Converting CO_2 and Alkaline Solid Wastes into Carbon-Negative Supplementary Cementitious Materials for Co-decarbonization of Multiple Sectors

(DE-FE0032395)

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Civil/Materials Engineering & Energy Economics
Missouri University of Science and Technology (**S&T**)

2024 FECM/NETL Carbon Management Research Project Review Meeting
August 5 – 9, 2024

Outline

- ❑ **Project Overview**
- ❑ Technology Background
- ❑ Project Scope
- ❑ Progress and Current Status
- ❑ Community Benefits
- ❑ Lessons Learned
- ❑ Plan for Future Development and Commercialization
- ❑ Summary

Project Overview

Overview

Title: Converting CO_2 and Alkaline Solid Wastes into **Carbon-Negative Supplementary Cementitious Materials (SCMs)** for Co-decarbonization of Multiple Sectors

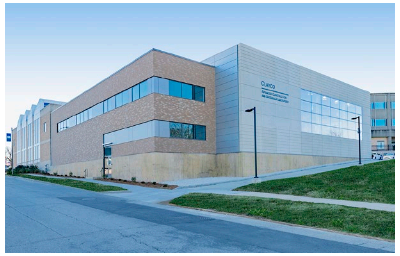
Performance Period: 10/1/2023 – 9/30/2025

Total Funding:

DOE:	$2,000,000
Cost share:	$500,000

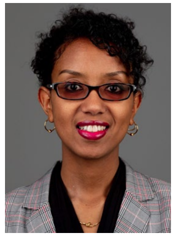
Project Overview
Team: Missouri S&T

- **STEM-intensive public research university**, founded in 1870, located in Rolla, MO
- **Campus and colleges**: 3 colleges; known primarily for the engineering programs
- **Fast developing innovation/education ecosystem**: Protoplex, Innovation Lab, STEM Center, BioX, etc., enabled by a $300M gift and state investment
- **Strong support for research facilities**:
  - Materials Research Center
  - Center for Research in Energy and Environment
  - Center for Infrastructure Engineering Studies
  - *Advanced Materials for Sustainable Infrastructure* as a signature research area



Hongyan Ma
Associate Professor of Civil/Materials Engineering
Director, Laboratory of Future Cements and Carbon-Negative Initiatives (**FuCCI**)
Lab Space: 2,000 ft^2
Expertise: Carbon-efficient and carbon-negative cement and concrete; functional construction materials; multi-scale modeling; energy storage…

Aditya Kumar
Associate Prof. of Materials Science and Engineering
Expertise: Sustainable cements; thermodynamics and kinetic modeling; machine learning



Mahelet Fikru
Associate Prof. of Economics
Expertise: Techno-economic analysis; economics modeling; optimization

Wenyu Liao
Assistant Research Professor of Civil Engineering
Manager, **FuCCI**
Expertise: Characterization of cement and solid wastes; concrete testing; carbon-negative innovation

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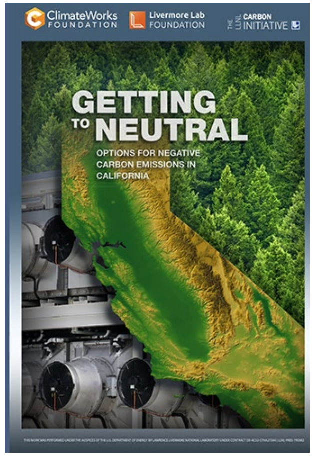
Project Overview

Team: Lawrence Livermore National Lab

- **<u>DOE/NNSA lab</u>**,
  founded in 1952, located in Bay Area, CA
- **<u>Campus</u>**: 2 sites; known for energy science & technology; open campus to academia & industry
- **<u>Large innovation ecosystem</u>**: Open campus; in vicinity to Berkeley, Stanford, MSIs; research programs with UC (e.g., Merced) & Livermore Lab Foundation
- **<u>Strong supports on research & development</u>**:
  - Advanced Manufacturing Lab
  - *Carbon Initiative*
  - High performance computing
  - *Getting to Neutral Report, etc.*

Jiaqi Li
Research Scientist
Porous media group: OpenLCA, SimaPro, GreenConcrete LCA; carbon analyzer, TGA-MS, etc.
Expertise: Carbon-efficient cement and concrete; advanced material characterization; life-cycle assessment

Lawrence Livermore National Laboratory



Project Overview
Overall project objectives

To develop a transformational process to convert **CO_2** and alkaline solid wastes into carbon-negative **blended SCMs** to meet the demand of cement/concrete market, as well as co-decarbonize and economically benefit multiple industrial sectors

- **CO_2**/flue gases
- Alkaline solid wastes (steel slags, off-spec coal ashes, MSWI ashes, …)
- Carbon-negative blended supplementary cementitious materials (SCMs)
- SCMs: substitution of portland cement (>50%)
- Multiple industrial sectors (e.g., cement manufacturing, power generation and steel making, which generate both CO_2 and solid wastes)

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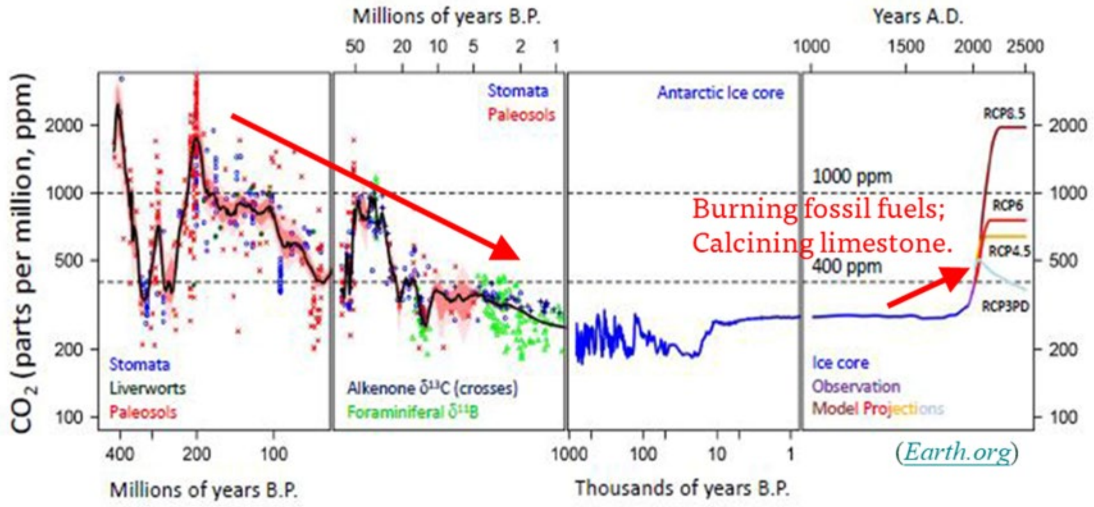
Technology Background

Why carbon-negative?

Driving Force of Climate Change:

- **422 ppm** in 2023 →**2-3**°C higher temperature and > **6m** higher sea levels (90% reliability)
  (*Foster & Rohling, 2013*)
- Warming effects may emerge after a 10-to-**30** years lag
  (*Ricke & Caldeira, 2014*)

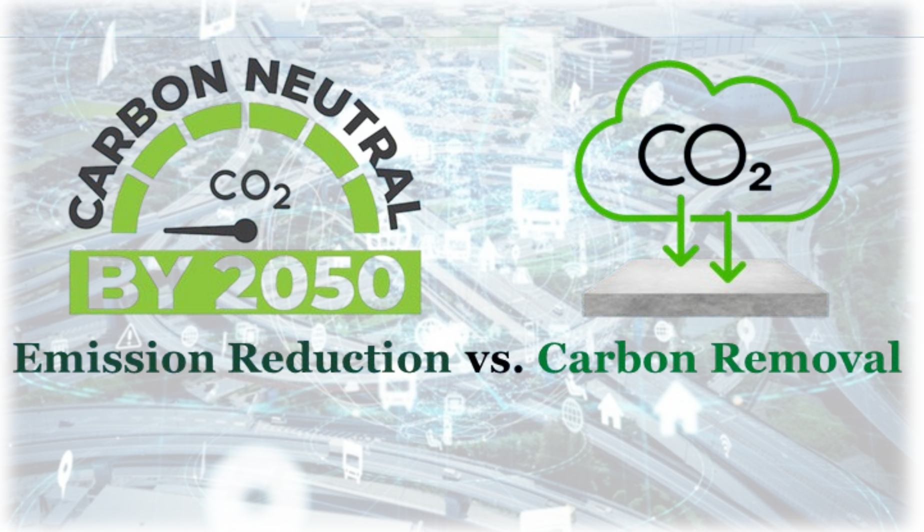


(*Earth.org*)

Immediate Actions?

- Emission Reduction and Carbon Neutrality: necessary but not enough
- **Carbon Negativity**: reduce CO_2 concentration (ppm)

i.e.: utilize and/or permanently store captured CO2



Technology Background

Why SCMs?

Decarbonization of cement/concrete

Need?

→ Annual production: 4.5 Gt cement; >30 Gt concrete
→ ~10% of anthropogenic CO_2 emission

Challenges

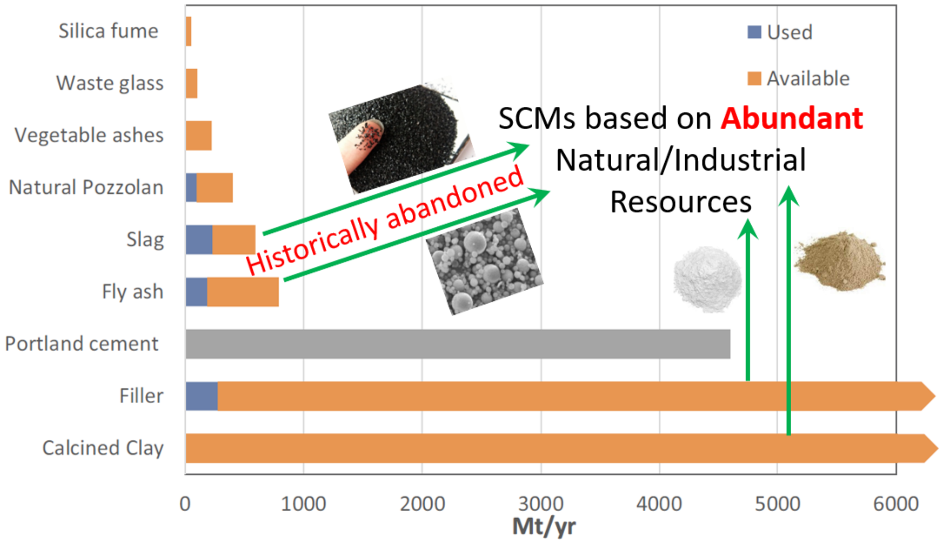
→ Reduce CO_2 emission by 24% by 2050 (IEA 2018)
→ Achieve net zero by 2050 (PCA/GCCA, 2021/2022)

Possibilities

→ Increasing use of carbon-efficient **SCMs**
→ Improving **efficiency of cement** production/utilization
→ Developing sustainable **alternative cements**

Limitation of resources

→ **Class C/F fly ash**? GGBS? Calcined clay?
→ How about **off-specification** industrial wastes?



[UN Environment, Scrivener et al., 2018, Cement and Concrete Research]

[www.lc3.ch]

Technology Background

Why (off-specification) alkaline solid wastes?

Off-spec **coal combustion** residues (2.5 Gt + 20 Mt/year)

Slags (**steel**, copper, lead, etc.; >15 Mt/year)

Waste-to-Energy (**WtE**) residues (>10 Mt/year)

Recycled concrete

Cement kiln dust

Mine tailings/waste rock

Waste glass

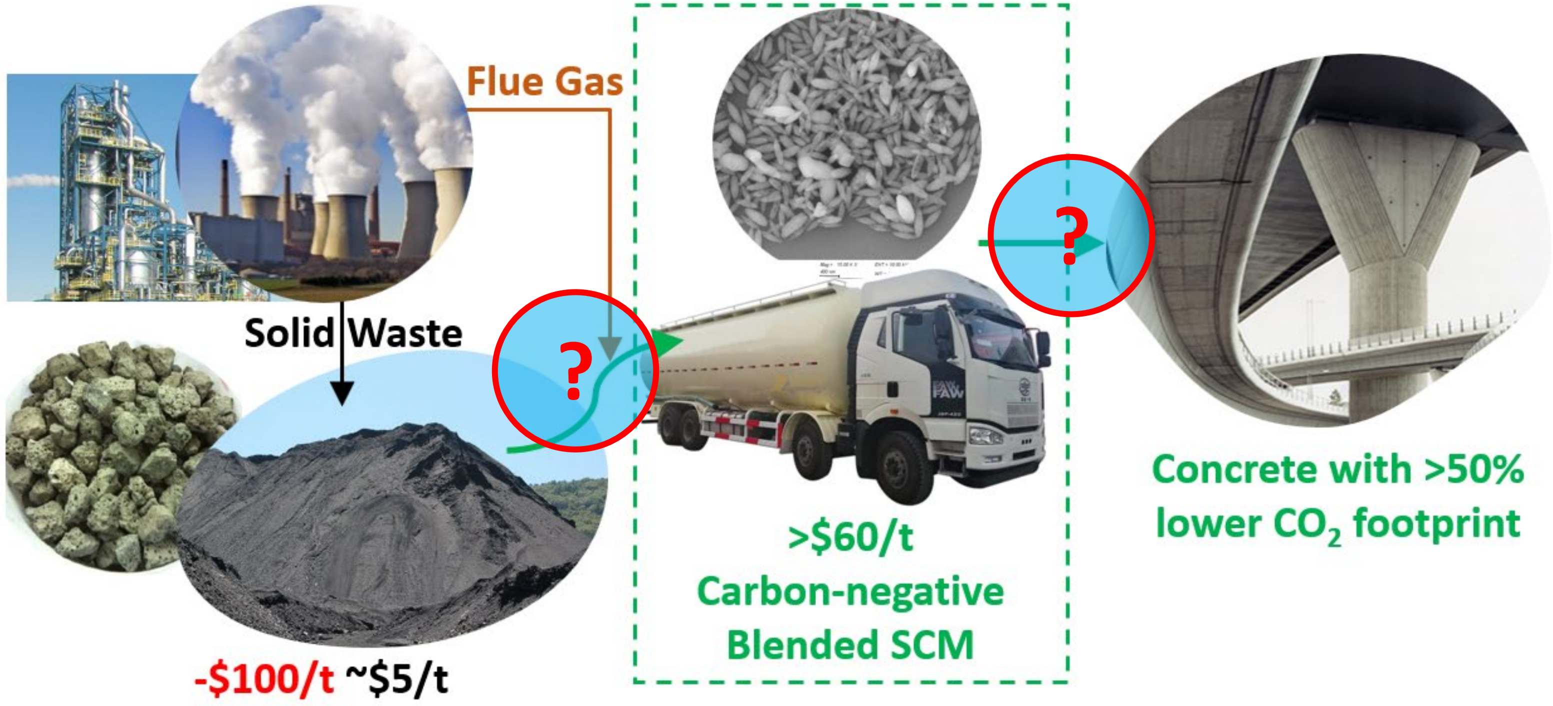
Sludge and Dirt

C&D wastes

Technology Background
The Technology

Use **CO2** to **upcycle** alkali aluminosilicate **solid wastes** into **carbon-negative blended SCMs**, which can substitute part of cement without compromising the performance of concrete

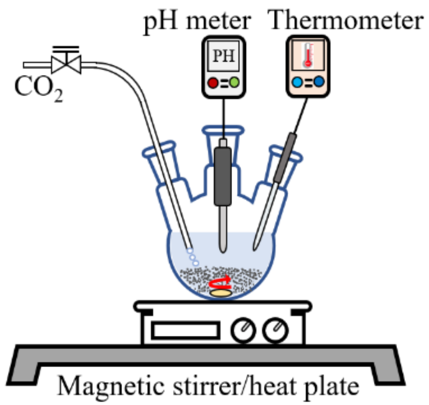
The product: nano-/micro-carbonates-aluminosilicate (**nCAS**)

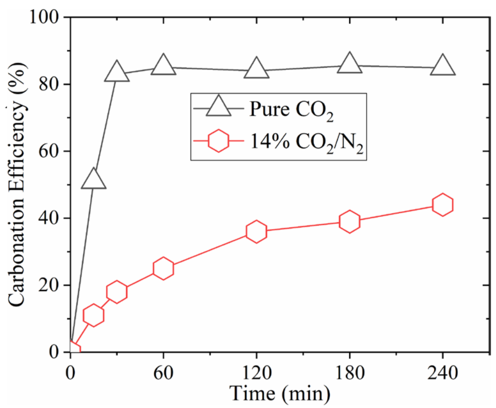


Background and Project Scope

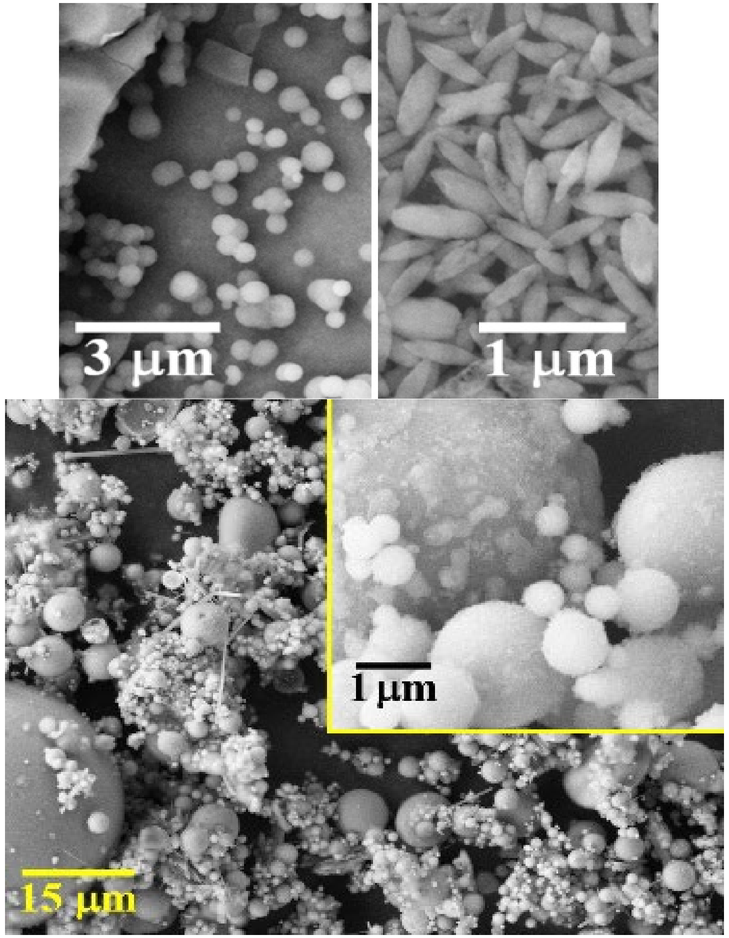
The Technology: carbon-negative process

Production



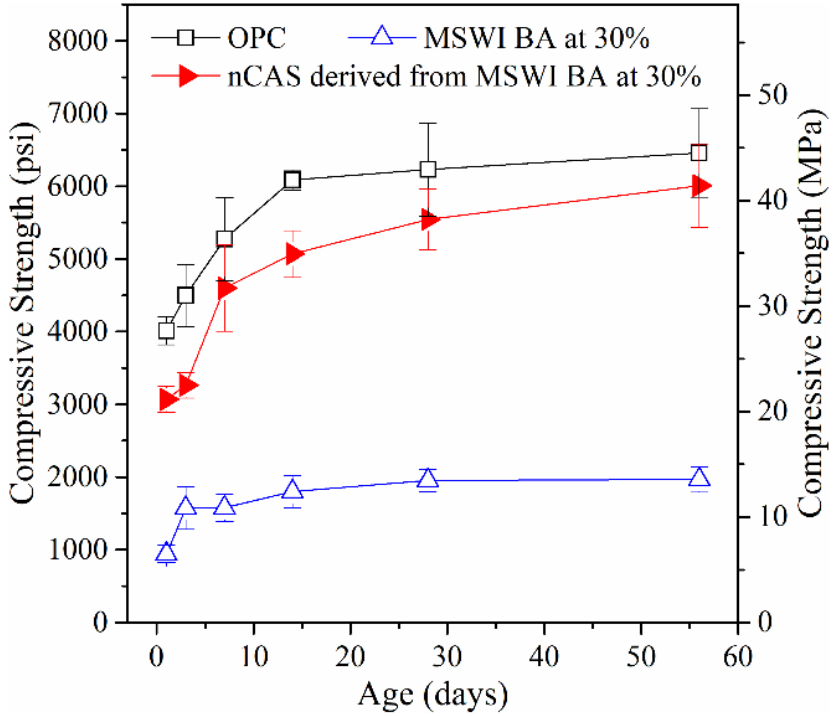


Carbonation efficiency



Carbonate nano-/submicron-particles formed following carbonation

Adaptive to low-quality feedstock?



MSWI bottom ash (BA):

Low reactivity?

Metallic aluminum?

Other detrimental substances?

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Project Scope
Steps and work plan

Task 1: Project Management and Planning

BP1

Task 2: Process model development and initial TEA and LCA
Task 3: Solid wastes sample collection and detailed characterization
Task 4: Optimization of carbonation route 1
Task 5: Optimization of carbonation route 2
Task 6: Tests of nCAS and nCAS-incorporated cement pastes

BP2

Task 7: Approach down-selection and final optimization
Task 8: Scale up production to achieve no less than 10 Kg CO_2 converted/day
Task 9: Standard performance tests of nCAS-incorporated cement-based materials
Task 10: Final TEA and LCA

Project Scope

Milestones/successful criteria

BP	Date	Success Criteria
BP1	9/30/2024	1) Comprehensive database of alkaline solid wastes encompassing up to **200** samples from diverse sources; 2) Achieving CaO/MgO-to-carbonate conversion rate **>65%**; 3) Machine learning model trained and validated, capable of predicting carbonation efficiency with >90% confidence; 4) Cement paste (water-to-binder ratio=0.4) with **≥50% nCAS** (containing **≥15%** $\mathbf{CO_2}$) substitution achieving 28-day compressive strength **>40 MPa**; 5) Supporting graduate students and postdoctoral researchers from underrepresented groups.

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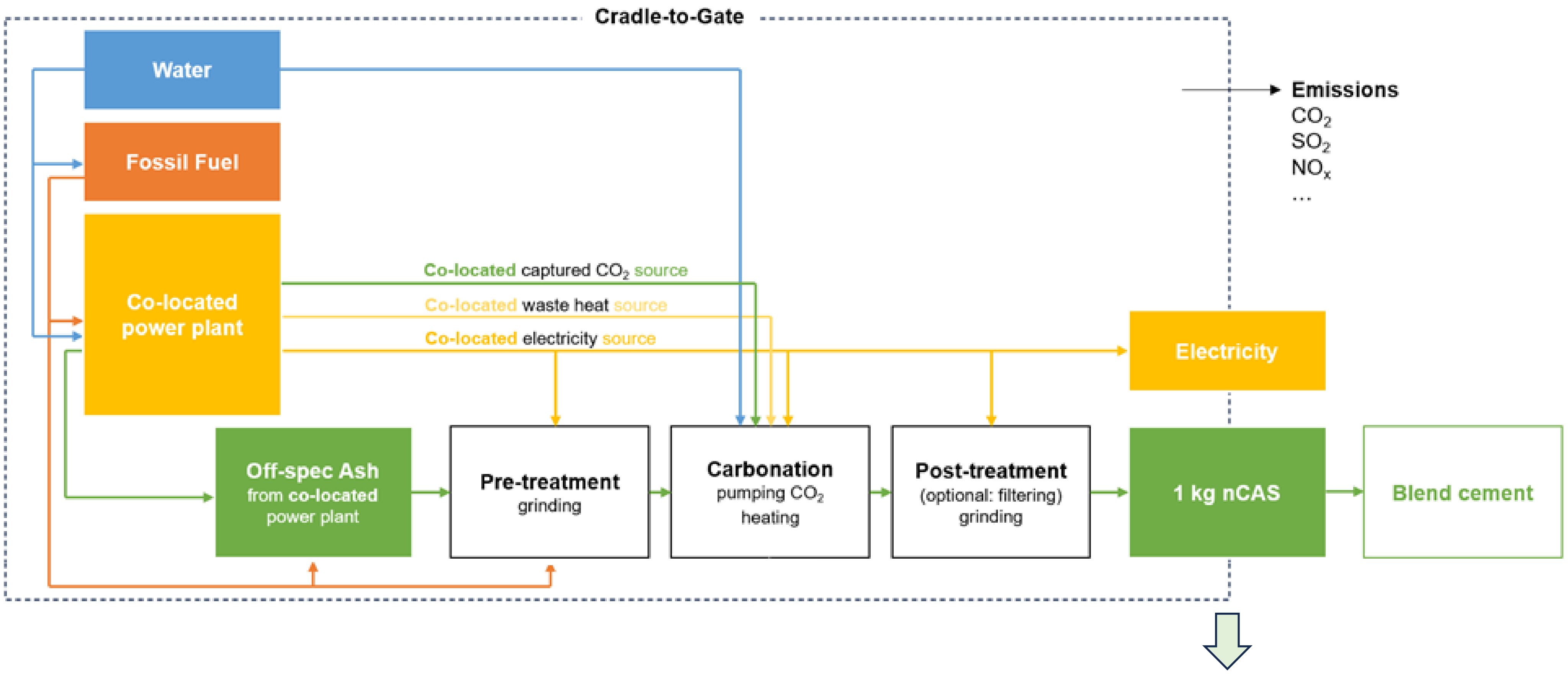
Progress and Current Status
Process model and preliminary LCA

- ❑ Base scenario
  Off-spec coal ash | co-located <u>coal power plant</u> (heat, electricity & CO_2 source) for carbonation



−0.1~−0.2 kg CO2e/kg nCAS

Progress and Current Status

Solid waste sampling and characterization

Municipal solid waste incineration (MSWI) ashes
- York County Solid Waste & Refuse Authority
- Covanta/**Reworld**

…

Coal ashes
- Electric Power Research Institute
- Local concrete producers

…

Steel slag
- SSAB
- Cleveland-Cliffs
- Harsco
- Reserve Management Group

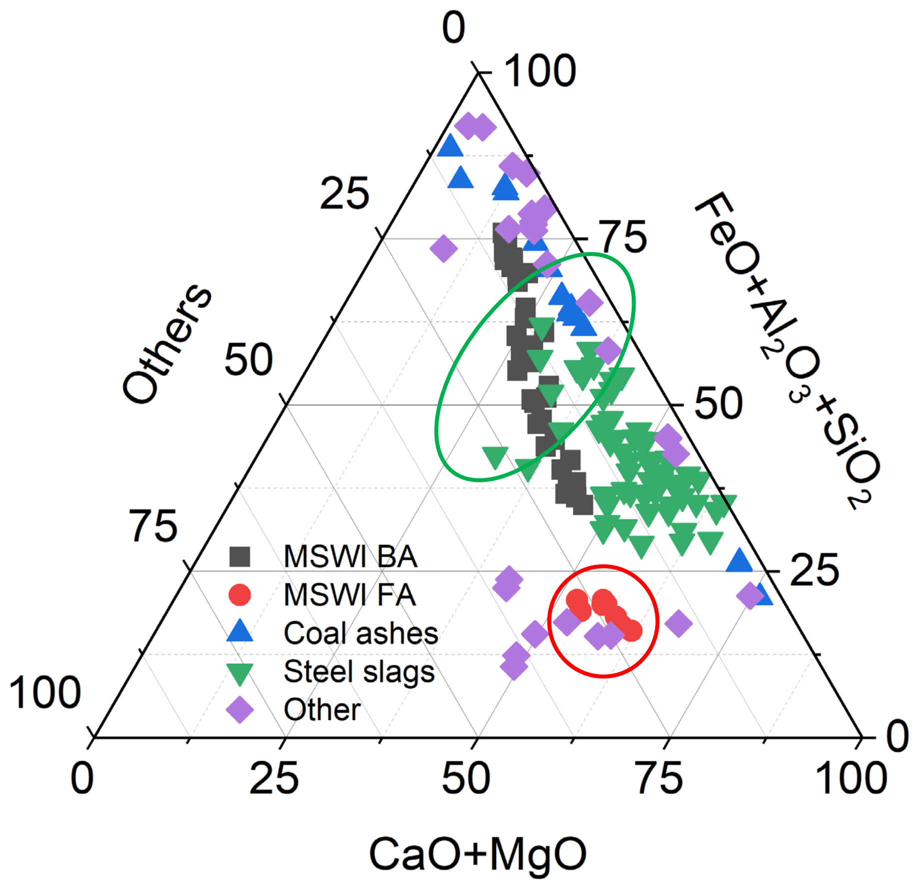
…

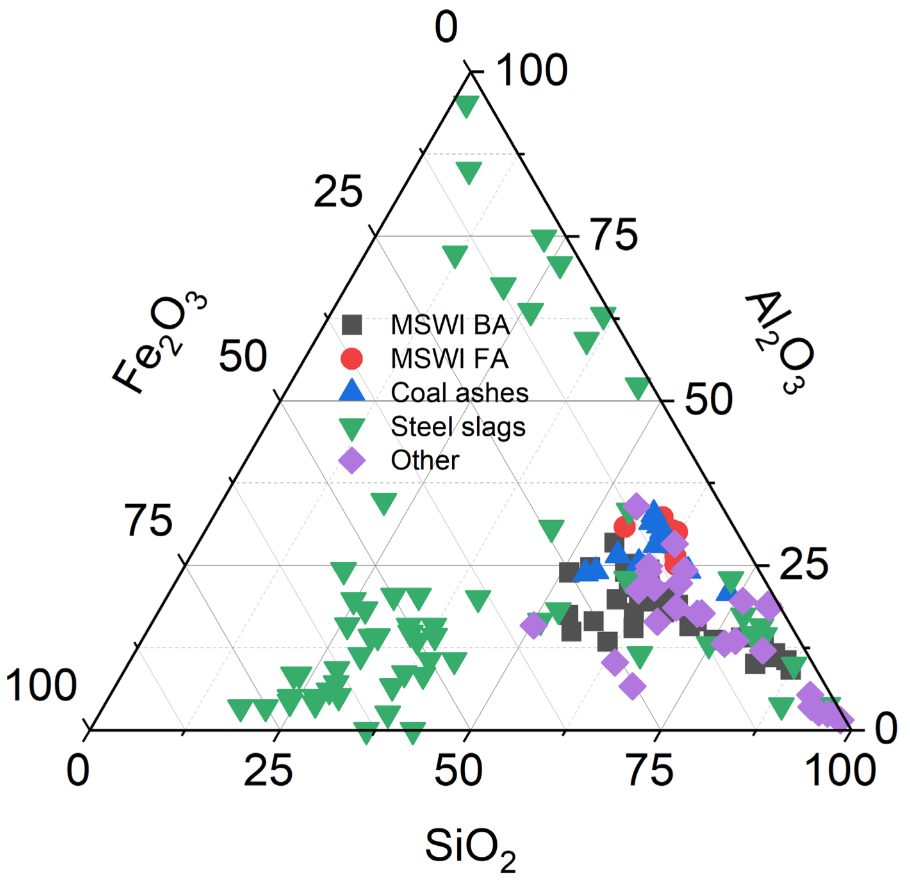
General
- Continental Cement
- Ash Grove
- Quapaw Tribe, OK

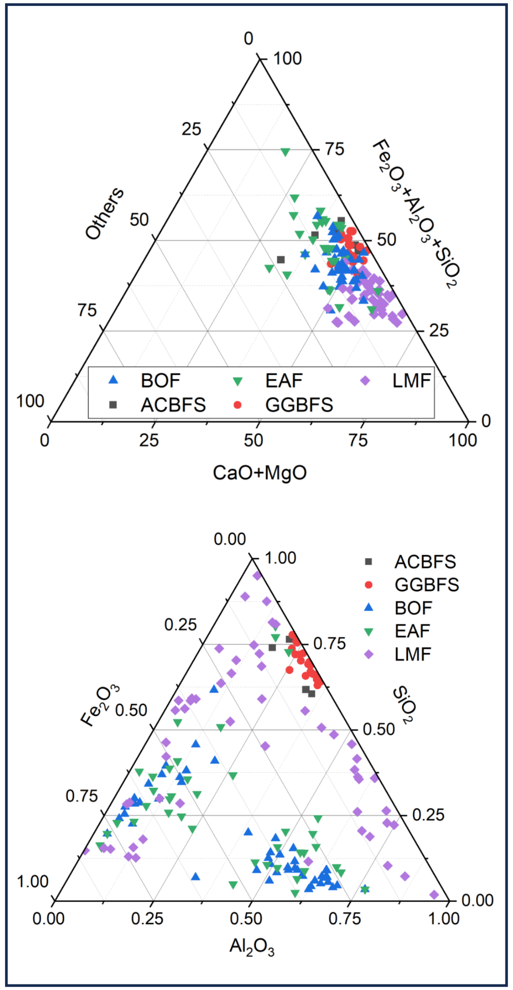
…

Progress and Current Status

Solid waste sampling and characterization: Compositional variation

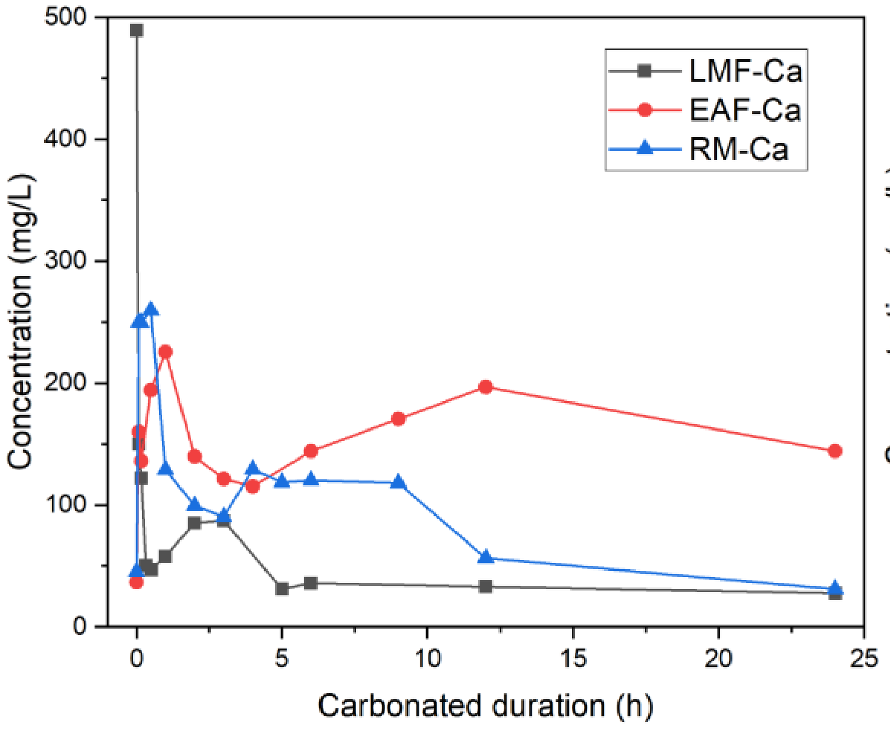


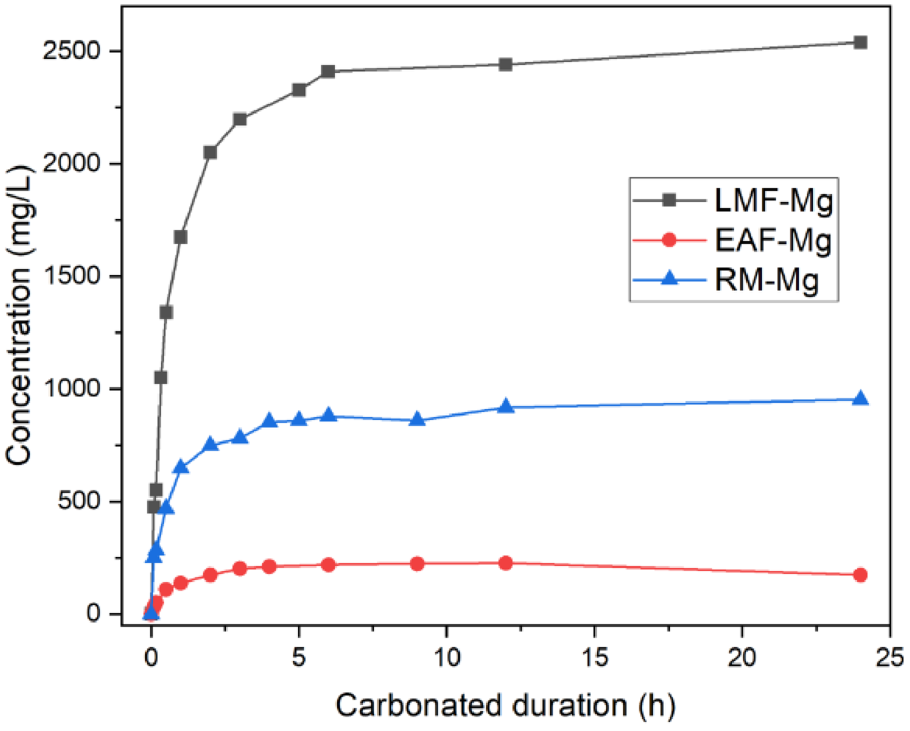


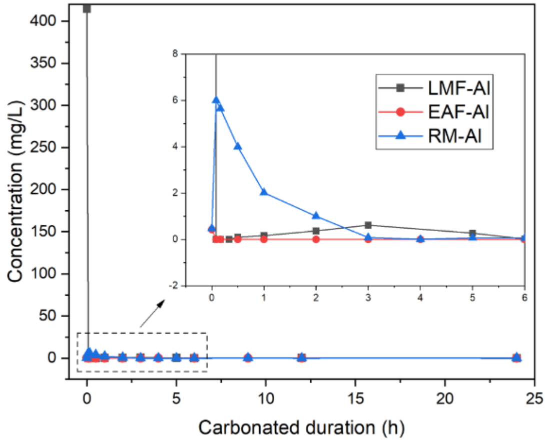


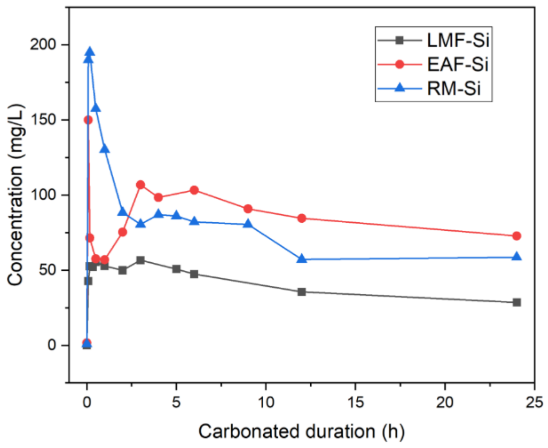
Steel slag

Progress and Current Status
Mechanism study: route 1, steel slag





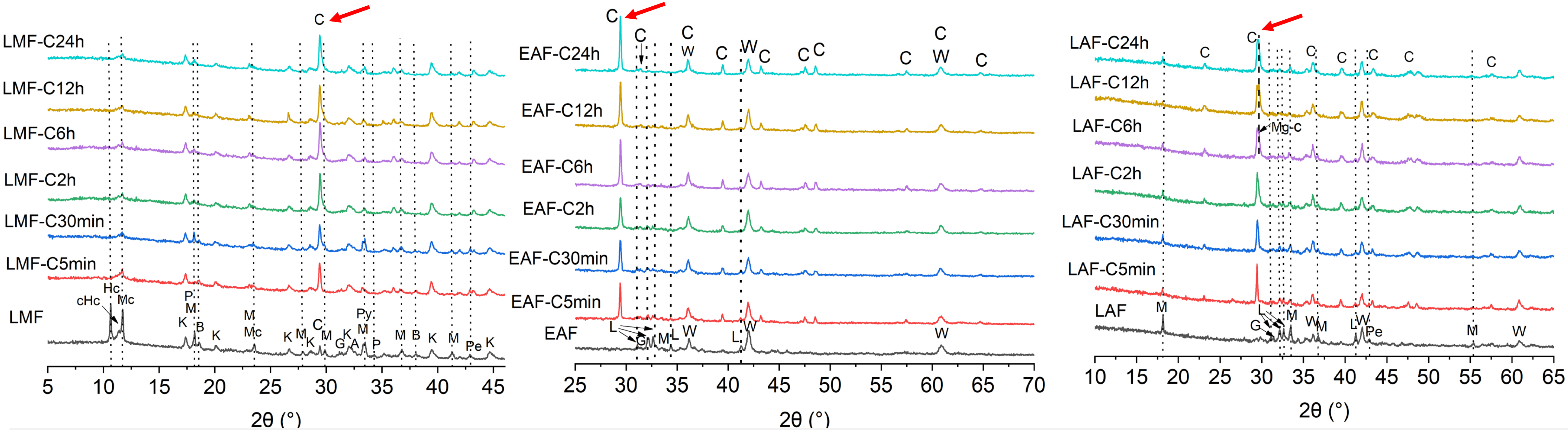




- Dissolution of Ca^{2+} and Mg^{2+} ions in water
- Carbonation: $\mathbf{Ca^{2+}}/Mg^{2+} + CO_3^{2-} \rightarrow \mathbf{CaCO_3}$ / $MgCO_3$

Progress and Current Status

Mechanism study: route 1, steel slag

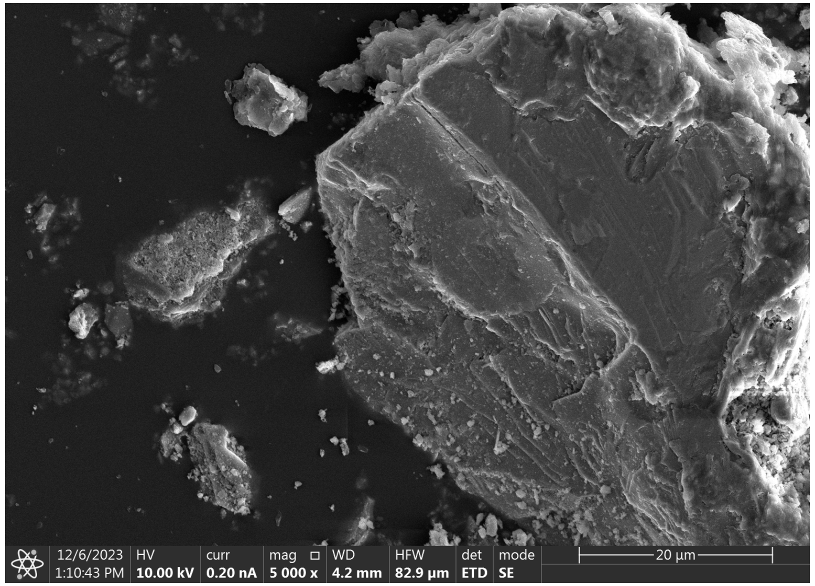


M: Mayenite, $Ca_{12}Al_{14}O_{33}$; **C**: Calcite, $CaCO_3$; **L: Larnite, Ca_2SiO_4**, **Am**: Amorphous; **Mc**: Calcium monocarboaluminate, $Ca_4Al_2(OH)_{12}(CO_3)(H_2O)_5$; **Hc**: Calcium hemi-carboaluminate, $Ca_4Al_2(OH)_{13}(CO_3)_{0.5}(H_2O)_4$; **cHc**: carbonatedcalcium hemi-carboaluminate, $Ca_4Al_2(OH)_{12.4}(CO_3)_{0.8}(H_2O)_4$

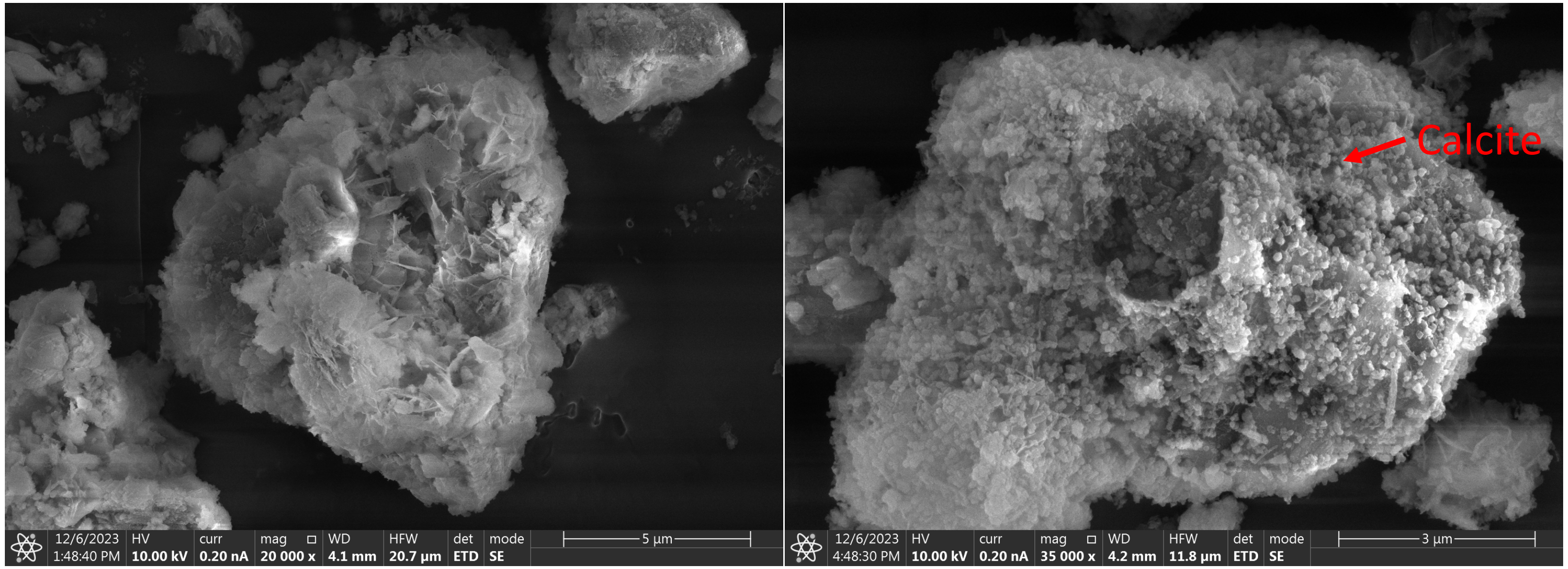
- The main carbonation **reactive minerals** in the slags are **larnite**, **mayenite**, and AFm phases (Mc, Hc, and cHc)
- The main carbonation **products** are **calcite** and **amorphous phases**, such as Al and Si gel

Progress and Current Status

Mechanism study: route 1, steel slag



Uncarbonated steel slag

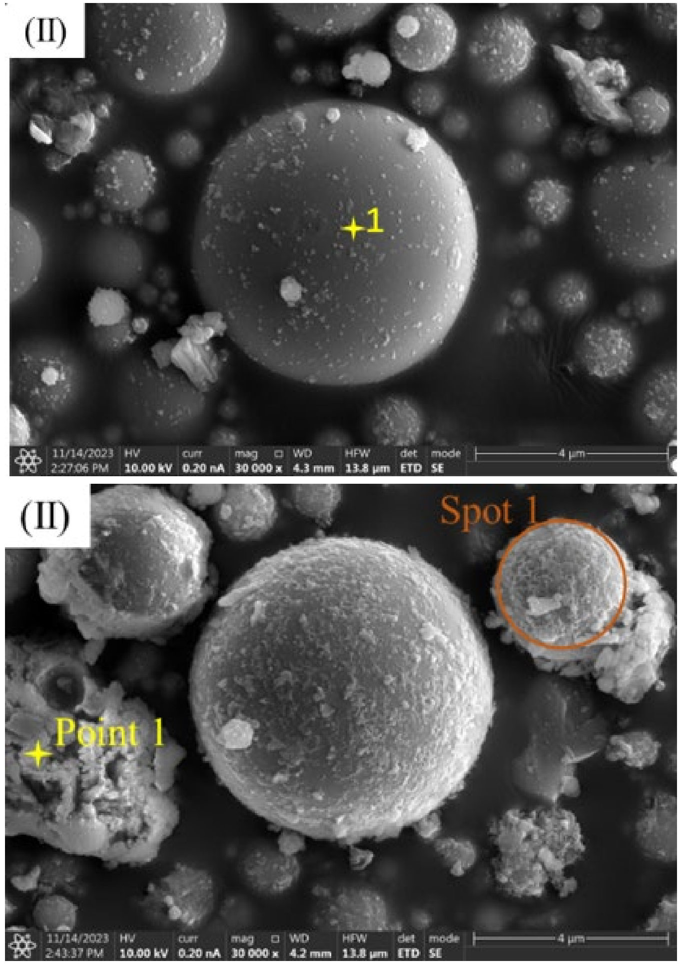


Carbonated steel slag

- The main carbonation **reactive minerals** in the slags are **larnite**, **mayenite**, and AFm phases (Mc, Hc, and cHc)
- The main carbonation **products** are **calcite** and **amorphous phases**, such as Al and Si gel

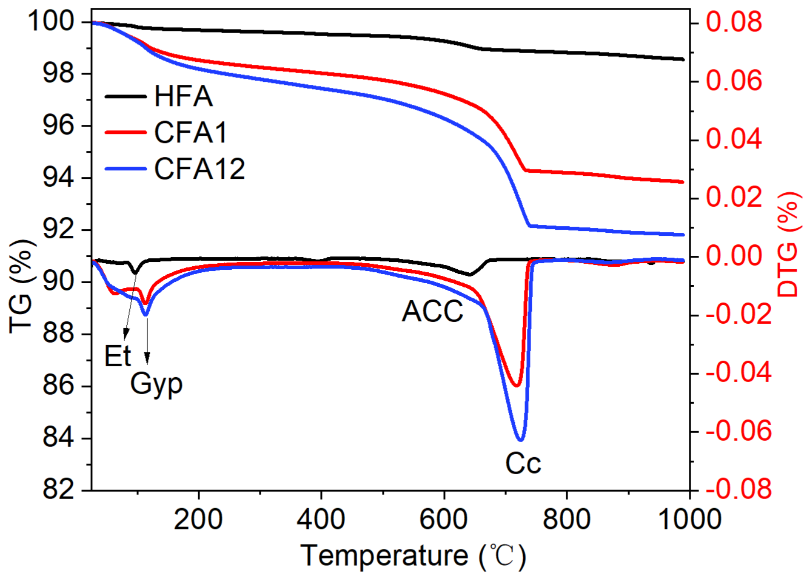
Progress and Current Status

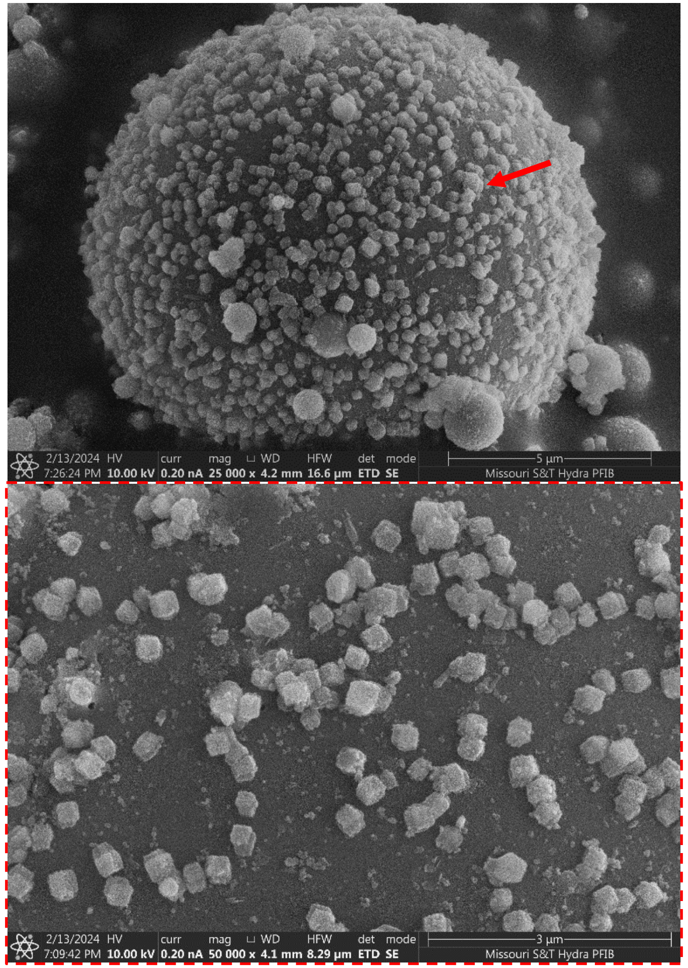
Mechanism study: route 1 and route 2, fly ash



Less water: route 2

Carbonation of fly ash

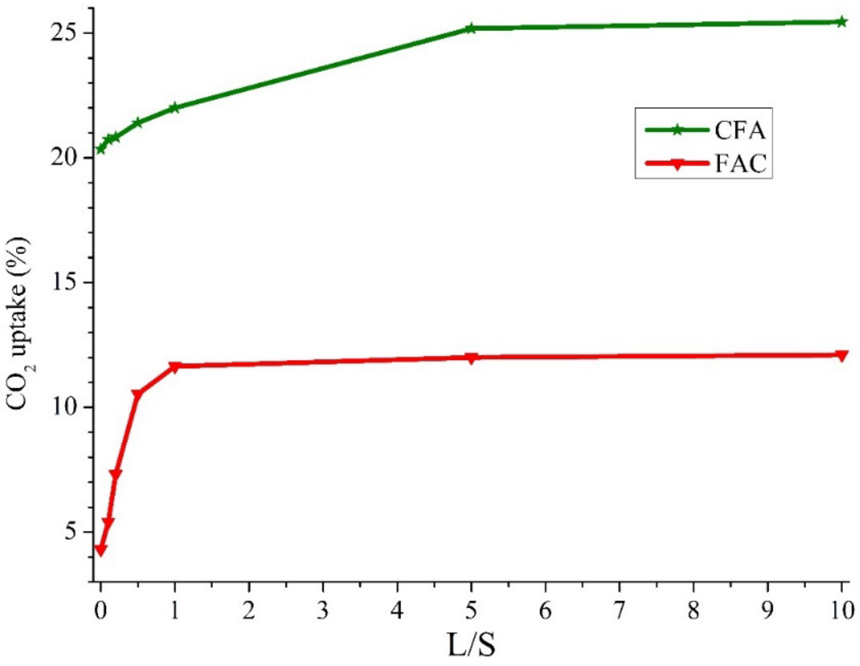




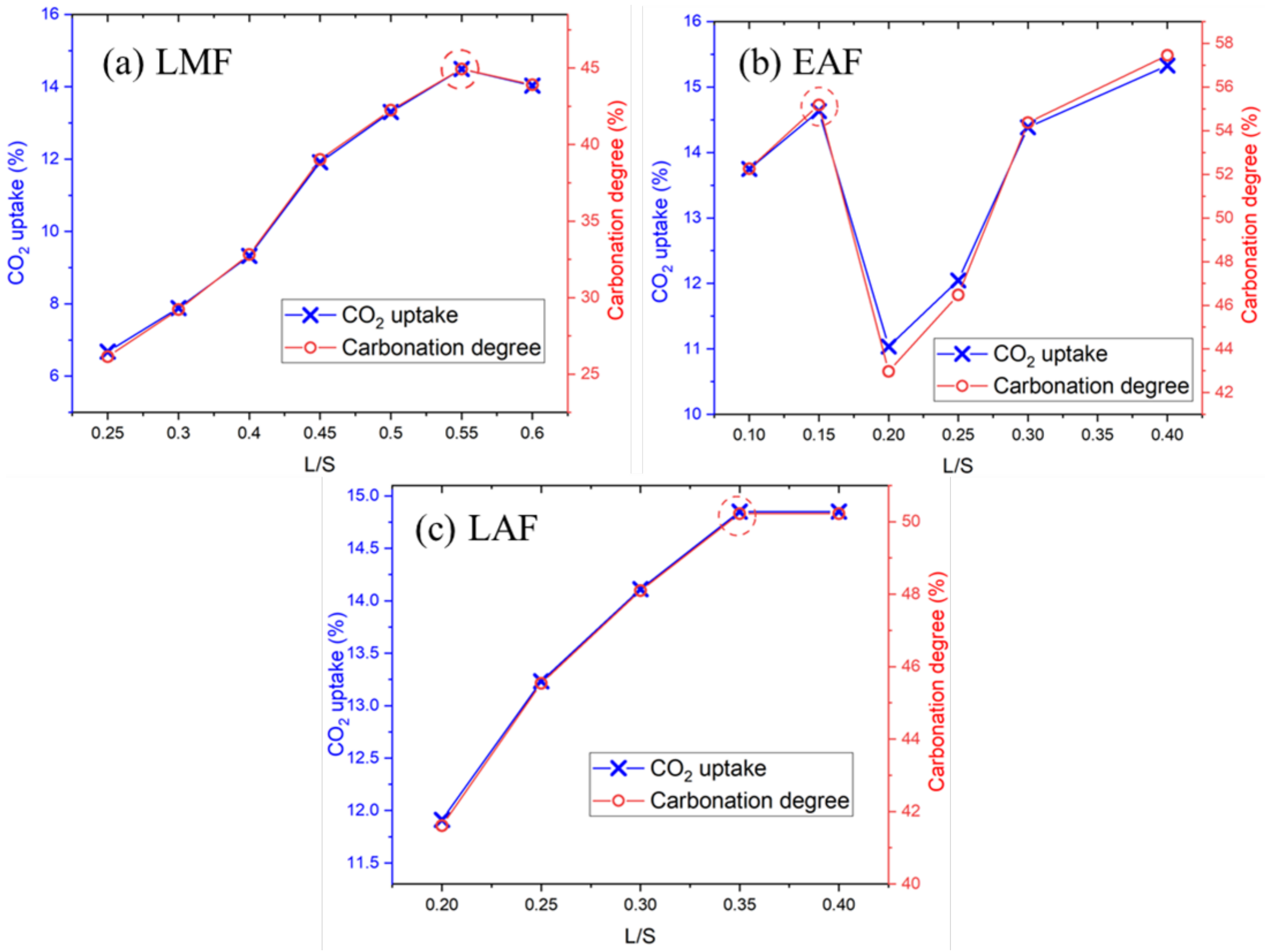
More water: route 1

Progress and Current Status

Process optimization: effects of L/S, T, P, C_{CO_2}, …



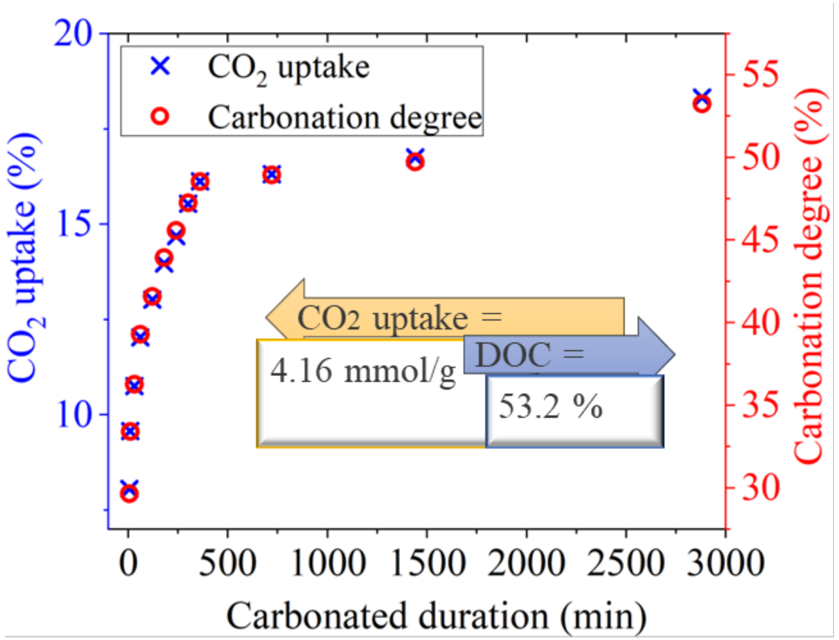
Fly ash (route 1 and route 2)



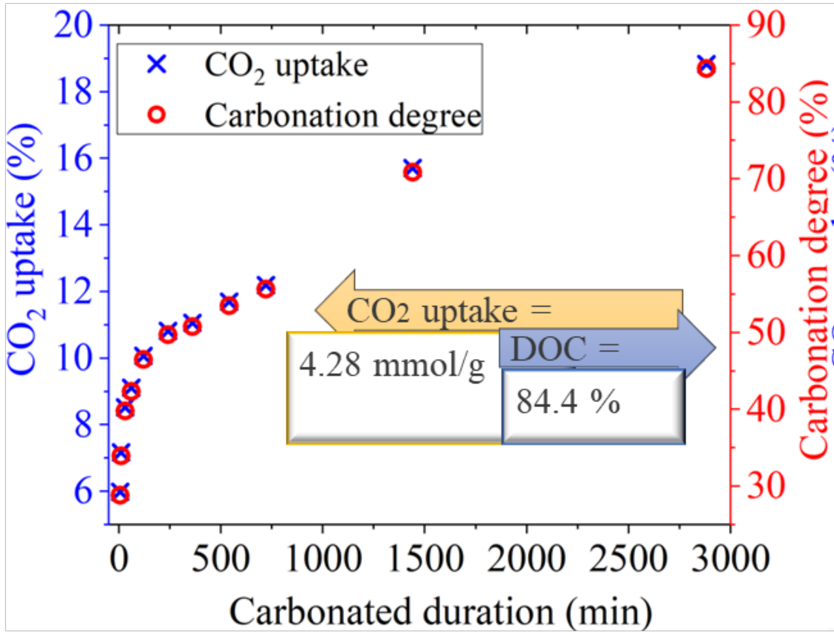
Steel slag (route 2)

Progress and Current Status

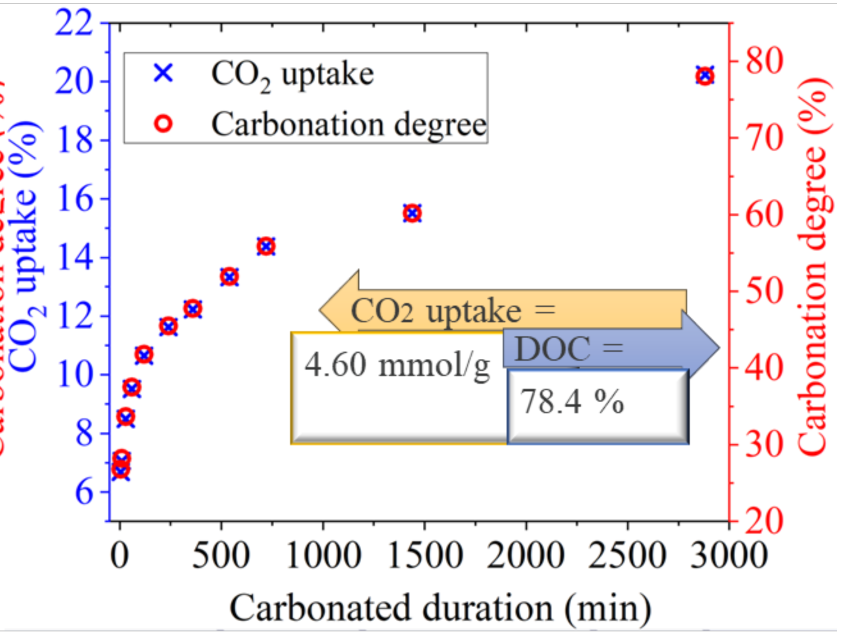
How much CO2 uptake?



LMF slag



EAF slag



Blended slag

- Steel slags: 15%-20%; >4 mmol/g
- Ashes: 5%-25%; up to 5.7 mmol/g
- MSWI FA? 10 mmol/g?

Progress and Current Status

Rate and kinetics of conversion: route 1

CaO/MgO-to-carbonate conversion rate

Sample	Type	Conversion rate @ 30 min	Time when conversion rate >65%	Maximum conversion rate
Steel slag	LMF	36.3%	/	**53.8%**
Steel slag	EAF	39.8%, ambient 65.5%, @60°C	24h	**84.4%**
Steel slag	LAF	33.6%	48h	**100%**
Coal fly ash	**FAC**	**70%**	**10 minutes**	81%
MSWI fly ash	**CFA-B8**	**69%**	**10 minutes**	75%
MSWI fly ash	**CFA-B7**	**79%**	**10 minutes**	82%
MSWI filter cake	CFA-B8	46%	/	60%

Similar total CO_2 uptake

Progress and Current Status

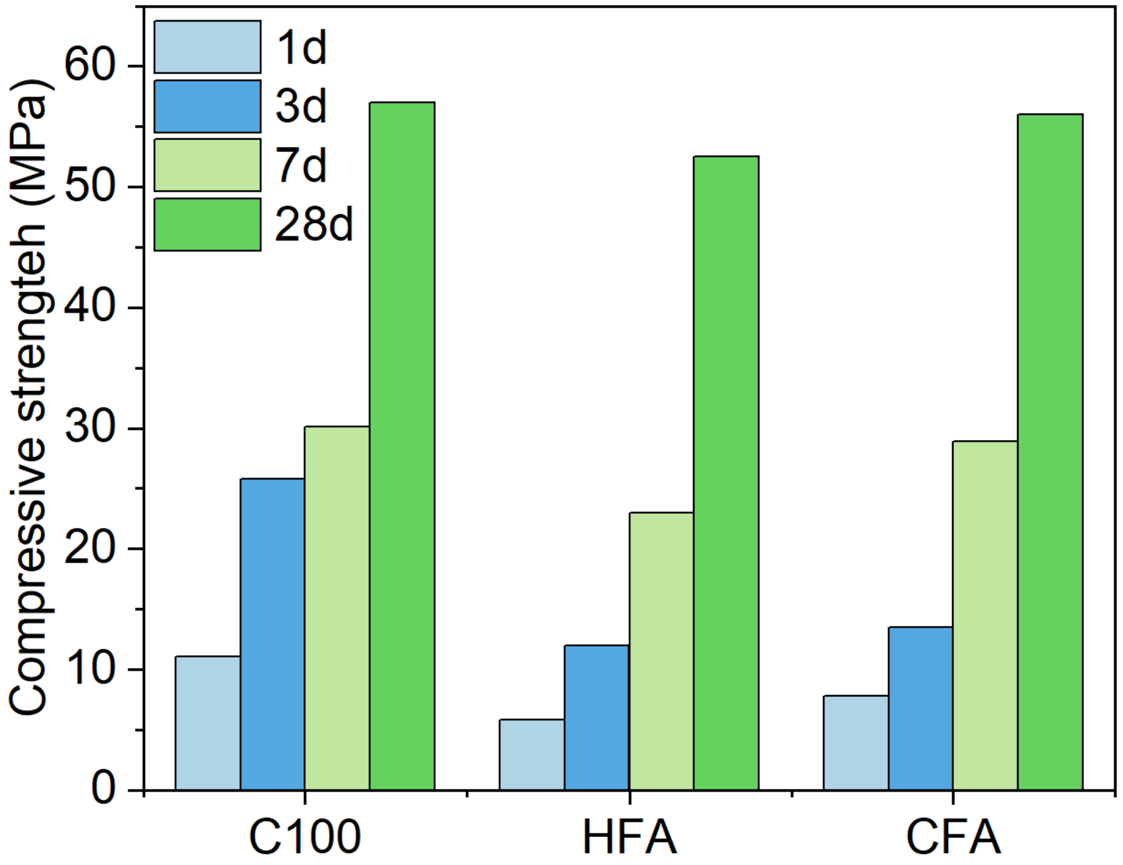
Rate and kinetics of conversion: route 2

CaO/MgO-to-carbonate conversion rate

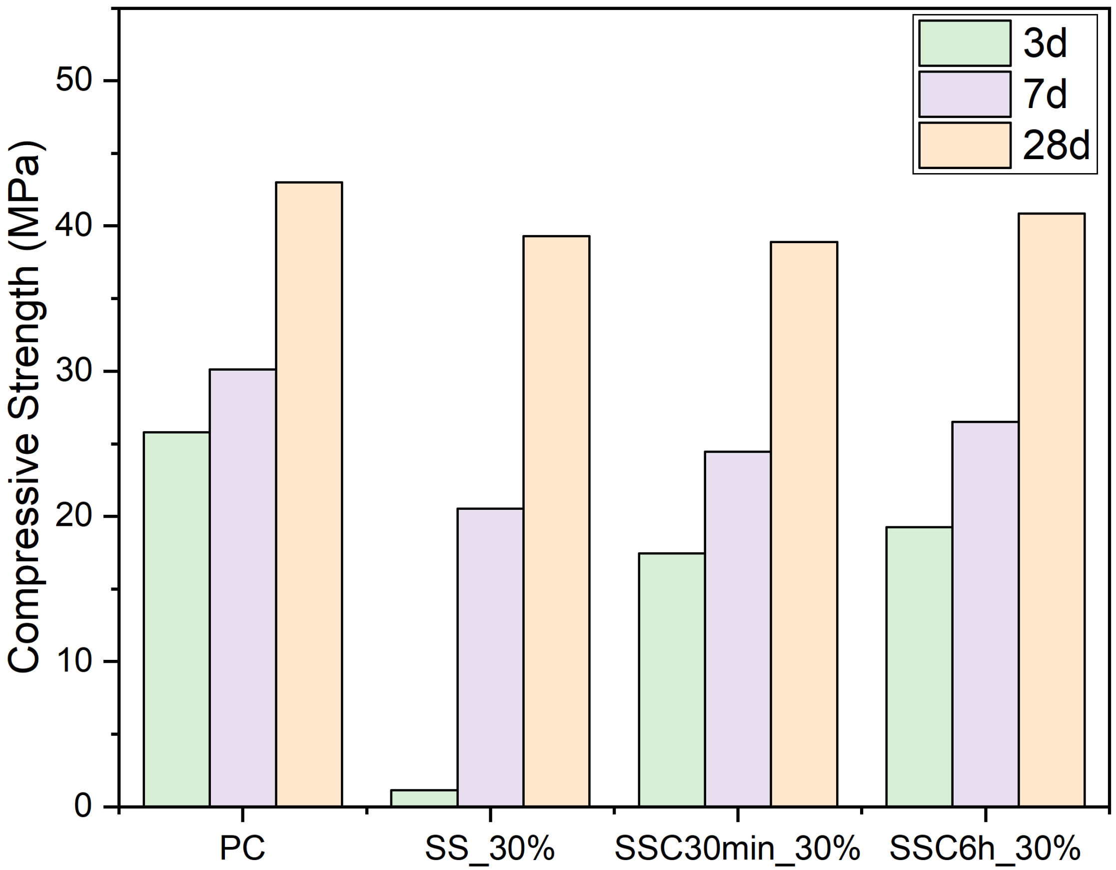
Sample	Type	Conversion rate @ 30 min	Conversion rate @ 120 min	Maximum conversion rate
Steel slag	LMF	32.3%	42.5%	44.9%
Steel slag	EAF	29.2%	41%	55.2%
Steel slag	LAF	20.9%	31%	53.1%

Progress and Current Status

nCAS-incorporated cement pastes



Fly ash, ideal composition



Steel slag, CC over-dosed

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Community Benefits
DEIA and workshop

- ❑ Hired one graduate student and one postdoctoral researcher from underrepresented groups
- ❑ Organized a high-school student workshop

7/26/2024, half-day workshop →
"Storing CO_2 in Infrastructure Materials to Combat Climate Change"

As part of the
2024 **National Summer Transportation Institute**
Co-sponsored by
USDOT
MoDOT
Missouri S&T
The National Museum of Transportation
Center for Infrastructure Engineering Studies
Center for Intelligent Infrastructure
Lab of Future Cements and Carbon-Negative Initiatives
…

Community Benefits

Justice40

- ❑ Prioritize processing solid wastes located in underserved communities
  - ➢ Sampling
  - ➢ Upscaling
  - ➢ Commercialization

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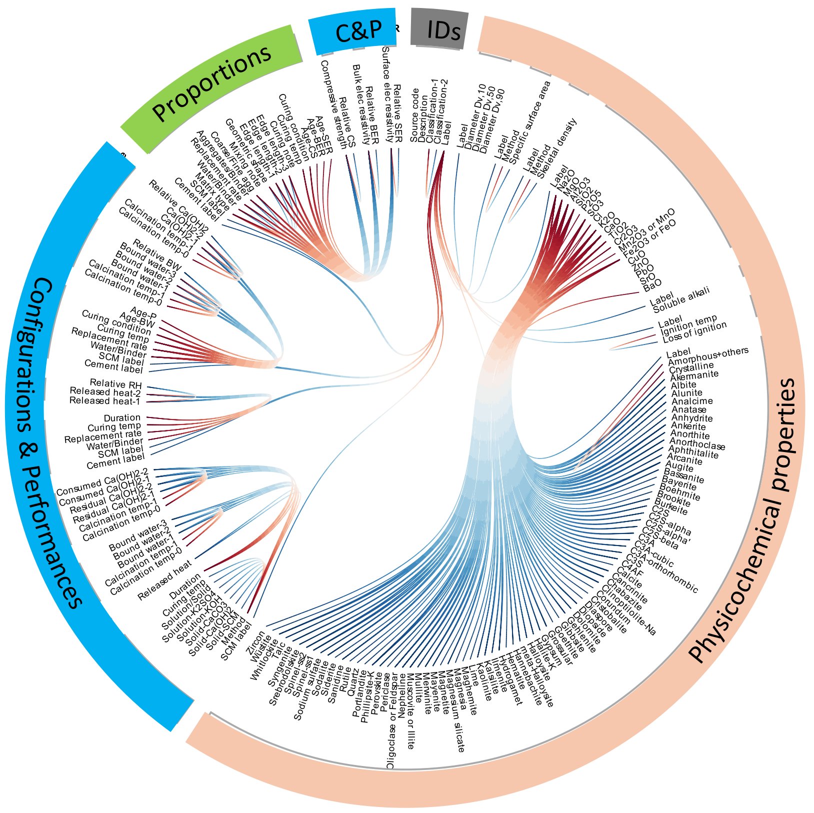
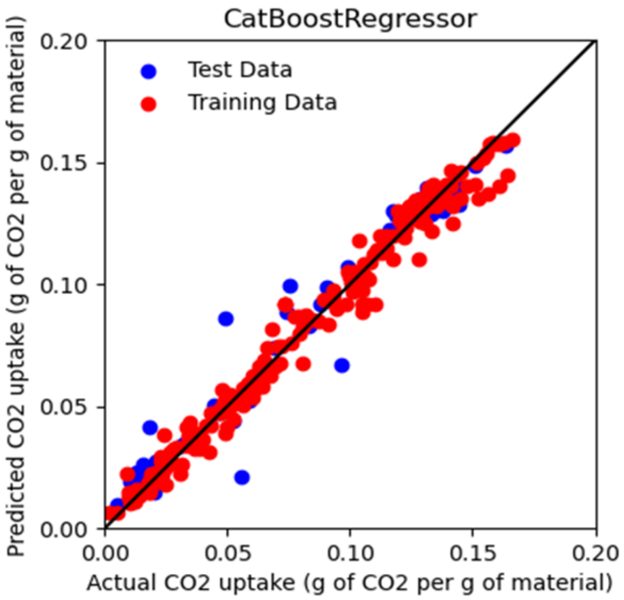
Lessons Learned

- Not all solid wastes are available for upcycling (willingness of owners)
- Some solid wastes may not be "reliable" feedstock (viability)
- Some solid wastes may not be available anymore (changes in practice)





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Plan for Future Development and Commercialization

- ➢ Meet technical milestones
- ➢ Scale up the reactors
- ➢ Pilot trial at MS&T
- ➢ Demo project with an innovation ecosystem
- ➢ Launching a startup
- ➢ Licensing
- ➢ Two business models
- ➢ …

The 0.2 m^3 reactor and 1 m^3 concrete batching plant at MS&T

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Summary

- 150 samples
- Carbonation protocols have been optimized
- Carbonation mechanisms have been studied
- >65% degree of carbonation conversion is feasible
- When used in cement paste to substitute cement, nCAS typically shows a filler effect in early age, and enables secondary reactions to boost late-age development
- Database and AI are under development

Open to more solid wastes, academic collaborators, and commercialization partners

Contact

Hongyan Ma

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