Storing CO_2 in Built Infrastructure: CO_2 Carbonation of Precast Concrete Products

Project Award No. DE-FE0030684 (10/2017 – 12/2020)

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National Energy Technology Laboratory

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Project Overview

- **Funding**

DOE:	$999,999
Cost share:	$250,000

- **Overall Project Performance Dates**

10/2017	Kickoff meeting
10/2017 – 03/2019	Budget period 1
No-cost extension	
07/2019 – 12/2020*	Budget period 2 (*pending NCTX)

Project Overview

- **Project Participants**

  Principal Investigator (PI): Brian R. Ellis

  Co-PIs: Victor C. Li; Steven J. Skerlos

  Post-doc Researcher: Duo Zhang

  Visiting Scholar: Beata Jaworska, Alex Neves Junior

  Graduate Students: Tae Lim; Jubilee Adeoye; Wei-Hsiu Hu

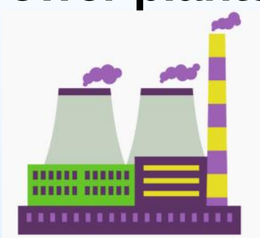
- **Overall Project Objectives**

  Utilize CO_2 and coal combustion fly ash in developing novel construction materials;

  Provide a net reduction in life-cycle emissions and cost.

Technology Introduction

Coal-fire power plants



Flue gas CO_2 **Fly ash**

+

Precast Concrete

Carbonation Curing

Process optimization

Novel Infrastructure Materials

Engineered Cementitious Composites (ECC)

Target products: **Railway ties**

- Faster production;
- Enhanced durability;
- Lower life-cycle cost

Technology Introduction

Technical/ Environmental Impacts	Current Railway Tie Products	Proposed Technology
Material Type	Pre-stressed Concrete – Brittle and subjected to cracking	Ultra-ductile ECC with intrinsically tight cracks
Tensile Ductility	<0.01%	>2%
Environmental Impacts for Production	High emission and cost for high-strength concrete and pre-stressing wires	Lowered emission and cost by CO_2 sequestration and reduced need for pre-stressing
Lifecycle Impacts	High lifecycle emissions, energy, and costs due to low durability	Lowered lifecycle emissions, energy and cost by longer durability and lower need for maintenance and repair

Technology Introduction

- **Project Challenges**
  - Enhancing CO_2 uptake efficiency to satisfy the demand for industrial production;
  - Maintaining high material ductility and durability;
  - Minimizing manufacturing cost for CO_2 product line;
  - Ensuring superior durability for railway tie applications

- **Technical/Economic Benefits**
  - Significant reductions in lifecycle emissions, energy and cost;
  - Demonstrate novel strategy for utilizing CO_2 in value-added construction products

Technical Approach/Project Scope

Objectives

- Demonstrate CO_2 utilization into novel durable ECC railway ties with lower lifecycle cost and environmental impacts

Success Criteria

- Carbonation process and mix design of ECC reaching a minimum of 10% CO_2 stored; ***Achieved***
- Carbonated ECC rail tie with life cycle carbon and energy footprints 20% lower than current concrete ties, meeting AREMA standards and passing TTCI Phase 1 (13-tie) test ***Ongoing***

Technical Approach/Project Scope

Task 1: Project Management and Planning

Task 2
Development of carbonation process

- Carbonation setup and process development

Task 3
Integration of ECC products

- Development of ductility and mechanical integrity

Completed

Task 4
Full-scale railway tie product integration

- Durability evaluation and full-scale railway tie development

Task 5
Life-cycle CO_2 emissions analysis

- Life-cycle inventory for carbonated ECC railway tie

Ongoing

Progress and Current Status

Bench-Top Reactor
(Budget Period 1)

Full-Size Reactor
1 m by 3 m

- **Temperature** – *up to 100°C*
- **Pressure** – *up to 5 bar*

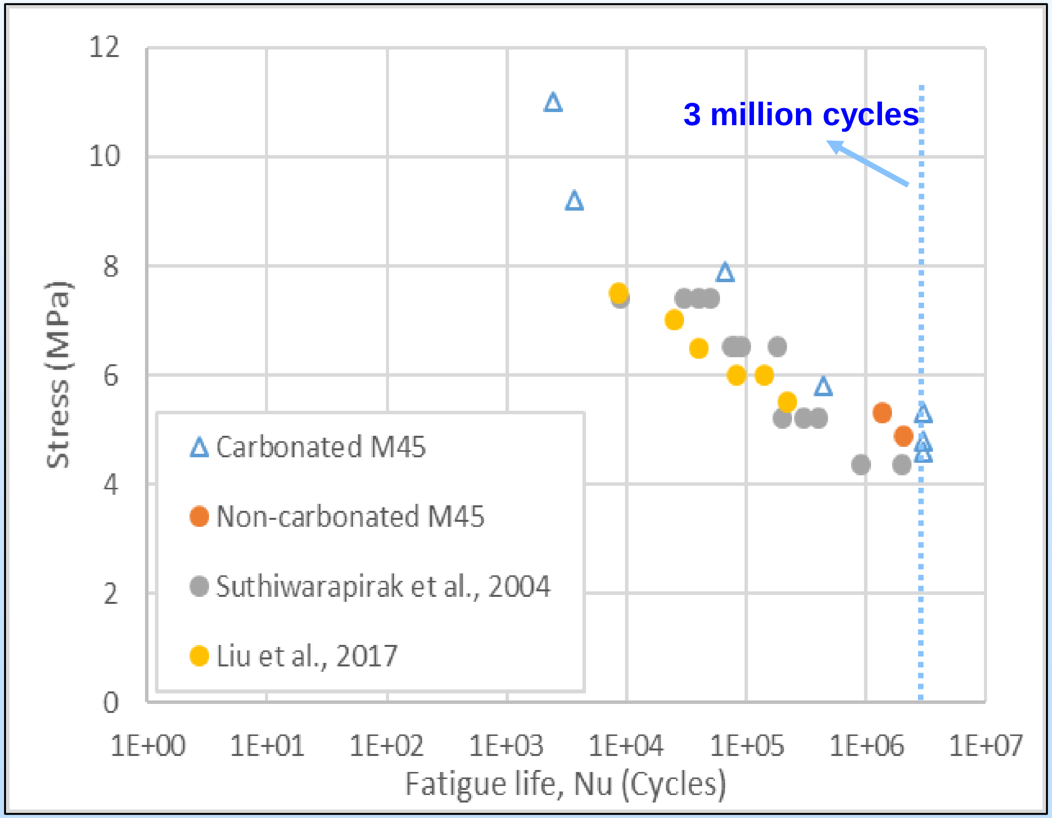
Progress and Current Status

ECC shows higher **flexural strength** after carbonation curing

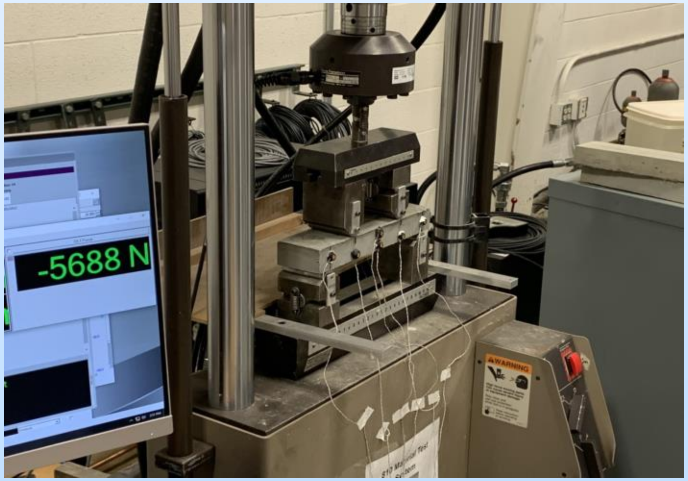
Material	No.	Ultimate Flexural Strength (MPa)	Average Flexural Strength (MPa)
Carbonated ECC	1	11.71	**12.03**
	2	10.85	
	3	13.52	
Non - Carbonated ECC	1	11.80	10.50
	2	9.38	
	3	10.33	

Progress and Current Status

ECC **fatigue resistance** is enhanced by carbonation curing

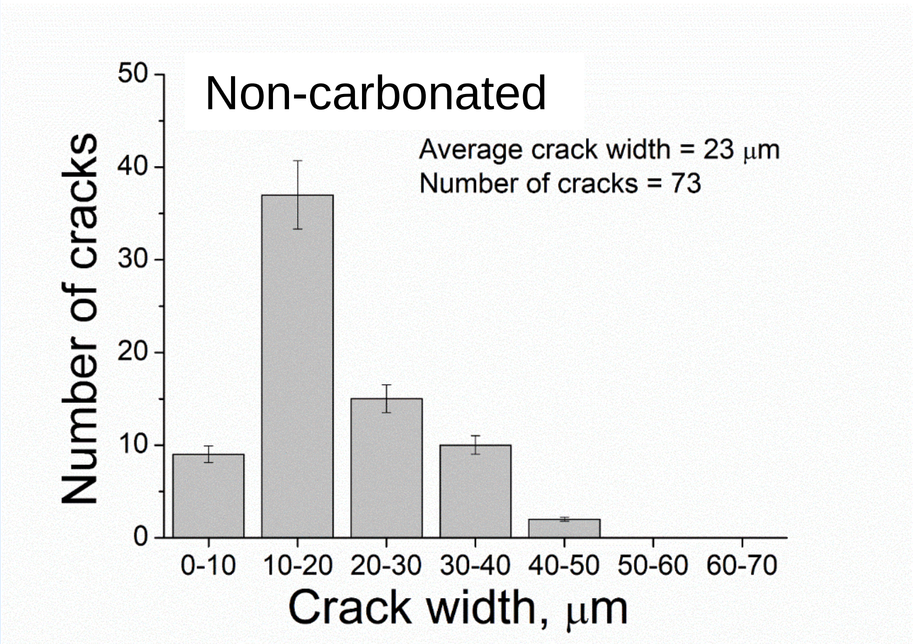


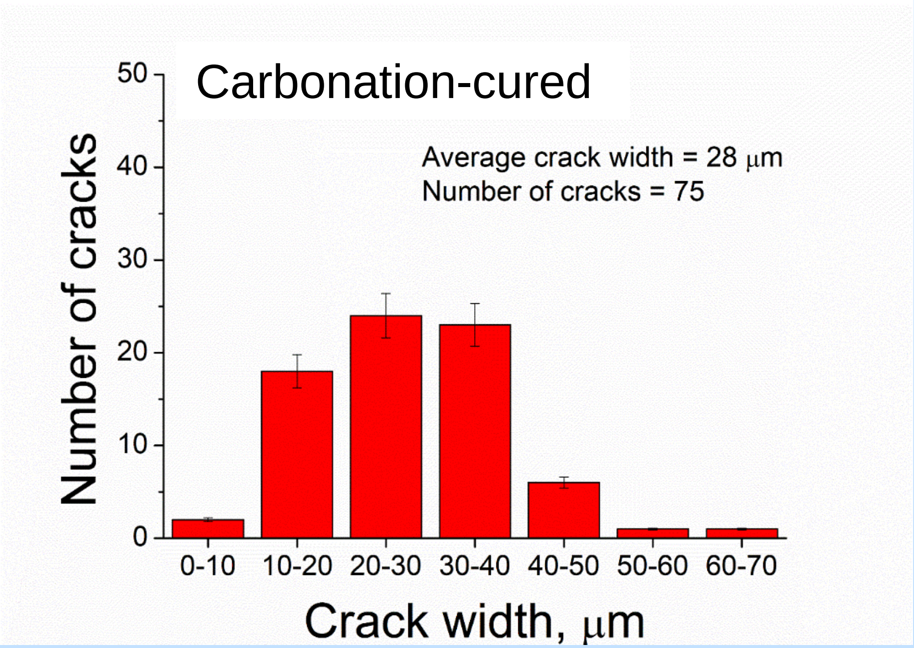
Fatigue Testing Configuration



Progress and Current Status

Crack width distribution is comparable between carbonation-cured and non-carbonated ECC

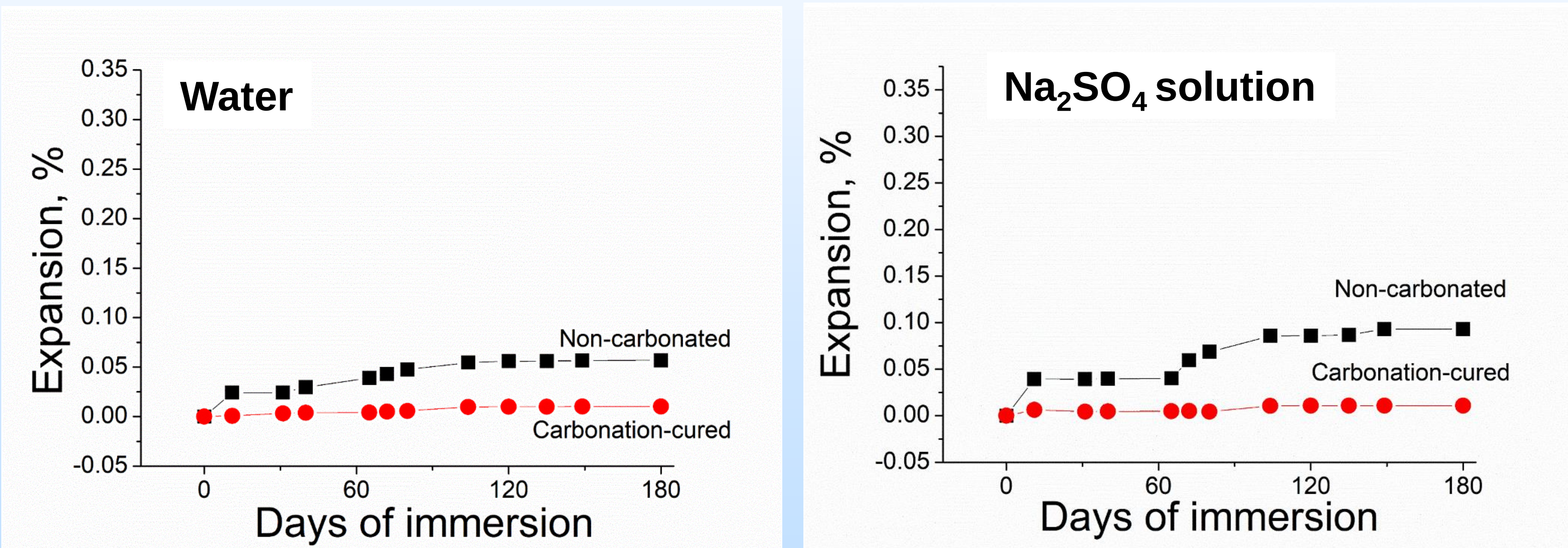




Cracks were measured when loaded to 3% strain

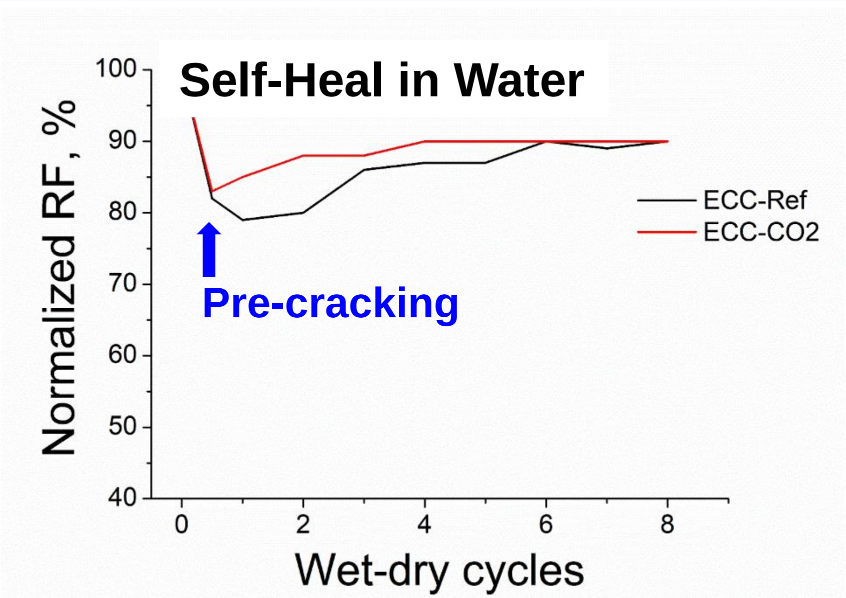
Progress and Current Status

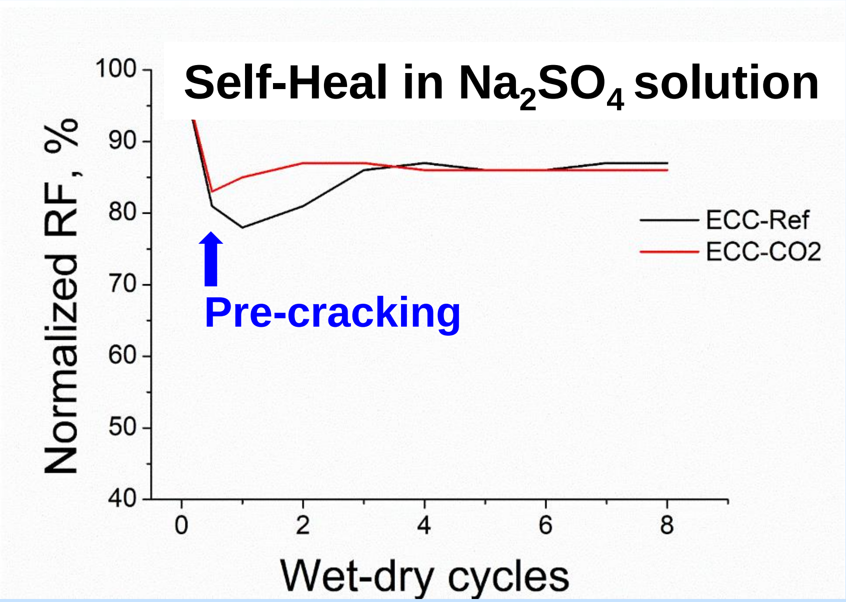
Carbonation curing improves ECC length stability



Progress and Current Status

Carbonation curing maintains ECC self-healing efficiency

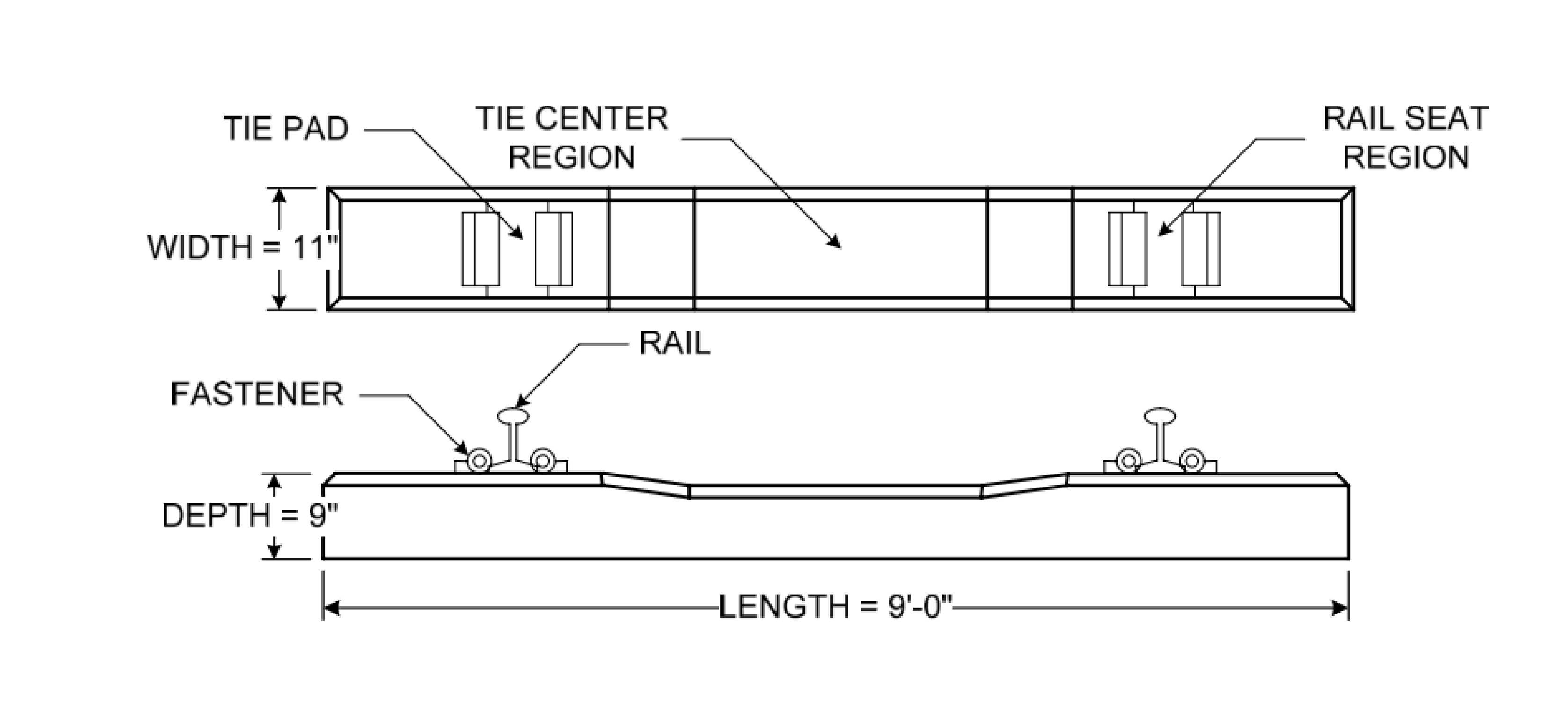




Resonance Frequency (RF) indicates comparable self-healing capability between carbonation-cured and non-carbonated ECC

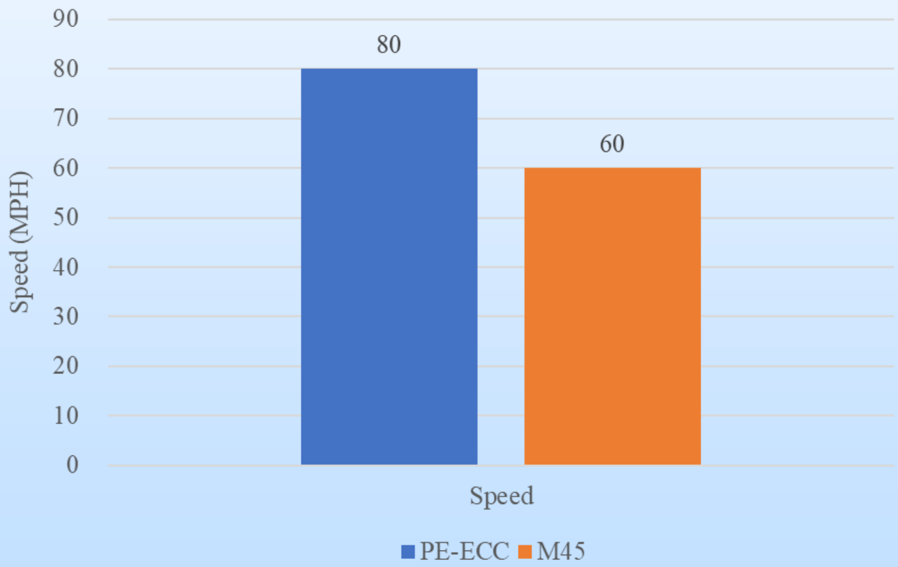
Progress and Current Status

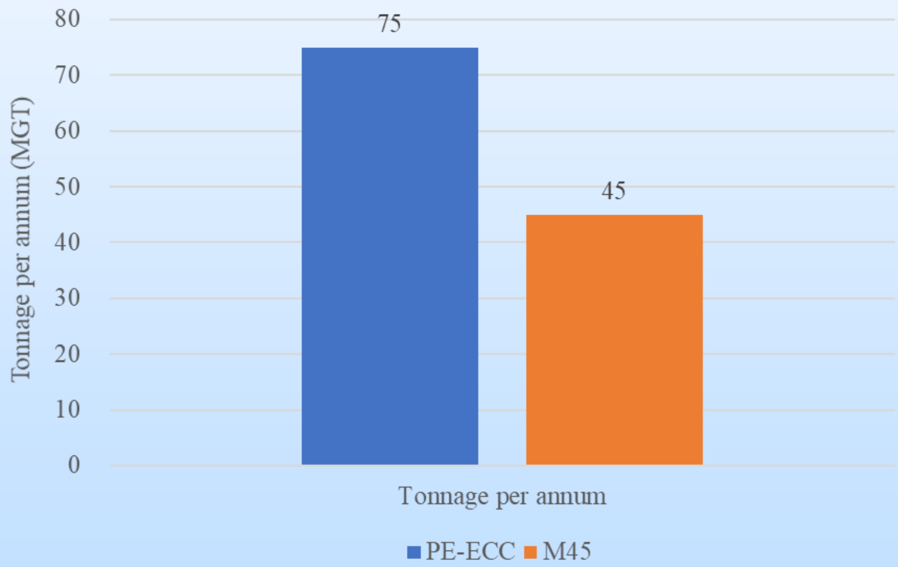
We are designing **full-size ECC railway tie** while setting up reactor



Progress and Current Status

Current ECC (M45) meets Class 3 track requirement and can be improved up to Class 5 by introducing PE-ECC

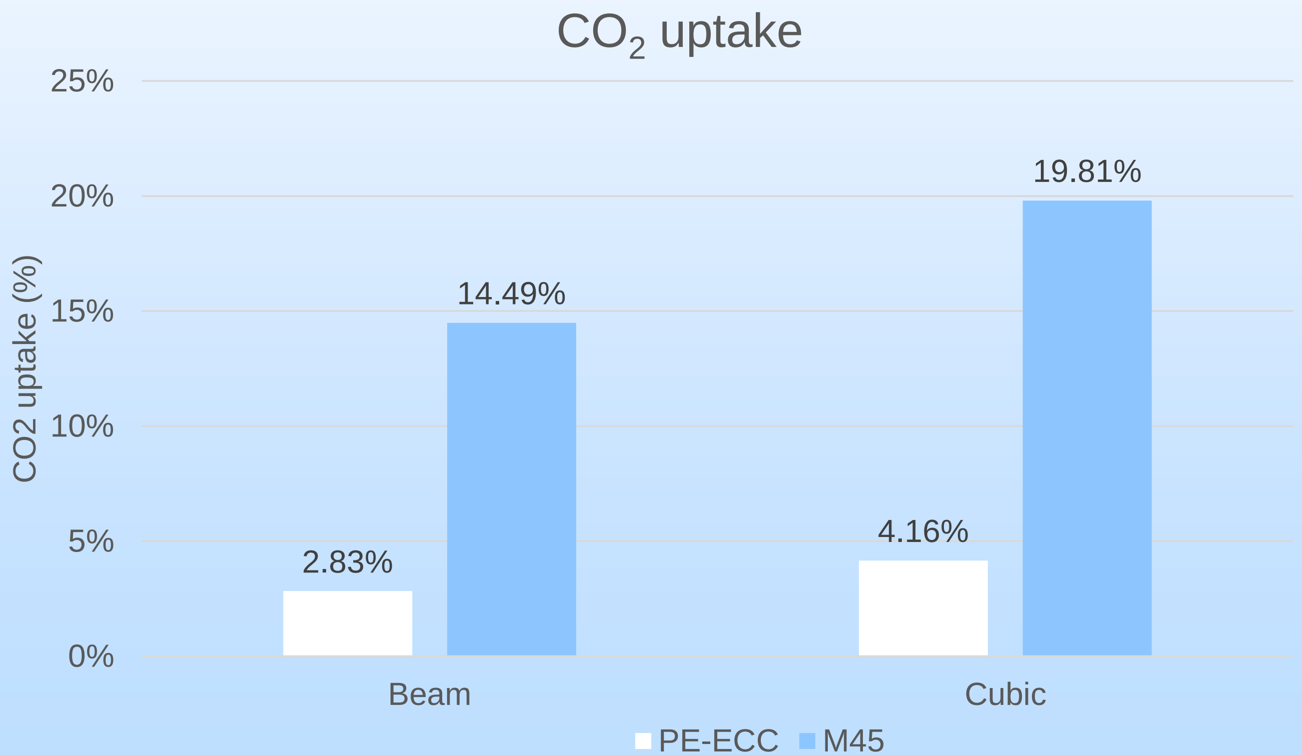




Allowable speed and tonnage will be substantially increased using PE-ECC railway tie

Progress and Current Status

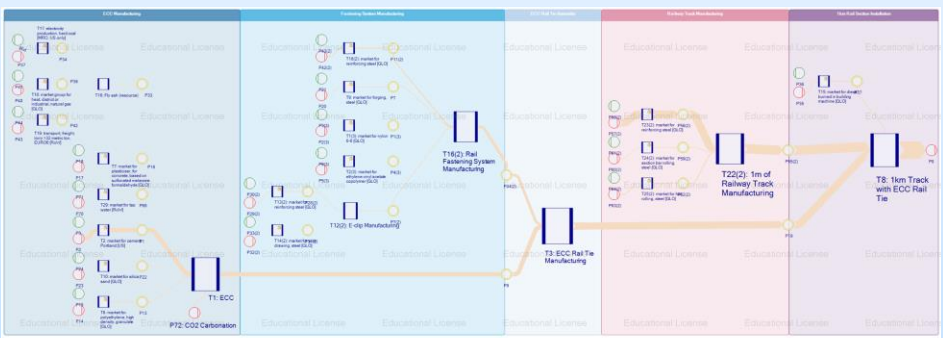
CO_2 uptake is lower for PE-ECC due to dense microstructure and can be restored using *pre-carbonated ingredients*



Progress and Current Status

We developed **consequential LCA** that integrates process-based LCA and Monte Carlo simulation

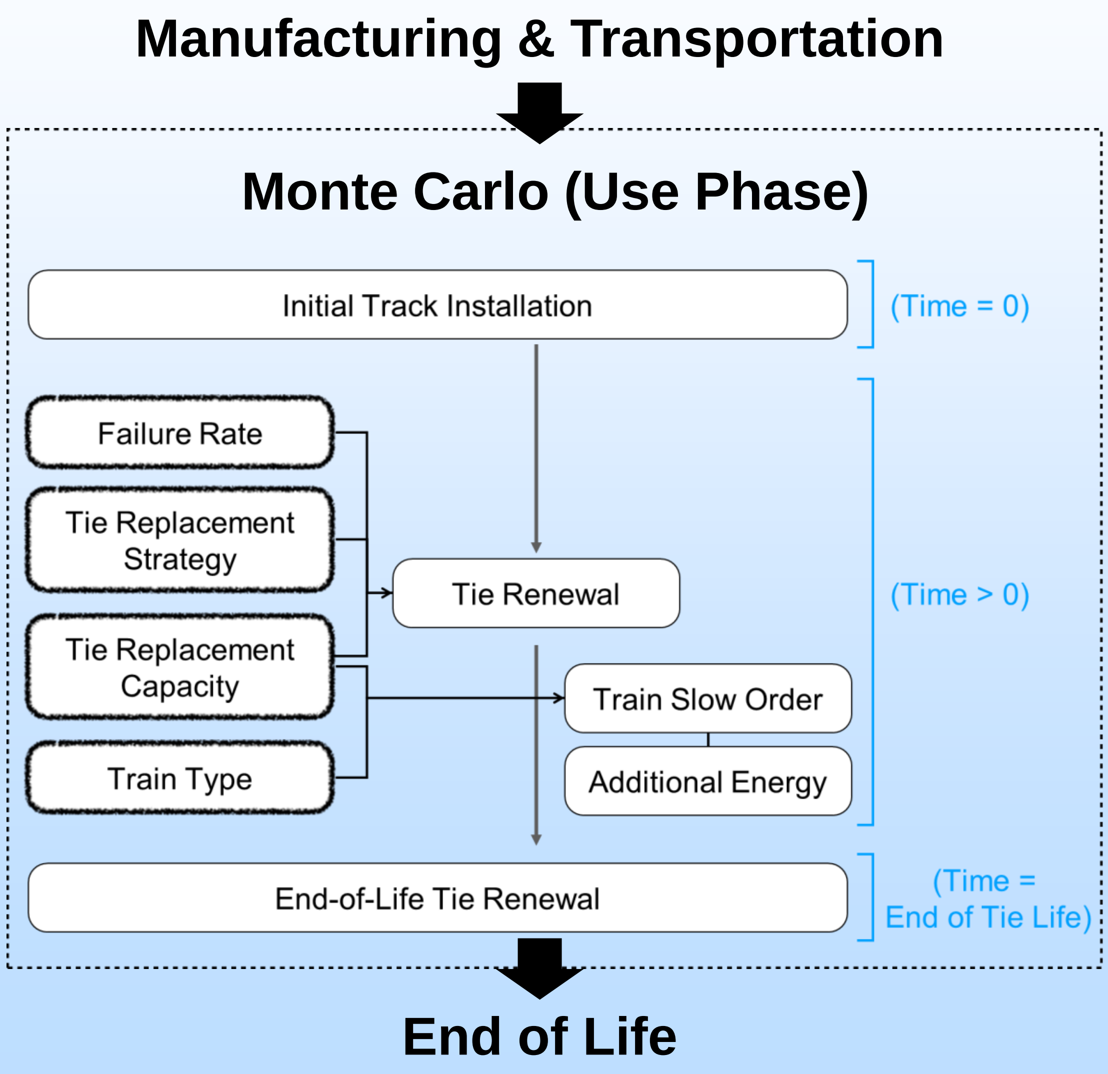
Process-Based LCA + **Monte Carlo Simulation**



- Tie failure rate
- Tie replacement strategy (spot vs. TLS)
- Tie replacement capacity (#ties/year for spot, TLS)
- Train type (coal, intermodal, intercity, HSR)
- Impact from adjacent ties

- Functional Unit: 1km of track service to trains
  - 1 km of rail
  - 2640 ties

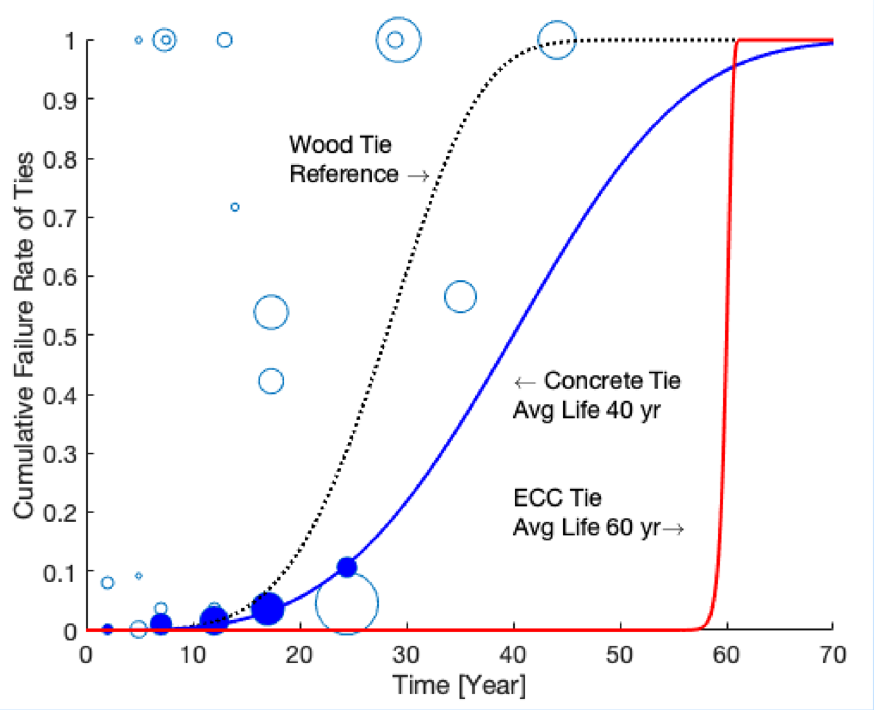
Progress and Current Status



Progress and Current Status

Concrete tie failure can be estimated by Weibull distribution

- Weibull failure distribution applied to concrete tie
    - Weibull parameters can be adjusted to fit 1) observed failure trend, 2) expected tie lifespan
- Each of the installed ties follow Weibull distribution, making it possible to conduct Monte Carlo simulation
- Past LCA studies assumed zero premature failure for concrete ties which is not consistent with reported data

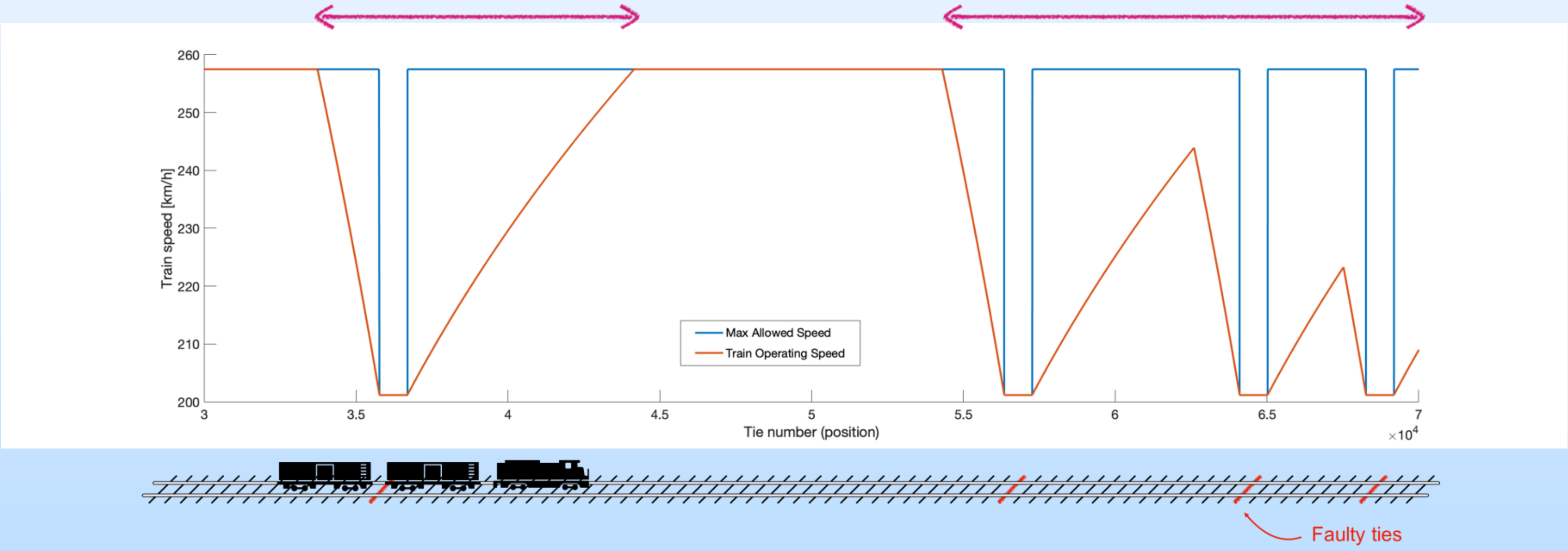


Progress and Current Status

Example of slow order implementation

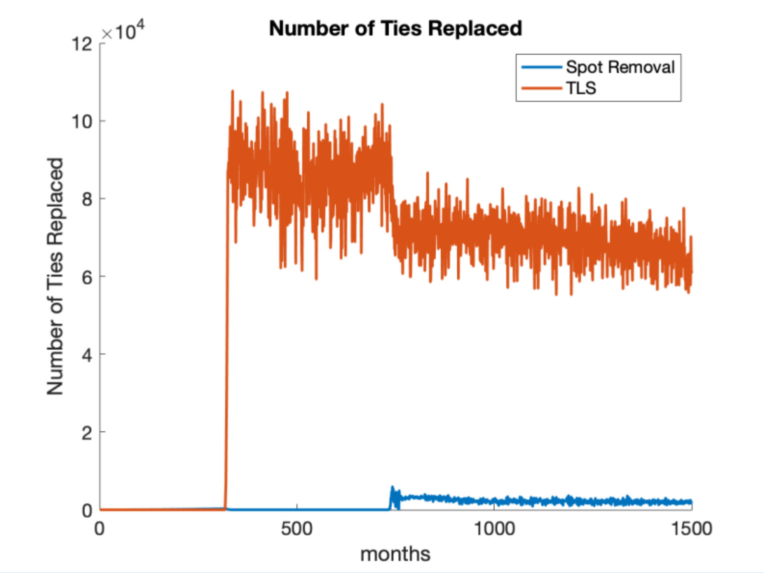
Total length of delay zone includes track length required for trains to change speed

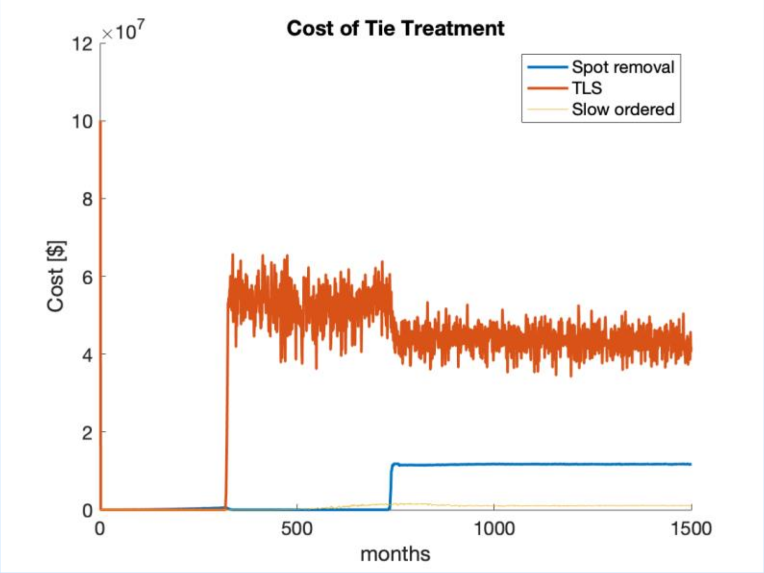
If multiple slow ordered zones exist, effective length of delay zone can extend



Progress and Current Status

Example Monte Carlo results





- 100 km track section
- Train type: intermodal freight
- Tie degradation rate: gradual, with average lifespan of 40 years

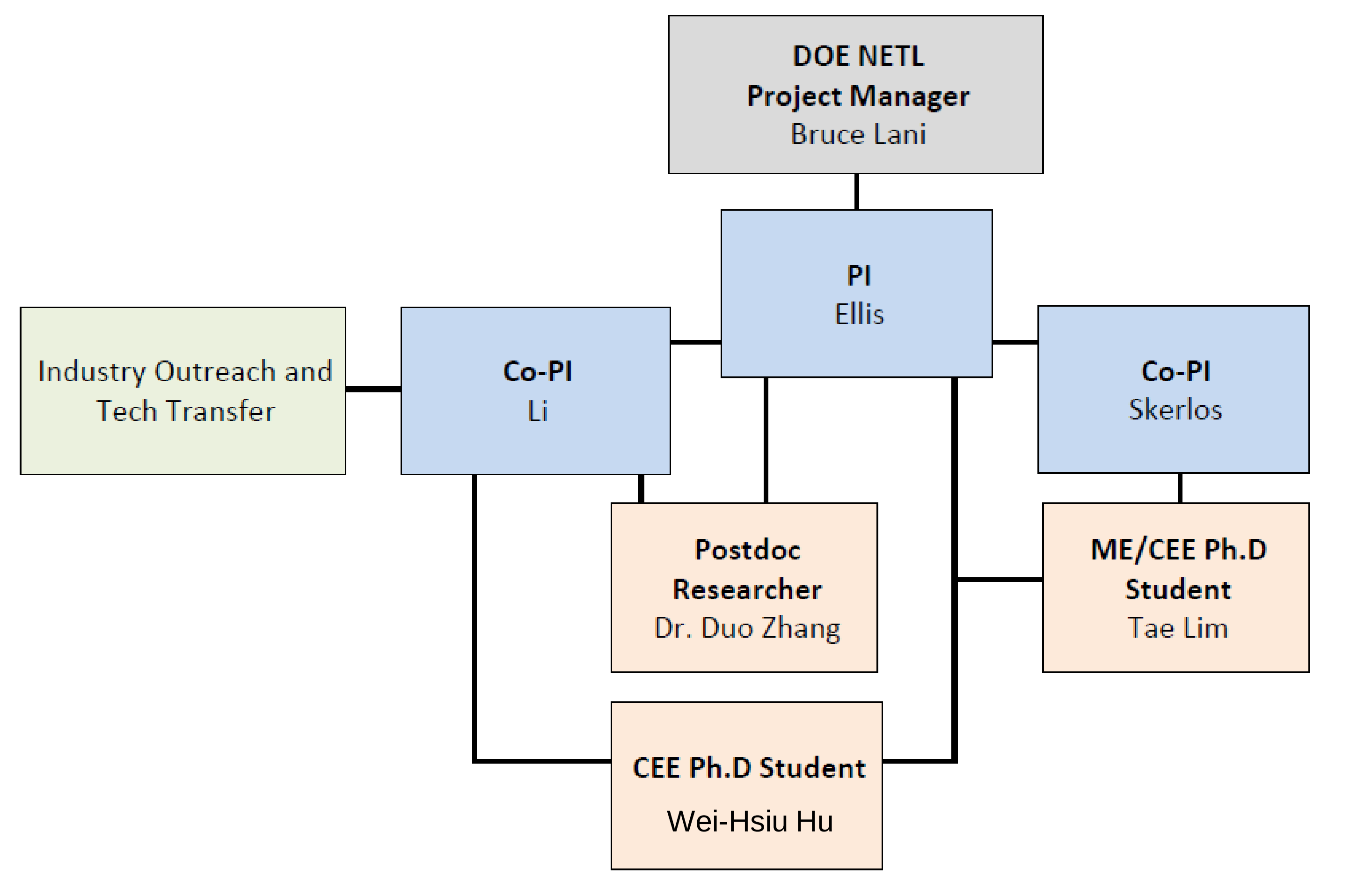
Summary Slide

- Carbonation curing leads to equivalent to superior ECC ***durability*** compared to the non-carbonated reference;
- Ongoing fatigue tests will provide further insights into ***lifetime prediction***;
- The novel ***consequential LCA model*** can reflect use-phase costs and impacts caused by railway tie failure, and will be implemented to full-size tie evaluation

Appendix

- **Organization Chart**
- **Gantt Chart**

Organization Chart



Gantt Chart

	Budgte Period 1						Budget Period 2					
	10/01/17-06/30/19						07/01/19-12/31/20					
Task 1 - Project Management and Planning												
<u>Milestones</u>												
(a) Project Management Plan	X											
(b) Kickoff Meeting	X											
Task 2 - CO2 Carbonation of Engineered Cementitious Composites (ECC) and Caustic Solid Waste Materials												
<u>Milestones</u>												
(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												
<u>Milestones</u>												
(d) Carbonated ECC with tensile ductility reaching a minimum of 2% strain					X							
Task 4 - Composite-Product (Rail Tie) Integration and Testing												
Subtask 4.1: Long term durability determination												
Subtask 4.2:Process Integration at Scale												
Subtask 4.3: Market Analysis for Carbonated ECC Rail Ties												
<u>Milestones</u>												
(e) Carbonated ECC meeting durability criteria of 50 years under accelerated testing conditions								X				
(f) Carbonated ECC rail tie meeting AREMA standards										X		
(g) Carbonated ECC rail tie with life cyclec cost 20% lower than current concrete ties											X	
Task 5 - Evaluation of Life Cycle CO2 Emissions Reduction												
Subtask 5.1: Separation of CO2 from Flue Gas												
Subtask 5.2: Consequential Life Cycle inventory of Carbonated ECC Rail Tie Production												
Subtask 5.3: Evaluating Carbonated ECC against Sustainability Necessary Conditions												
Subtask 5.4 – Techno-economic Feasibility Study and Technology Gap Analysis												
<u>Milestones</u>												
(h) Carbonated ECC rail tie with life cycle carbon and energy footprints 20% lower than current concrete ties												X