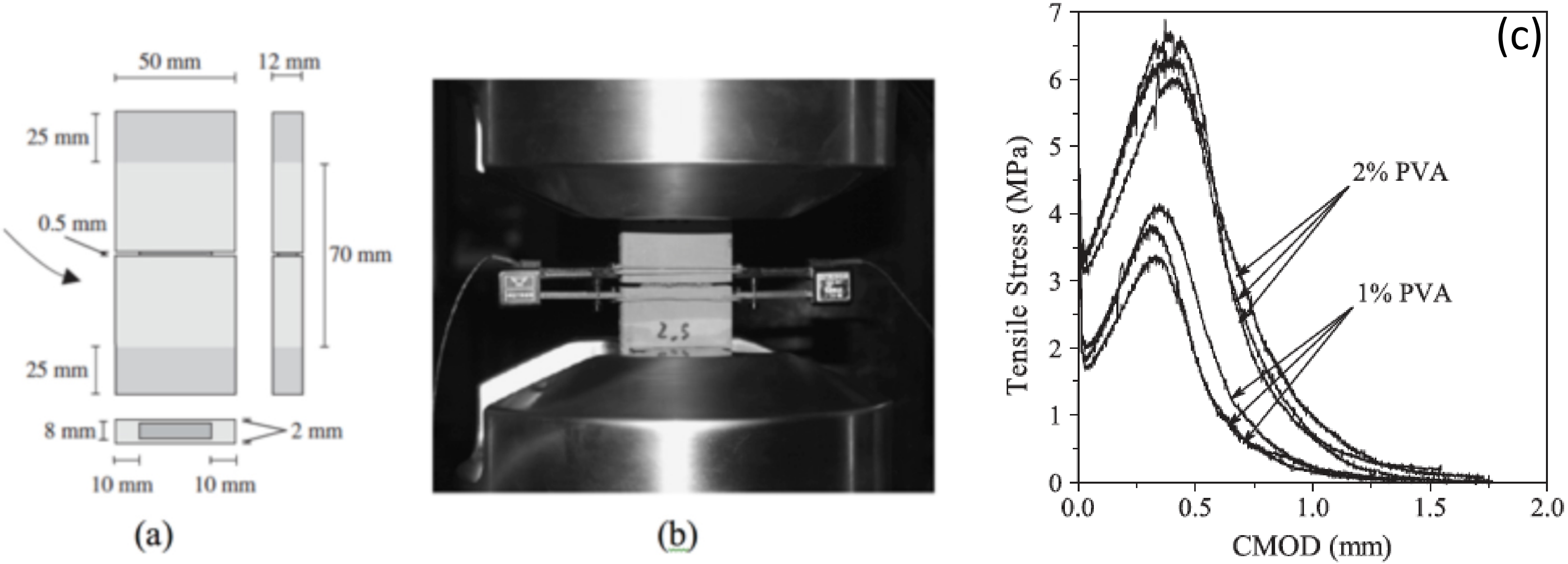


Before **After**

SEM EDS data showing calcite precipitation along fiber/matrix interface after contact with high P_{CO2} water

Subtask 3.3: *Meso-scale σ-δ relationship characterization*

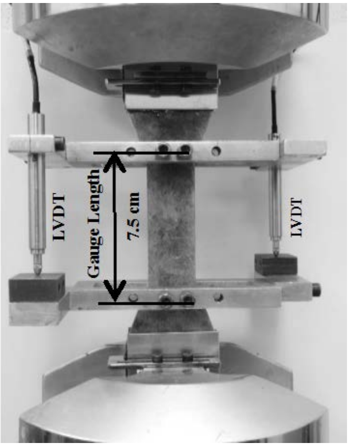
This subtask seeks to quantify the ability of the carbonated ECC to resist opening of a single crack

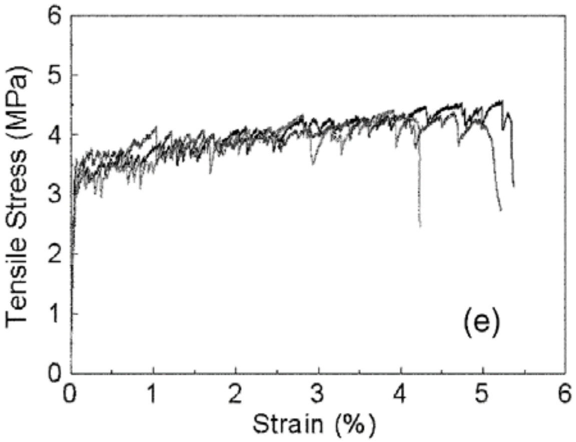


(a) Deep notched coupon specimen designed for (b) measuring the σ-δ relationship; (c) typical stress-CMOD curve.
(figures from Pereira *et al.* (2005), *Cement Concrete Res.*)

Subtask 3.4: *Micromechanical analysis of composite response and re-design route*

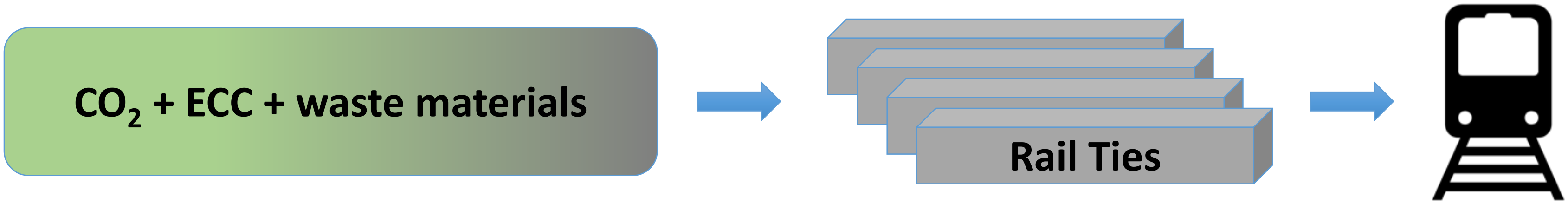
A micromechanical model will be adopted in this subtask for the purpose of (1) developing insights on the effects of fiber, matrix and fiber/matrix interfacial property changes resulting from carbonation process on composite tensile ductility, and (2) identification of re-design routes at the microstructural level in the event of loss of ductility.





Ideal tensile stress-strain curve of ECC obtained using the JSCE recommended test procedure.

Task 4: *Composite-product (rail tie) integration and testing*



This task will appraise the long term durability of the new materials developed through efforts of Tasks 2 and 3. A suite of durability tests will be undertaken as part of this task, including carrying out the standard industry track testing of full-scale ECC rail ties.

<u>Key:</u> ensure that carbonated ECC ties will meet AREMA standards

Subtask 4.1: *Long term durability determination*

- **Investigation of the ability for self-healing through use of resonant frequency measurements before and after exposure of pre-damaged ECC coupon specimens to: (*i*) water, (*ii*) sulphate environments**

- **Direct tensile re-loading tests will also be conducted to assess the restoration of material stiffness, strength and tensile ductility after self-healing**

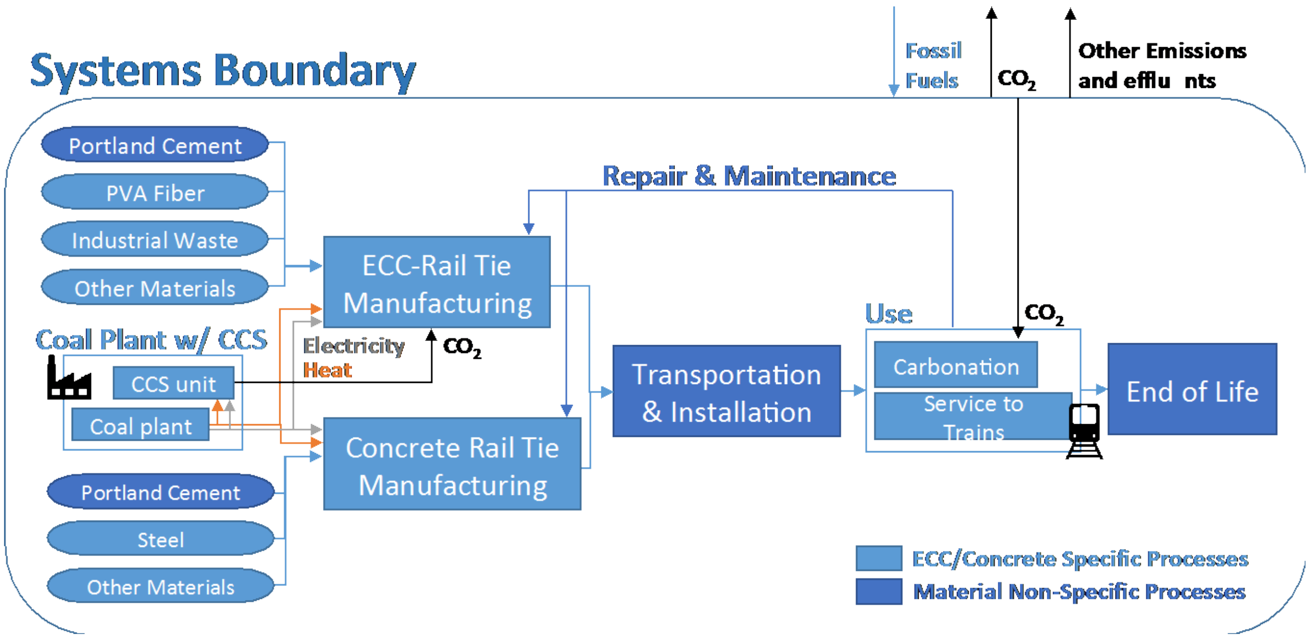
Subtask 4.2 & 4.3: *Process integration and costing at scale*

Full scale carbonated ECC rail ties will be field tested to evaluate their performance under typical train loads. Prototyped ECC ties will be tested at the Federal Railroad Administration's Transportation Technology Center in Pueblo, Colorado.

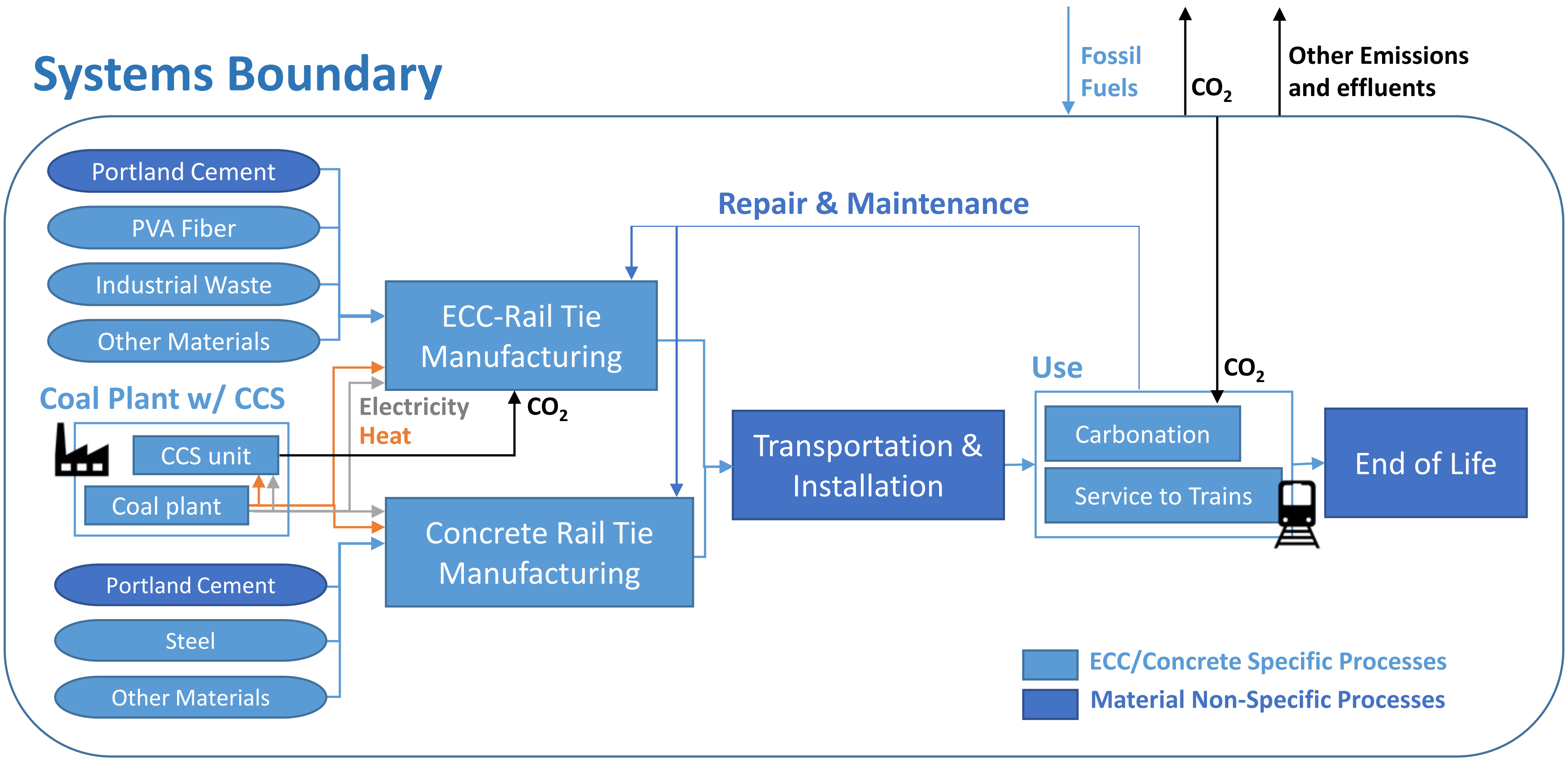
Image from: www.fra.dot.gov

Task 5: *Evaluation of life cycle CO_2 emissions reduction (subtasks 5.1 & 5.2)*

- **Goal of LCA**: Evaluate net energy and emissions reduction potential as well as carbon storage capacity of carbonated Engineered Cementitious Composite (ECC) rail tie compared to concrete rail tie
- **Functional Unit**: Service provided by rail ties across 1 km section of rail over a period of 50 years



Task 5: *Evaluation of life cycle CO_2 emissions reduction (subtasks 5.1 & 5.2)*



Task 5: *Evaluation of life cycle CO_2 emissions reduction (subtasks 5.1 & 5.2)*

- **Existing data and knowledge**
  - Past LCA studies on ECC (Keoleian et al. 2005, Keoleian et al. 2005), conventional concrete rail tie (Crawford 2009), pulverized coal plant equipped with aqueous MEA-based carbon capture and sequestration (Koornneef et al. 2008, Petrescu et al. 2017, Tang et al. 2014)
  - Expertise on deterioration and mechanical properties of ECC (Li 2008, AREMA, Yang et al 2007, Lepech et al. 2009, Kan et al. 2010) and concrete rail tie (Lutch et al. 2009)
  - Knowledge on options for replacement power and energy penalty associated with CCS (Carapellucci et al. 2015, Supekar and Skerlos 2017)
- **Uncertainties and scenarios**
  - Electricity and heat integration options for ECC manufacturing as well as technology options to provide replacement power from additional demand (Supekar and Skerlos 2017, Zhai et al. 2015)
  - Tradeoff between increased input CO_2 purity for ECC and additional power and fuel for purification process
  - The level of industrial waste stream integration and associated CO_2 reduction potential (Zhou et al. 2015, Shin et al. 2015, Huang et al. 2013)
- **Short-term tasks**
  - Build bill of materials for ECC and concrete rail tie using NETL LCA Guidelines
  - Explore heat and electricity integration option for manufacturing with a coal plant
  - Analyze impact of rail tie deterioration on train operation

Subtask 5.3: *Evaluating carbonated ECC against sustainability necessary conditions*

Necessary Conditions:

Sustainable Technology Systems

THE ANSWERS TO ALL THESE QUESTIONS MUST BE **FAVORABLE**

1. does the system make significant progress toward an unmet and important environmental or social challenge? YES
2. is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits? NO
3. is the system likely to be adopted and self-sustaining in the market? YES
4. is the system so likely to succeed economically that planetary or social systems will be worse off (rebound effect)? NO

Subtask 5.4: *Techno-economic feasibility and technology gap analysis*

- Evaluate the economic competitiveness of and barriers to entry for carbonated ECC precast concrete rail ties in the rail tie market (building on subtask 4.3)

- Evaluate the current state of development of all critical process components for storing flue gas CO_2 in precast ECC concrete materials

  → provide a clear path to commercialization of the new process/ technology.

Subtask 5.4: *Techno-economic feasibility and technology gap analysis*

Technology gap analysis:

- Identification of all remaining research needs related to upscaling and integration of the CO_2 conversion process at coal-fired power plant facility

Project Timeline

	Start Date	End Date	Cost	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
				Budgte Period 1 10/01/17-03/31/19						Budget Period 2 04/01/19-09/30/20					
Task 1 - Project Management and Planning	10/1/17	9/30/20	$56,593												
Subtask 1.1: Revised PMP	10/1/17	9/30/20													
Subtask 1.2: Quarterly and Monthly Reporting	10/1/17	9/30/20													
Subtask 1.3: Meetings	10/1/17	9/30/20													
Subtask 1.4: Reporting and Deliverables	10/1/17	9/30/20													
Milestones															
(a) Project Management Plan				x											
(b) Kickoff Meeting				x											
Task 2 - CO2 Carbonation of Engineered Cementitious Composites (ECC) and Caustic Solid Waste Materials	10/1/17	12/31/18	$372,627												
Subtask 2.1: CO2 carbonation of ECC	10/1/17	3/31/18													
Subtask 2.2: CO2 Carbonation of Caustic Solid Waste Materials	4/1/18	9/30/18													
Subtask 2.3: Process optimization for Maximal CO2 Storage	4/1/18	9/30/18													
Subtask 2.4: Geochemical Modeling of CO2 Mineral Sequestration in Cementitious Composites	7/1/18	12/31/18													
Milestones															
(c) Carbonation process and mix design of ECC reaching a minimum of 10% CO2 stored							x								
Task 3 - Optimization and Material Characterization of Carbonated ECC Products	1/1/18	3/31/19	$188,094												
Subtask 3.1: Matrix Characterization	1/1/18	6/30/18													
Subtask 3.2: Fiber/Matrix Interface Characterization	4/1/18	9/30/18													
Subtask 3.3: Meso-scale $\sigma-\delta$ relationship characterization	7/1/18	12/31/18													
Subtask 3.4: Micromechanical analysis of composite response and re-design route	10/1/18	3/31/19													

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Budget

	Budget Period 1		Budget Period 2		Total Project	
	10/01/17-03/31/19		04/01/19-09/30/20			
	Government Share	Cost Share	Government Share	Cost Share	Government Share	Cost Share
Applicant	$407,082	$172,294	$592,917	$77,706	$999,999	$250,000
Total	$407,082	$172,294	$592,917	$77,706	$999,999	$250,000
Cost Share	70.27%	29.73%	88.41%	11.59%	80%	20%

	Budget Period 1											
	10/1/17-12/31/17		1/1/18-3/31/18		4/1/18-6/30/18		7/1/18-9/30/18		10/1/18-12/31/18		1/1/19-3/31/19	
	Q1	Total Project	Q2	Total Project	Q3	Total Project	Q4	Total Project	Q5	Total Project	Q6	Total Project
Federal Share	$36,286	$36,286	$52,918	$89,204	$102,500	$191,704	$135,449	$327,153	$69,551	$396,704	$19,968	$416,672
Non-Federal Share	$15,009	$15,009	$21,889	$36,898	$42,397	$79,295	$56,026	$135,321	$28,768	$164,089	$8,260	$172,349
Total Planned	$51,295	$51,295	$74,807	$126,102	$144,897	$270,999	$191,475	$462,474	$98,319	$560,793	$28,228	$589,021

	Budget Period 2											
	4/1/19-6/30/19		7/1/19-9/30/19		10/1/19-12/31/19		1/1/20-3/31/20		4/1/20-6/30/20		7/1/20-9/30/20	
	Q7	Total Project	Q8	Total Project	Q9	Total Project	Q10	Total Project	Q11	Total Project	Q12	Total Project
Federal Share	$97,221	$513,893	$97,221	$611,114	$97,221	$708,335	$142,107	$850,442	$97,221	$947,663	$52,336	$999,999
Non-Federal Share	$12,942	$185,291	$12,942	$198,233	$12,942	$211,175	$18,917	$230,092	$12,942	$243,034	$6,966	$250,000
Total Planned	$110,163	$699,184	$110,163	$809,347	$110,163	$919,510	$161,024	$1,080,534	$110,163	$1,190,697	$59,302	$1,249,999

Acknowledgments

Collaborators

Jubilee Adeoye

Dr. Alex Neves Junior

Tae Lim

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