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

Award No. DE-FE0030684

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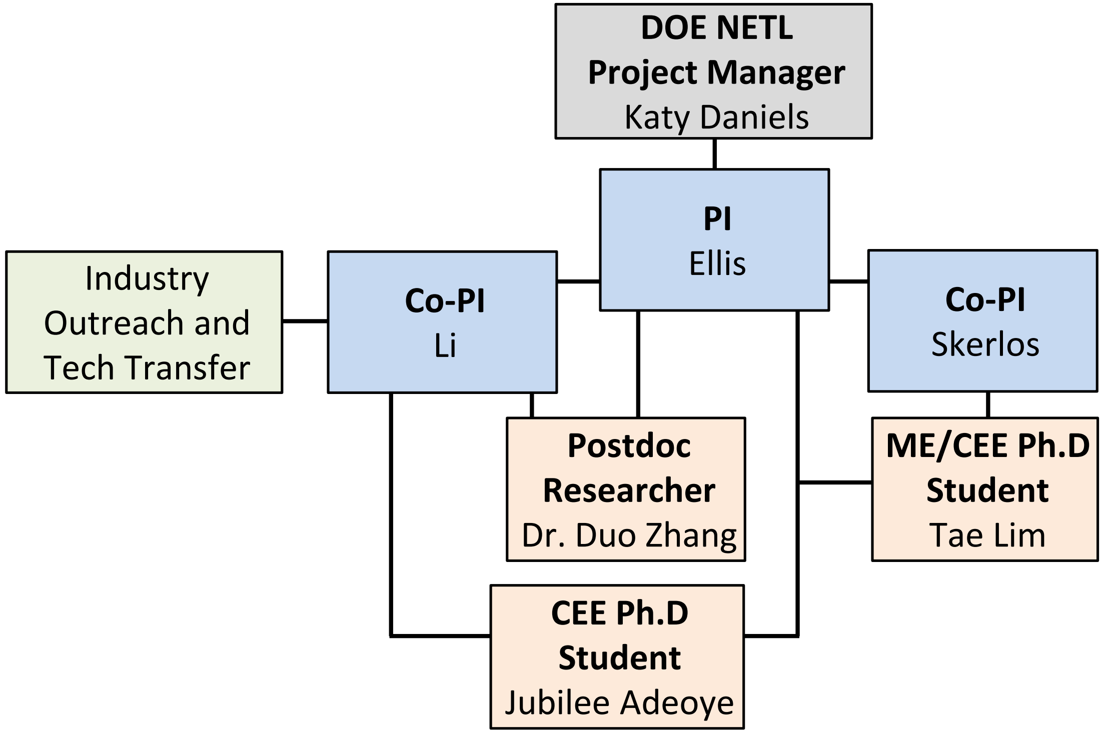
NETL Project Review Meeting, August, 2019

Project Overview



a. **Funding:**
- **DOE:** **$999,999**
- **Cost share:** **$250,000**

b. **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**

c. **Project Participants**
- *Principal investigators*: Brian R. Ellis, Victor C. Li (co-PI), Steven J. Skerlos (co-PI)
- *Post-doc research fellow*: Duo Zhang
- *Visiting scholars*: Beata Jaworska, Alex Neves Junior
- *Graduate students*: Tae Lim, Jubilee Adeoye

d. **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 Background: Coupling CO_2 storage with novel cement materials to support sustainable infrastructure

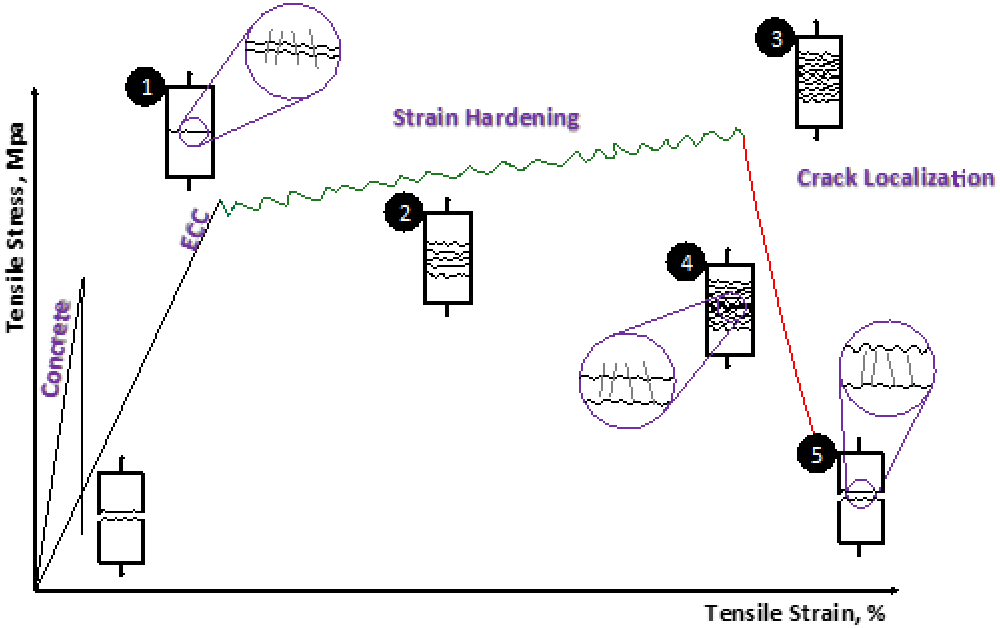
Engineered Cementitious Composite (ECC)

Advantages:

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

Challenges:

- Maximize CO_2 sequestration without compromising ECC ductility



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

Technology Background

Coal-fire power plants

Flue gas CO_2

Fly ash

Carbonation Curing

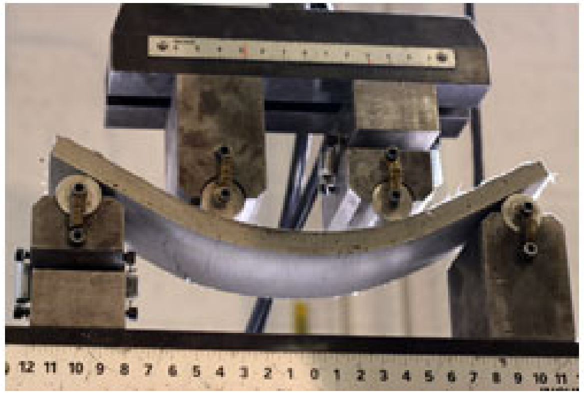
Precast Industry

CO_2 + unhydrated cement

CO_2 + hydration products

Process optimization

Novel Infrastructure Materials



Engineered Cementitious Composite

Micromechanics models

Target products: **Railway ties**

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

Project Scope

Task 1: Project Management and Planning

Budget Period 1
10/2017 – 06/2019

Task 2
Development of carbonation process

- Carbonation setup and process development

Task 3
Integration of ECC products

- Development of ductility and mechanical integrity

Success Criteria: Carbonation process and mix design of ECC reaching a minimum of 10% CO_2 stored

Budget Period 2
07/2019 – 12/2020

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

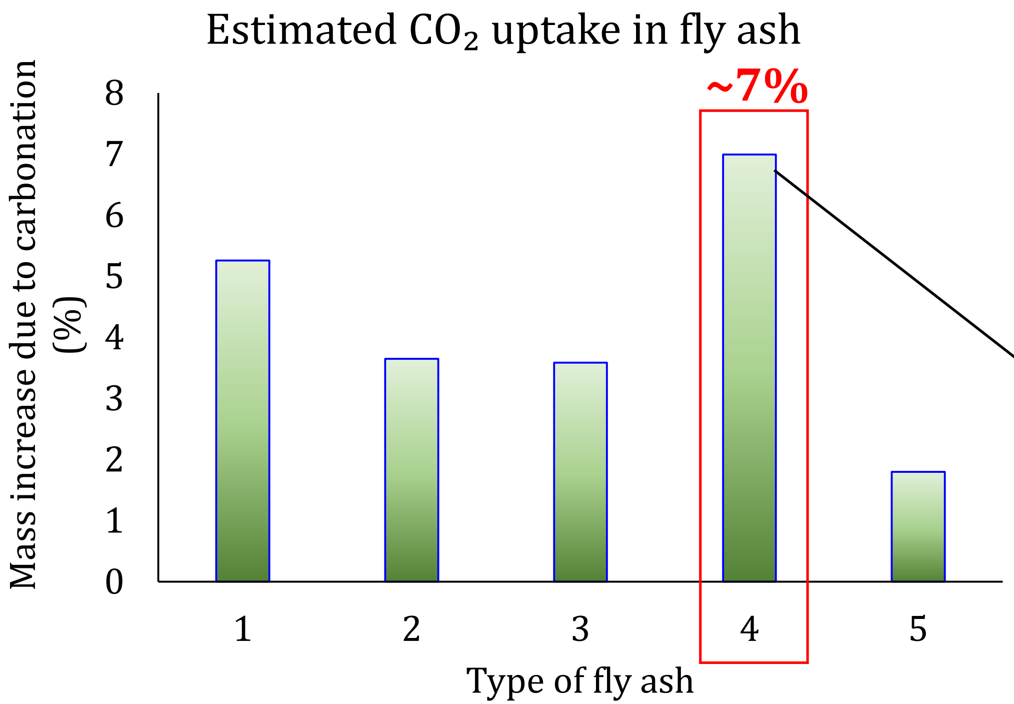
Success Criteria: Carbonated ECC rail tie with life cycle carbon and energy footprints 20% lower than current concrete ties, meeting AREMA standards

Products:

- Zhang, D., Li, V. C., & Ellis, B. R. (2018). Optimal pre-hydration age for CO_2 sequestration through Portland cement carbonation. *ACS Sustainable Chemistry & Engineering*, 6(12), 15976-15981.
- Wu, H. L., Zhang, D., Ellis, B. R., & Li, V. C. (2018). Development of reactive MgO-based Engineered Cementitious Composite (ECC) through accelerated carbonation curing. *Construction and Building Materials*, 191, 23-31.
- Li, V.C., Ellis, B.R., & Zhang, D. Sustainable ductile construction material with CO_2 sequestration. Patent Application Submitted. (containing 2 prospective journal manuscripts)

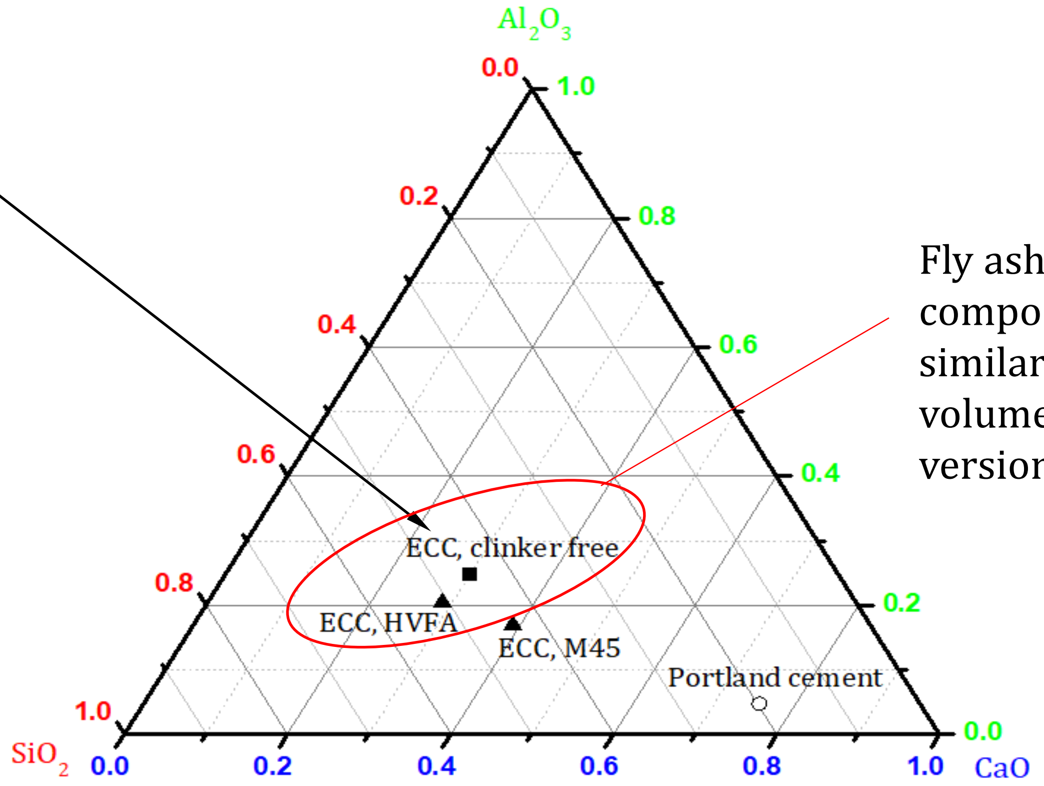
Progress - Task 2. Development of carbonation process

Fly ash carbonation



1 2 3 4 5 **Class F fly ash**

CO_2 uptake ~ 0



Fly ash #4 shows compositional similarity to high-volume fly ash ECC version.

Carbonation condition:

Pure CO_2, 75 psi, for 24 hours

Subtask 2.2. CO_2 carbonation of caustic solid waste: (2) Steelmaking slag

Sample ID	Slag 1	Slag 2
Moisture content	9.8%	3.2%
CO_2 uptake, by mass	7.7%	1.9%

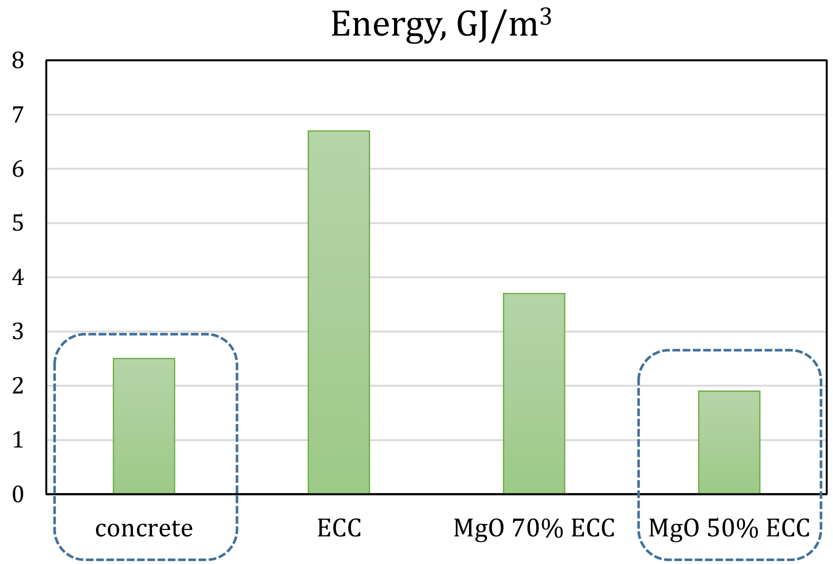
Steel slag demonstrates ability of sequestering CO_2.

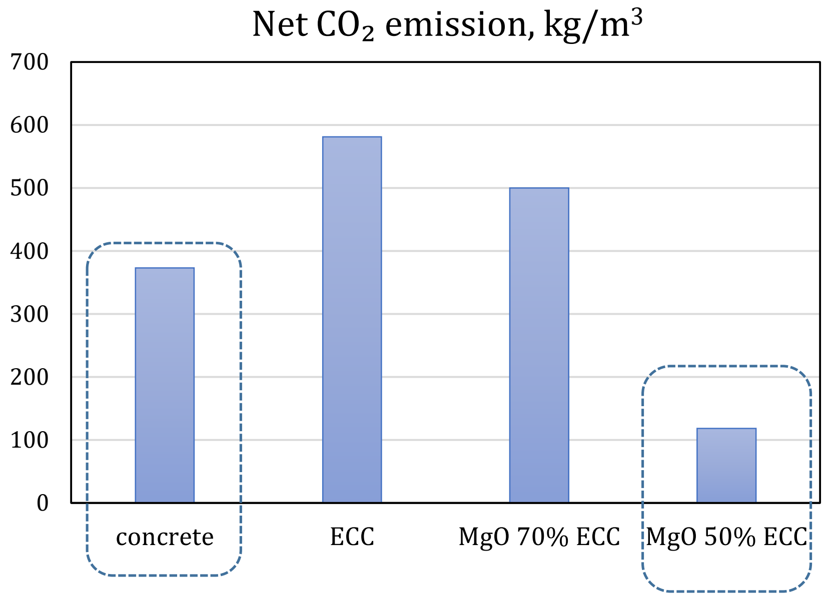
>1000 µm   425-1000 µm   212-425 µm   105-212 µm   75-105 µm   < 75 µm

>1000 µm   425-1000 µm   212-425 µm   105-212 µm   75-105 µm   < 75 µm

Subtask 2.2. CO_2 carbonation of caustic solid waste: (3) reactive MgO cement

- Clinkering temperature is lower for MgO (700°C) than Portland cement (1450°C).
- MgO takes up more than 40% CO_2 to form binding properties.

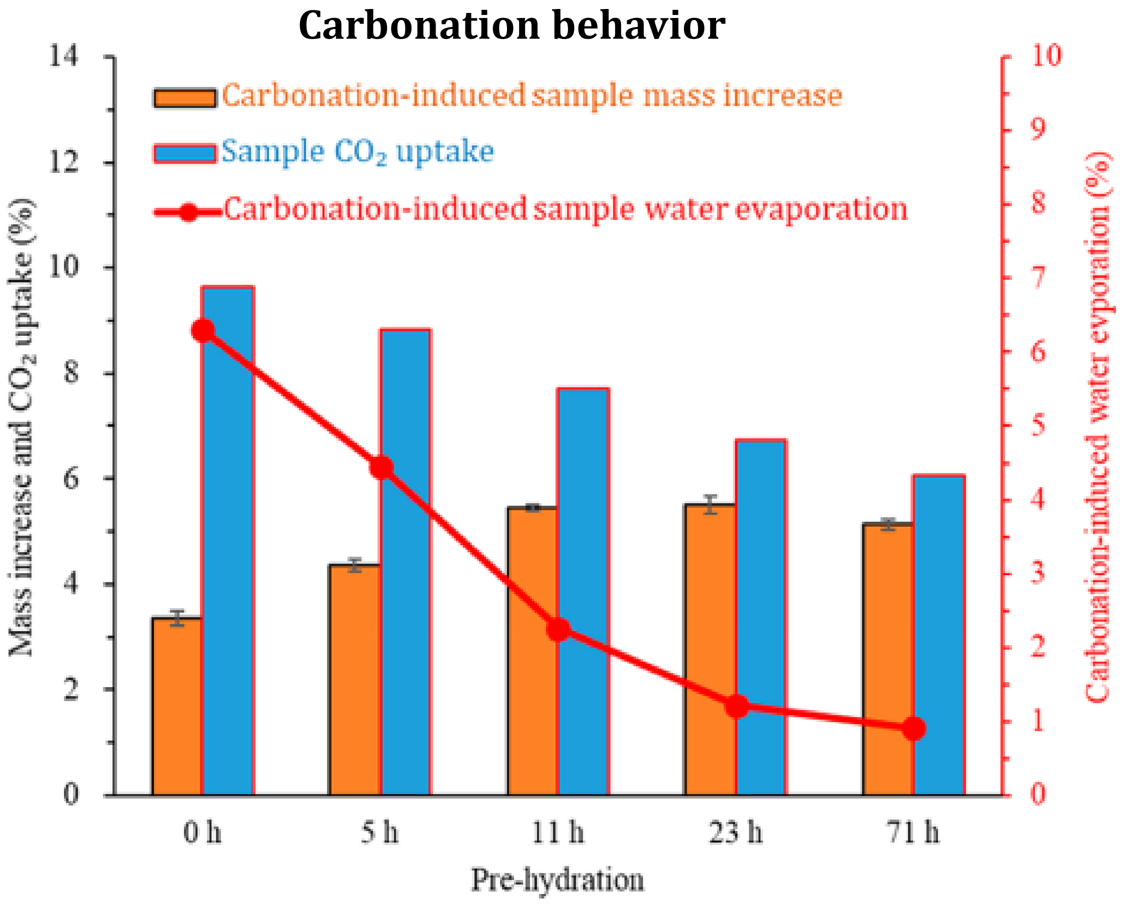


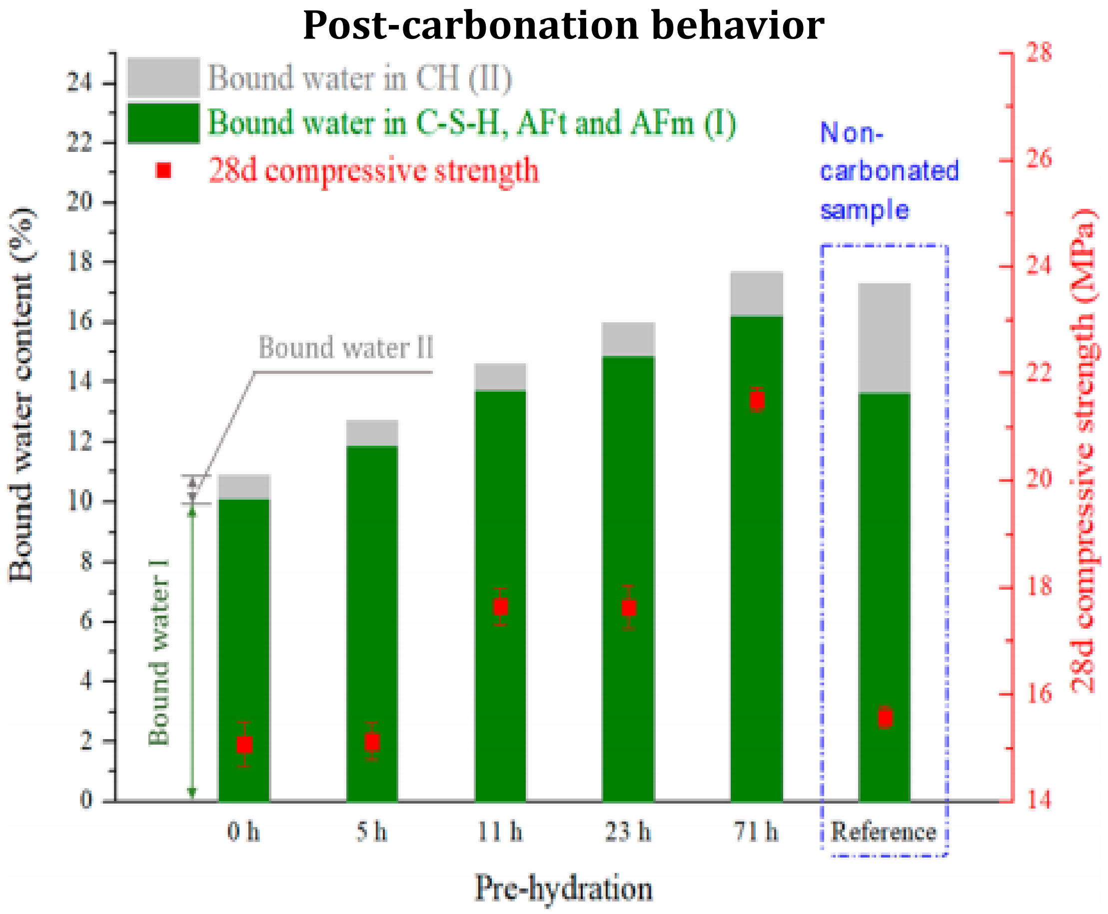


"50%MgO + 50% Fly ash" were used for ECC integration.

Published in Wu et al., 2018, Constr Build Mater.

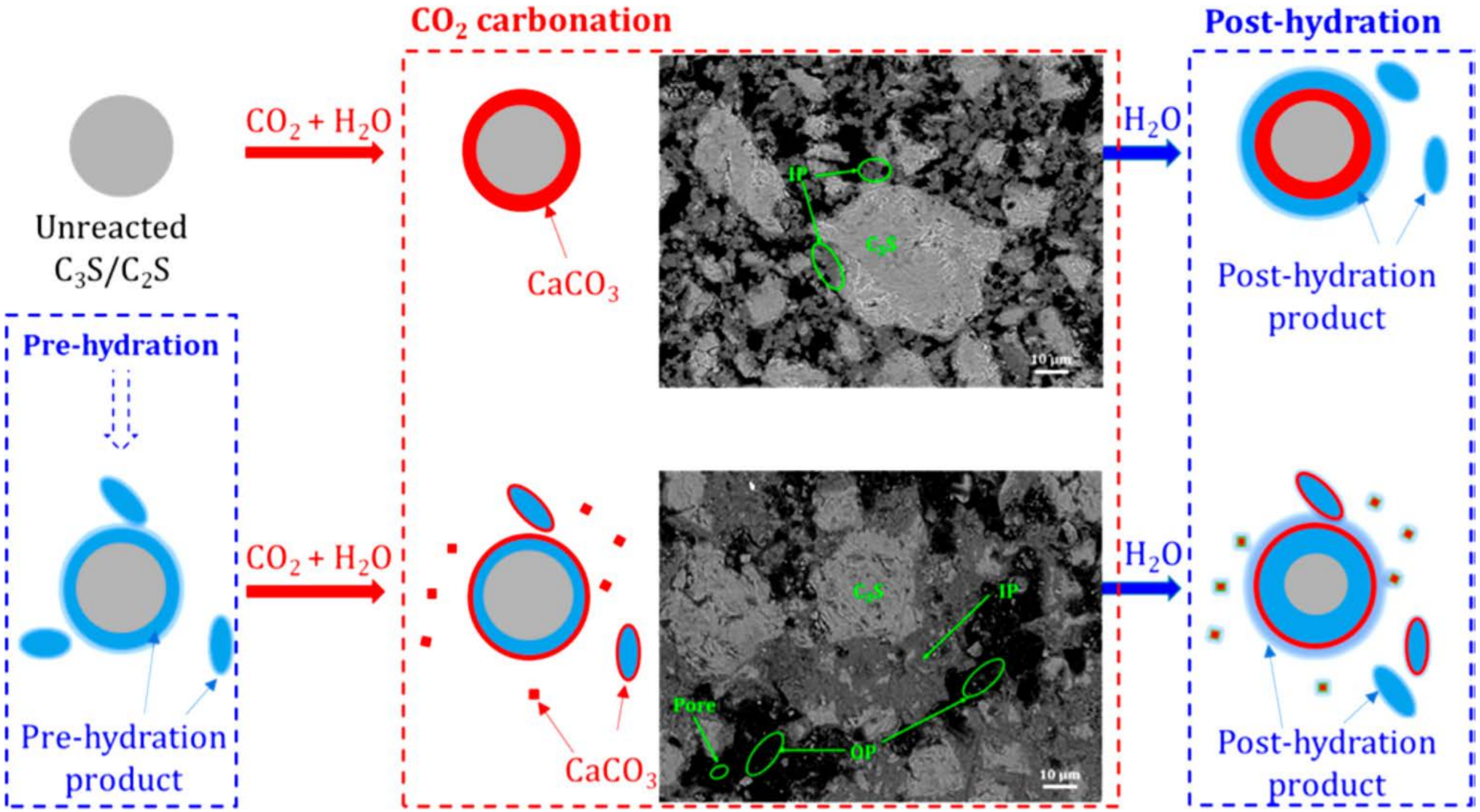
Subtask 2.3. Process optimization for maximal CO_2 storage





- A new parameter – “pre-hydration” is identified in process optimization.
- Longer pre-hydration reduces CO_2 uptake but increases long-term strength and bound water content.

Subtask 2.3. Process optimization for maximal CO_2 storage

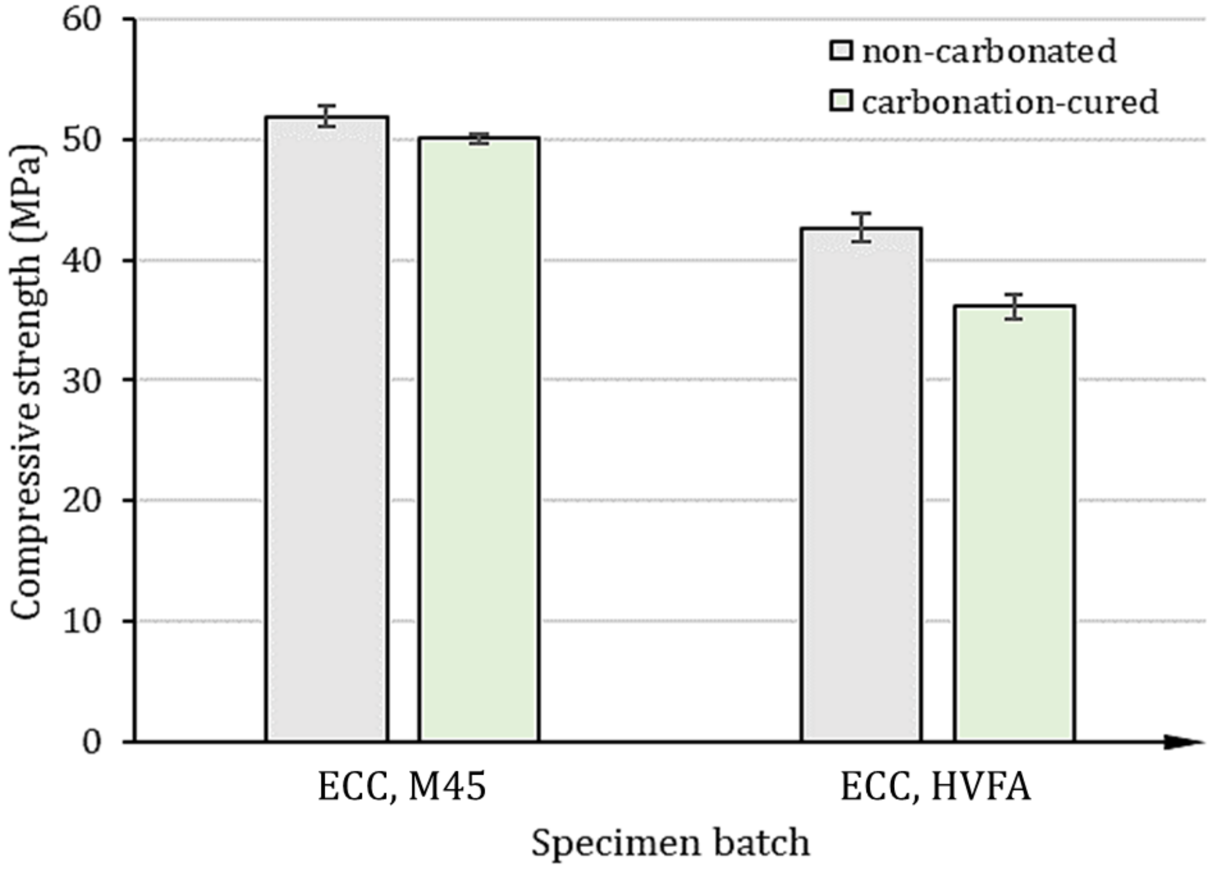


Microstructural characterization suggests that longer pre-hydration is beneficial for dispersing hydration products through enabling a seeding effect during post-carbonation hydration.

Published in Zhang *et al*., 2018, *ACS Sustainable Chem Eng*

Subtask 3.1. Matrix characterization

Compressive strength



ECC M45: compressive strength is comparable between carbonation curing and non-carbonated reference.

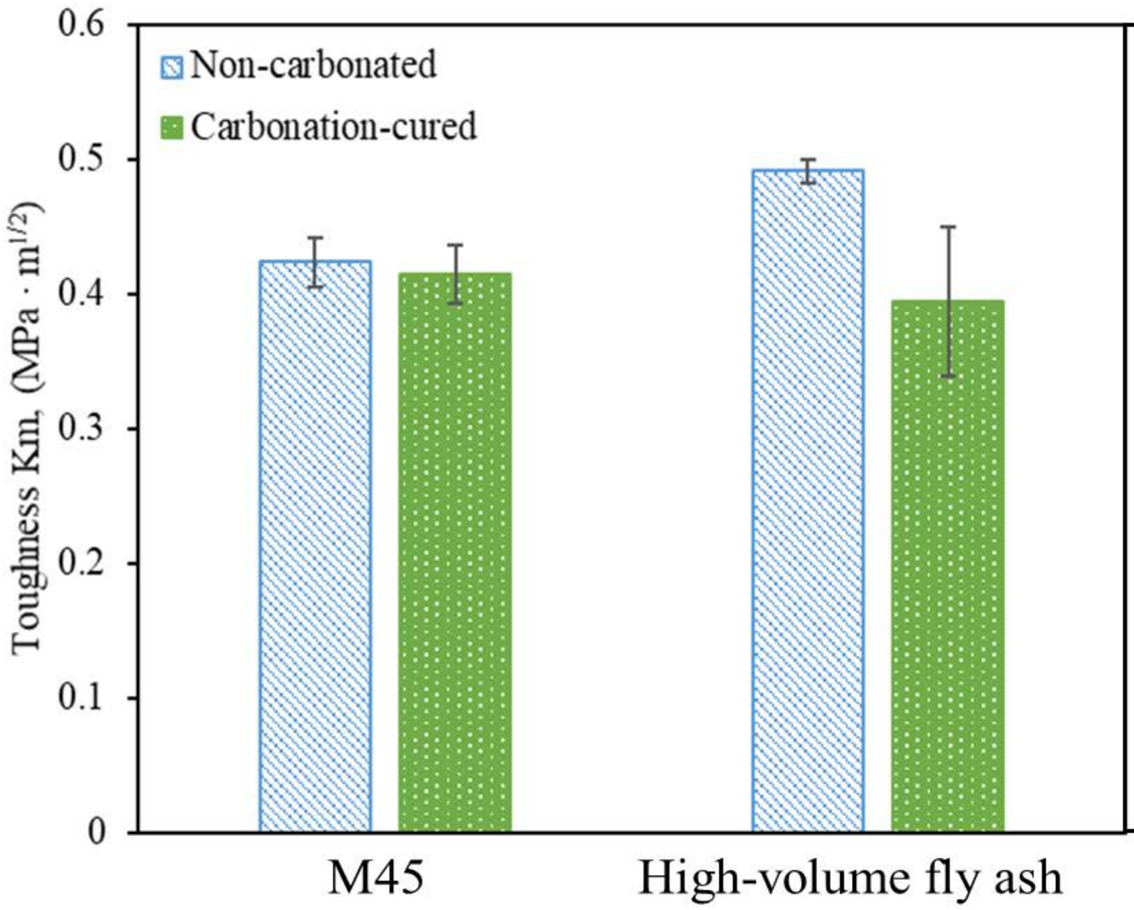
ECC high-volume fly ash: carbonation curing slightly reduced compressive strength.

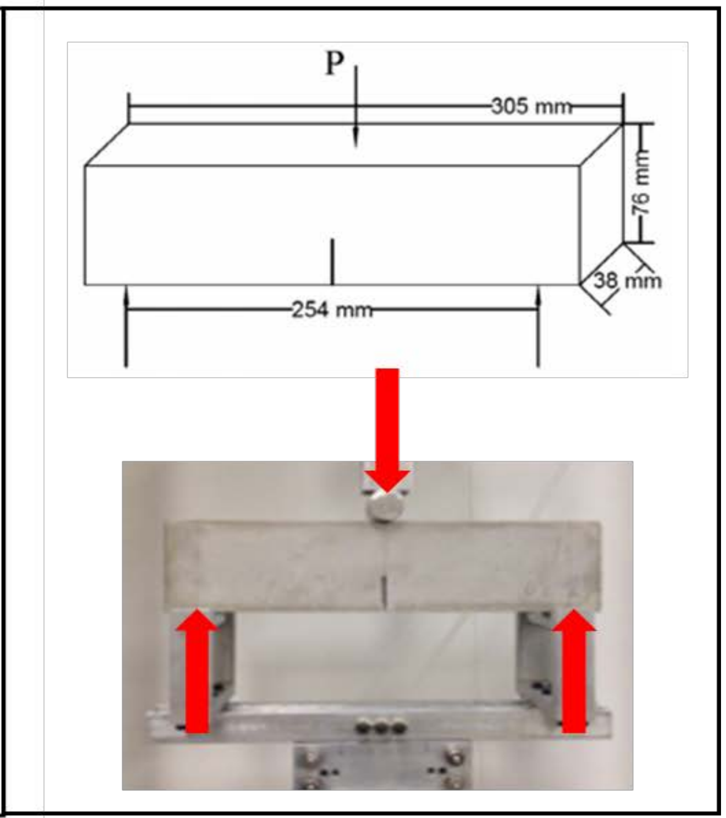
M45: fly ash/cement =1.2

HVFA: fly ash/cement =2.2

Subtask 3.1. Matrix characterization

Fracture toughness **Km**, according to ASTM E399

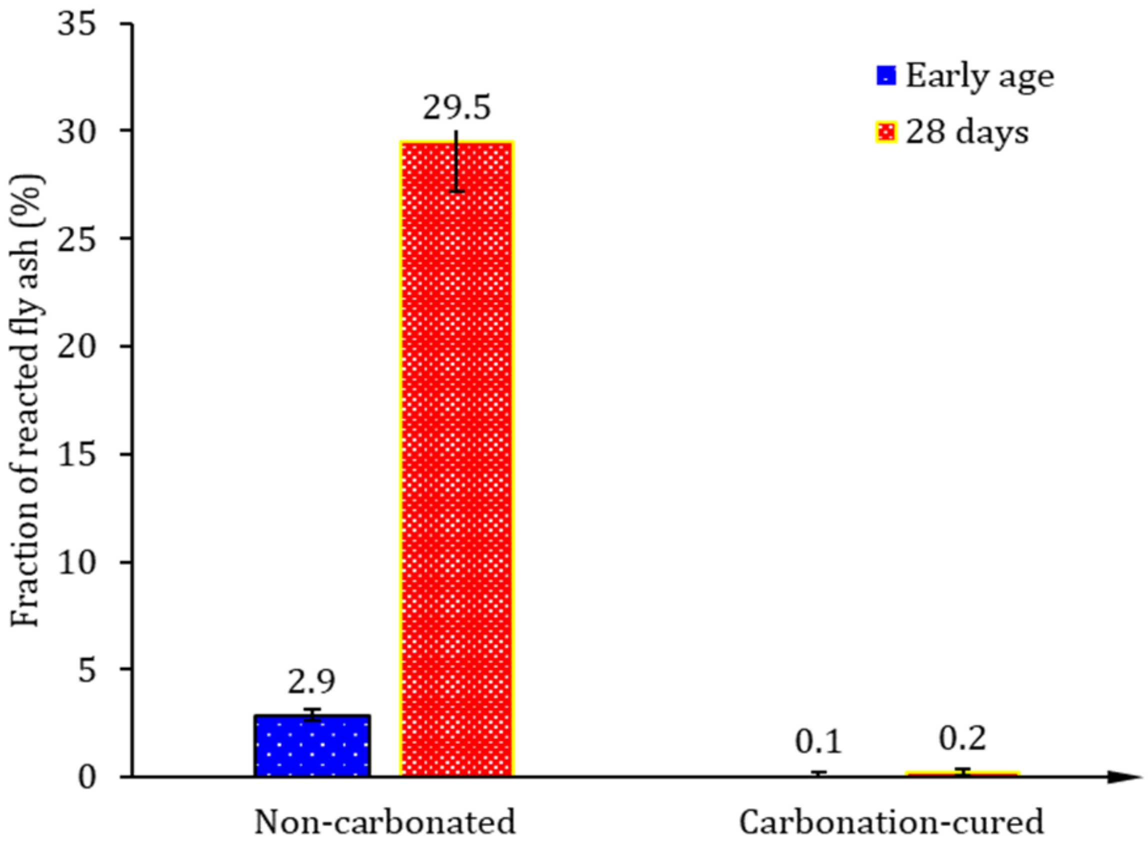




- **ECC M45**: comparable fracture toughness between carbonation curing and non-carbonated reference.
- **ECC high-volume fly ash**: fracture toughness is reduced after carbonation curing.

Subtask 3.1. Matrix characterization

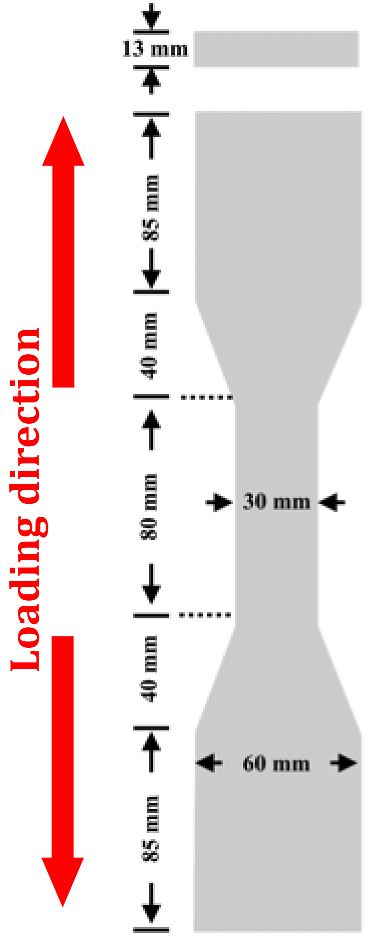
Fly ash reaction degree, by selective dissolution test according to RILEM TC 238-SCM



- Pozzolanic reaction degree of fly ash is significantly **reduced** by carbonation curing
- This is attributed to low alkalinity in the carbonated materials

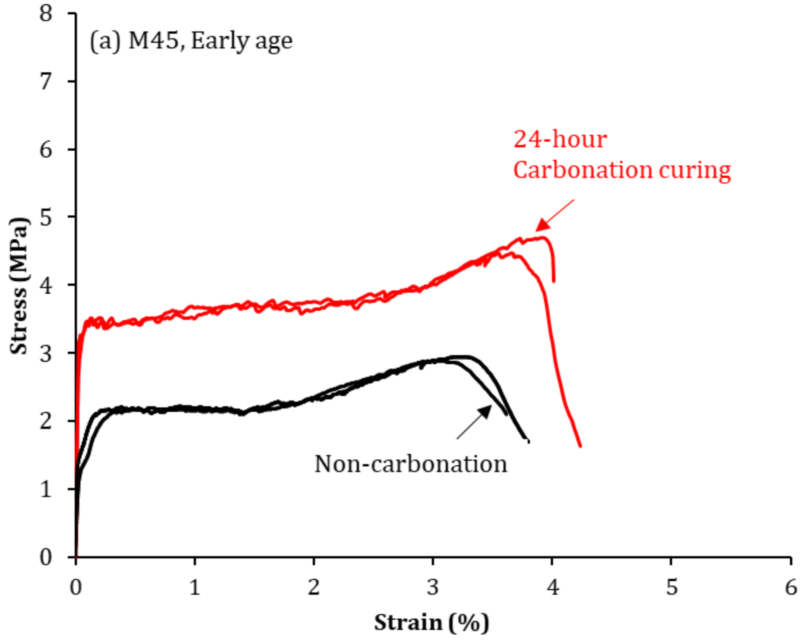
Subtask 3.4. Micromechanical analysis of composite response and re-design route

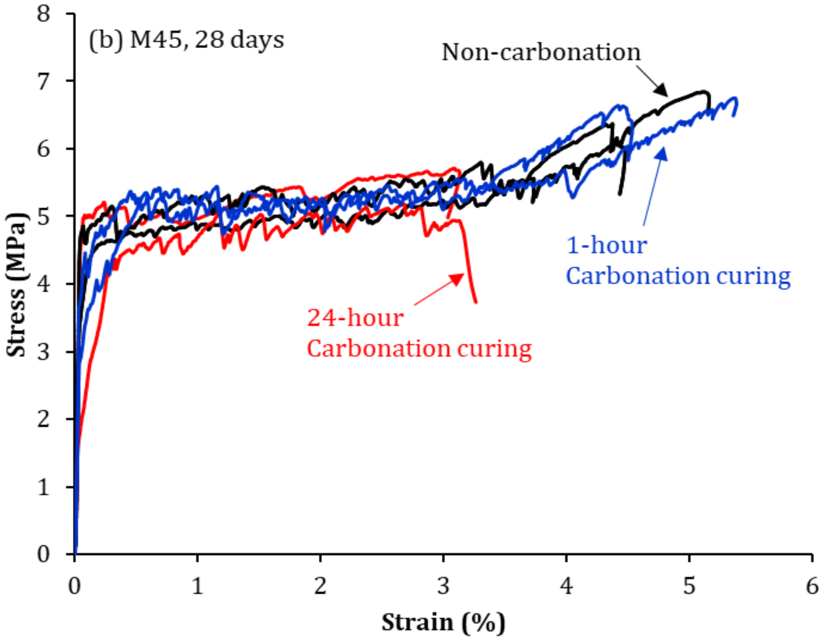
Uniaxial tensile experiment, according to JSCE recommendation

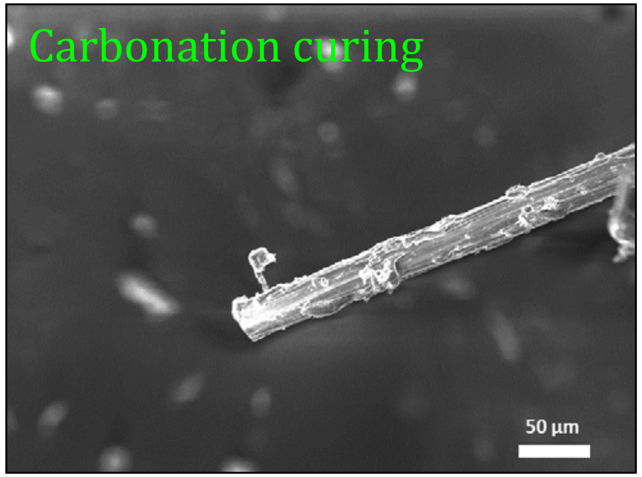


- Testing ages: early (immediately after carbonation) and 28 days;
- Tension loading rate: 0.5mm/min.

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







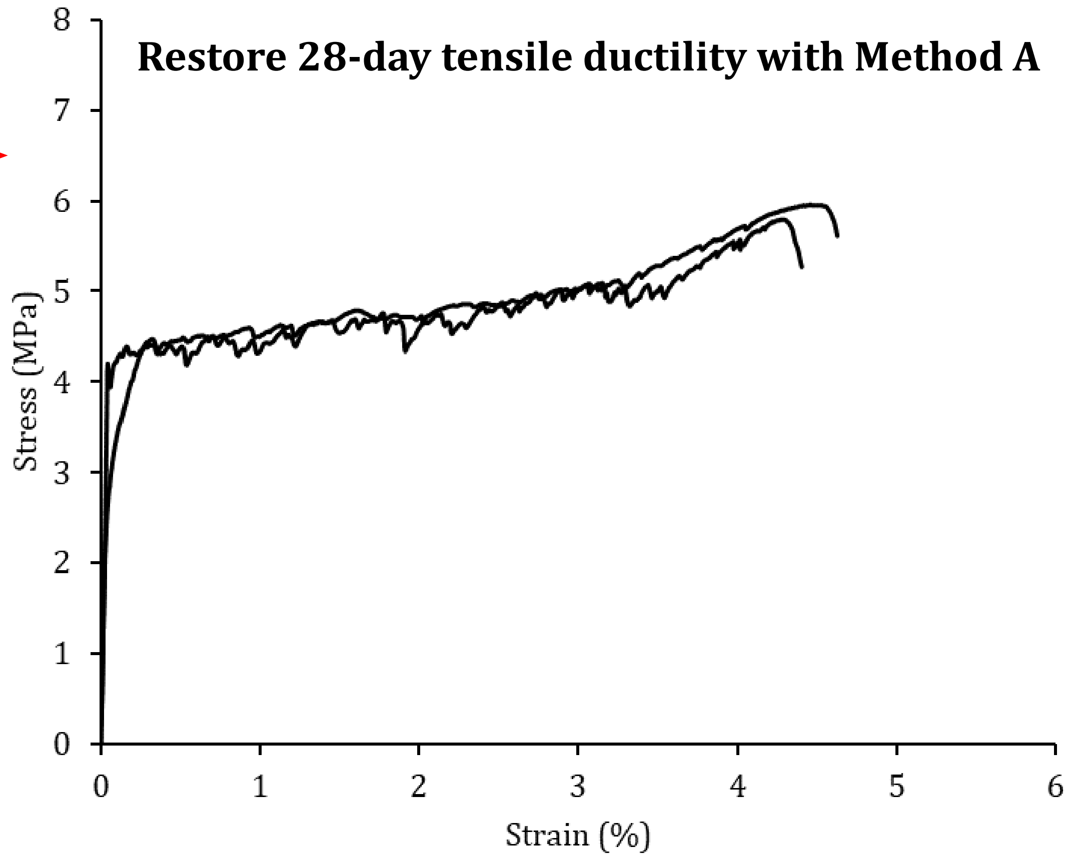
Fiber surface abrasion after tension test.

- **Early age**: carbonation curing expedited development of tensile strength and ductility;
- **28 days**: carbonation curing led to comparable tensile strength, but slightly reduced tensile ductility (>3%)
- Combined fiber breakage and surface abrasion represent the failure of PVA fibers in carbonation-cured ECC.

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

To restore tensile ductility at 28 days, we attempted:

A. Incorporation of artificial flaw;
B. Fiber surface modification;
C. Incorporation of high volume fly ash;
D. Incorporation of MgO mineral.

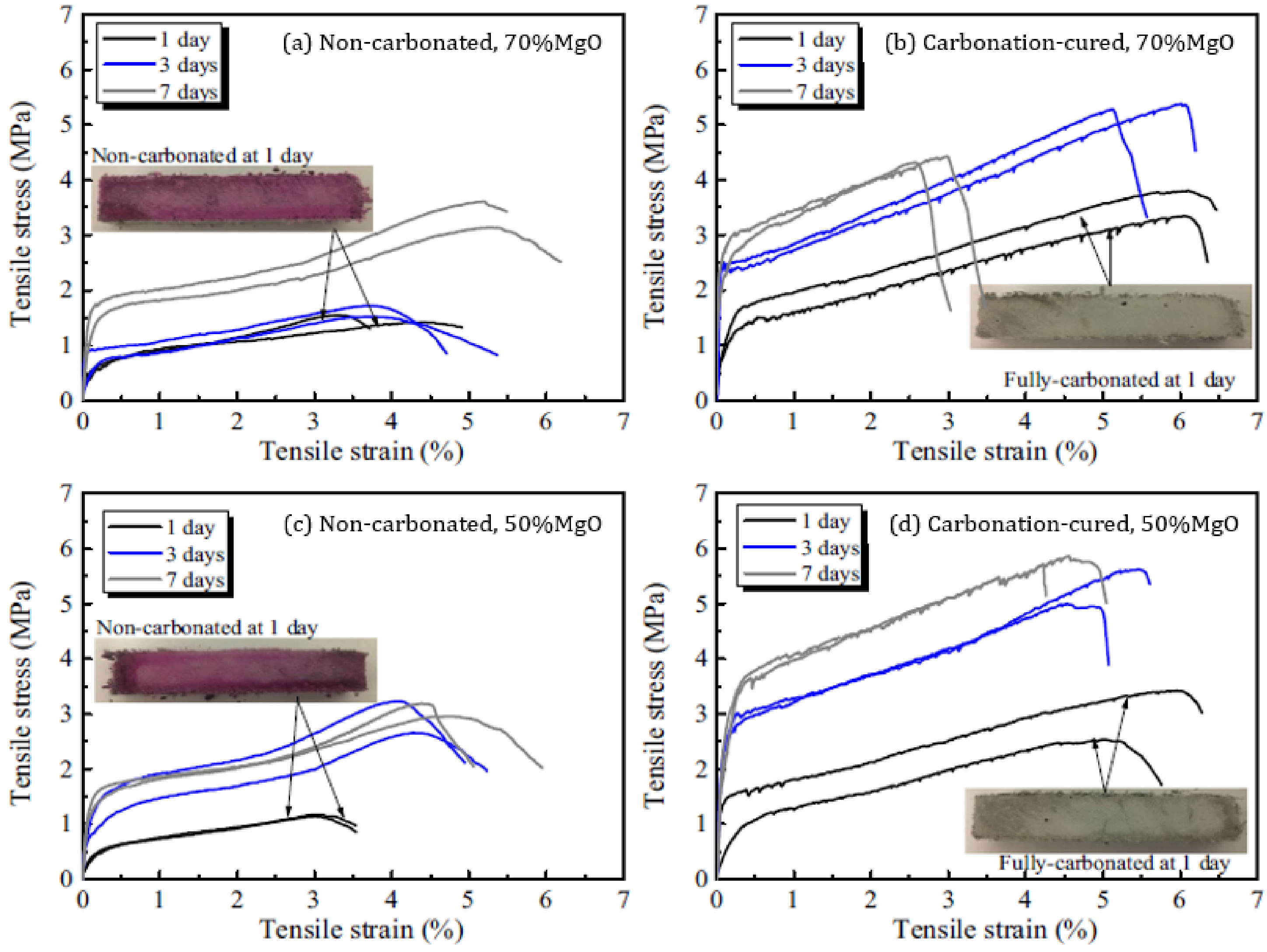


Method A was proven the most effective approach to restore tensile ductility of carbonation-cured ECC

Compressive strength:	**50 MPa**
Ultimate tensile strength:	**5.8 MPa**
Tensile strain capacity:	**4.5% > 2% (proposed goal)**

Subtask 3.4. Micromechanical analysis of composite response and re-design route: Alternative binders ECC

ECC based on binary blends of reactive MgO cement and fly ash



- ECC made with MgO-fly ash blends can achieve tensile ductility up to 5%.
- MgO-ECC can be used as a low-carbon alternative of ECC M45 for precast applications.
- MgO-ECC demonstrates potentials of self-healing.

Published in Wu et al., 2018, Constr Build Mater.

Progress Summary of Tasks 1-3

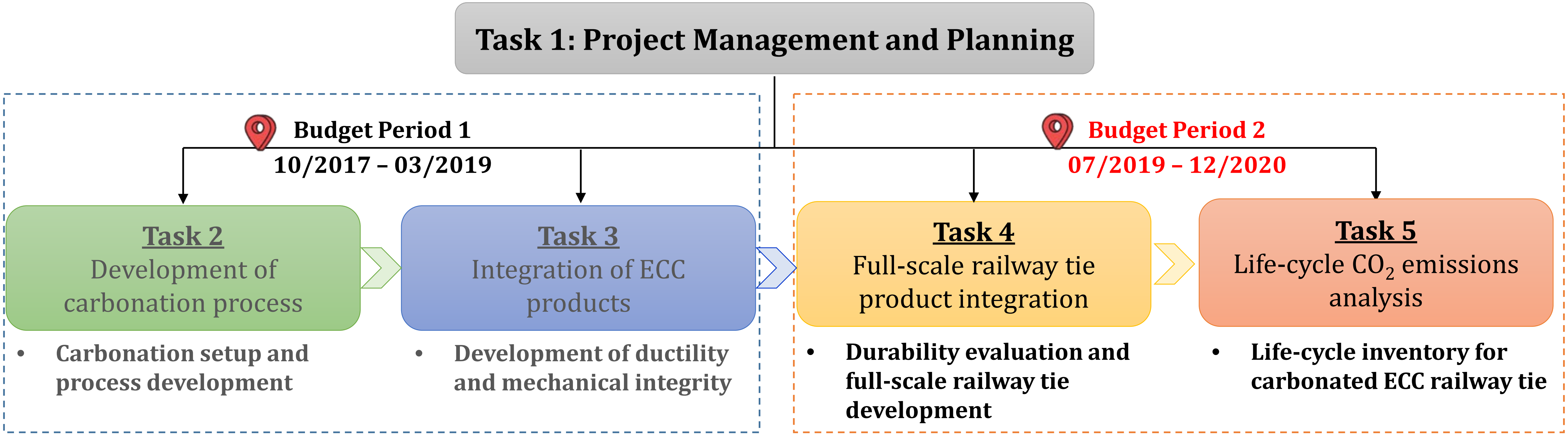
- Laboratory setups
  - Carbonation reactors at 1-8 atm
  - TGA/DSC
  - Full-scale carbonation chamber: to be manufactured by Chonhunteda Composite Co.,Ltd
- New carbonation process
  - Optimal carbonation condition (within 48 hours) and achieved ~30% CO_2 uptake
- Mechanical properties (ECC-M45)
  - Tensile strength: accelerated by carbonation curing at early age, and comparable at 28 days
  - Tensile strain capacity: slightly reduced by carbonation curing but can be restored to >4%
- New classes of ECC with alternative binders
  - Fly ash-based cement-free ECC
  - MgO-based ECC

Continuing and Future work (Tasks 4-5):

- Performance evaluation and full-scale railway tie experiments

Future Plans:

Task 4. Composite-product integration and testing



Task 4. Composite-product integration and testing

Milestone:
Carbonated ECC meeting durability criteria of 50 years under accelerated testing conditions

Subtask 4.1. Long-term durability

(a) Intrinsic crack width:
- Crack numbers
- Crack width → histogram of crack width distribution

(b) Permeability:
- Water permeability under loaded condition *versus* unloaded condition
- Observation of crack width and closure due to self-healing

(c) Sulfate attack:
- Changes in mass, length, mechanical integrity and ductility will be assessed in various sulfate and alkaline solutions

(d) Fatigue:
- Four-point flexural loading fatigue experiment with observation of crack propagation

(e) Self-healing:
- Self-healing in Water and Na_2SO_4 solution.

Task 4. Composite-product integration and testing

Subtasks 4.2 and 4.3. Process Integration and Costing at Scale

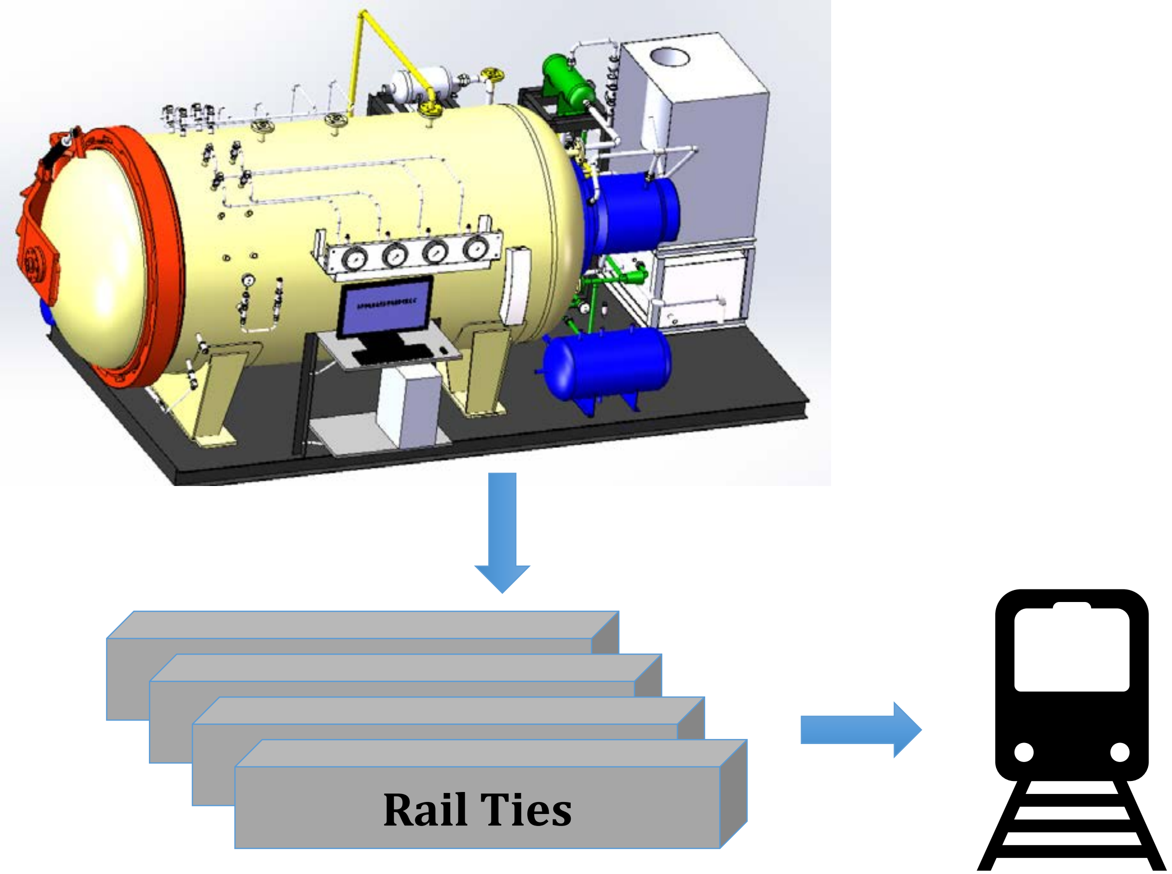


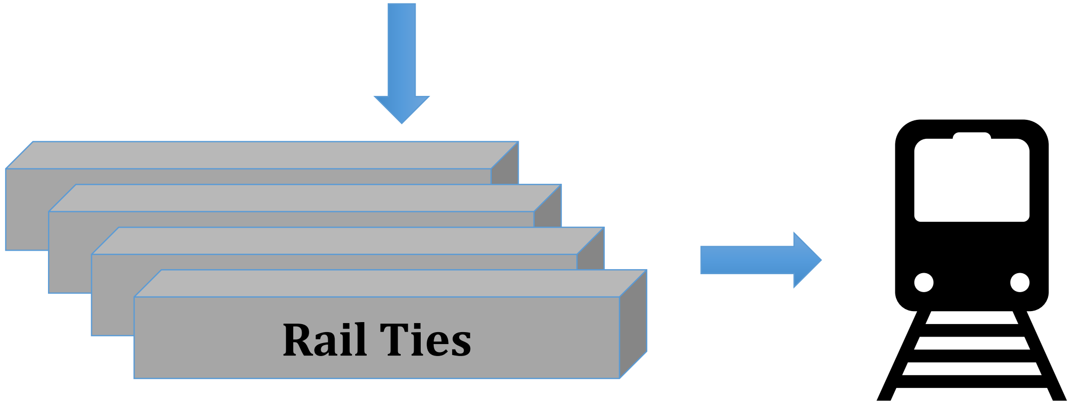
Image from: www.fra.dot.gov

Task 4. Composite-product integration and testing

Subtasks 4.2 and 4.3. Process Integration and Costing at Scale

Milestone:
Carbonated ECC rail tie meeting AREMA standards

Milestone:
Carbonated ECC rail tie with life cycle cost 20% lower than current concrete ties



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Funding Support:

U.S. DEPARTMENT OF ENERGY

Award Number: DE-FE0030684

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