Concrete Innovations: Carbon Reduction Strategies

Eco-Efficient and Carbon-Negative Supplementary Cementitious Materials Derived from Solid Wastes

Hongyan Ma, Ph.D.
Francisco Benavides Scholar and Associate Professor of Civil (Materials) Engineering
Missouri University of Science and Technology
10-18-2023

FuCCI Laboratory of **Fu**ture **C**ements and **C**arbon-negative **I**nitiatives

Outline

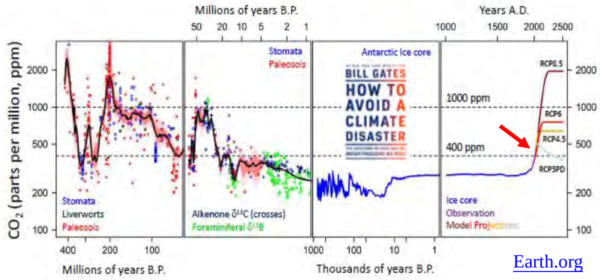
Eco-Efficient and Carbon-Negative
Supplementary Cementitious Materials (SCMs)
Derived from Solid Wastes

- **Introduction: Why?**
- **Eco-Efficient SCMs**
- **Carbon-Negative SCMs**
- **Concluding Remarks and Collaborations**

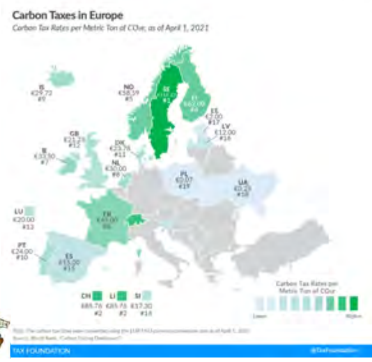
Why "Eco-Efficient"→"Carbon-Negative"?

Climate Change?

- Atmospheric CO2 concentration is the major driver of climate change (*paleoclimatology*).
- 422 ppm in 2023!
- Reduce emissions?
- Net-zero/carbon-negative?



Earth.org



Economic Benefits?

- EU: 18 countries are levying carbon tax, toped at $130 per metric ton CO2*e* (SE); which will increase since EU targets at reduce emissions to 40% of 2005 levels by 2030.
- Canada: $24/t CO2, and will rise to $130/t before 2030, as to reduce emission to 70% of 2005 levels.
- **US**: no carbon tax yet; but White House has set a target (in 2021) to reduce emission to 50% of 2005 levels by 2030. *Expecting carbon tax or credit?*
  Q45 - $130-180/t CO_2 (2022)

Be prepared for either reducing tax or earning credit?
See the market potential?

3

Why "SCMs"?

Decarbonization of cement/concrete

Need?

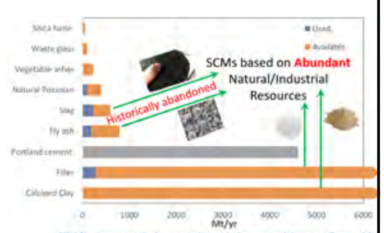
→ Annual production: 4.5 Gt cement; >30 Gt concrete
→ ~10% of anthropogenic CO_2 emission
→ Energy-intensive industry + Limited service life

Challenges

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

Possibilities

→ Increasing use of low-C, low-E **SCMs**
→ Improving **efficiency of cement** production/utilization
→ Developing sustainable **alternative cements**



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

Limitation of resources

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

[www.lc3.ch]

Why not other options?

4

Why "Solid Wastes"?

A World Without Wastes

5

Outline

Eco-Efficient and Carbon-Negative
Supplementary Cementitious Materials (SCMs)
Derived from Solid Wastes

- **Introduction: Why?**
- **Eco-Efficient SCMs**
- **Carbon-Negative SCMs**
- **Concluding Remarks and Collaborations**

6

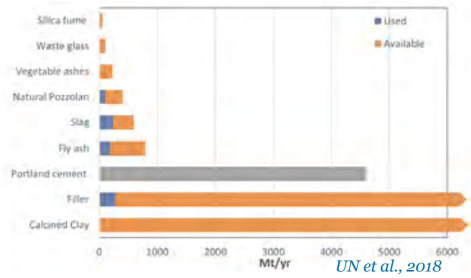
Eco-Efficient SCMs
What?

- × Class F fly ash
- × Class C fly ash
- × Slag cement/GGBFS
- × Silica fume
- × Metakaolin
- × ...

PCA

Unconventional SCMs that have been discarded in waste streams and underused, or *alternative SCMs*:

- √ **Reclaimed coal ashes** (FA/BA)
- √ **MSWI residues**
- √ Steel slag/air-cooled BFS
- √ Other slags
- √ Red mud
- √ Recycled concrete fines
- √ Selected mine tailings
- √ ...



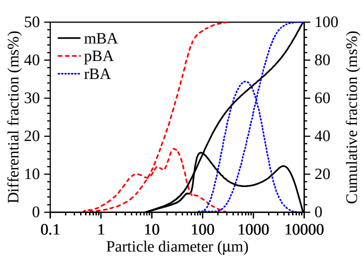
UN et al., 2018

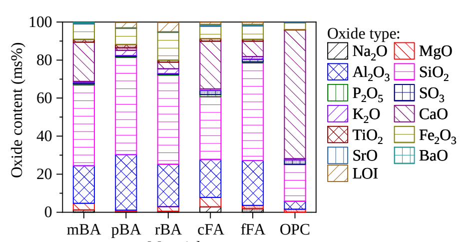
7

Eco-Efficient SCMs
BA/reclaimed coal ashes

mBA: from dry collection
pBA: from dewatering, mixed with FA
rBA: reclaimed from a pond

mBA pBA rBA



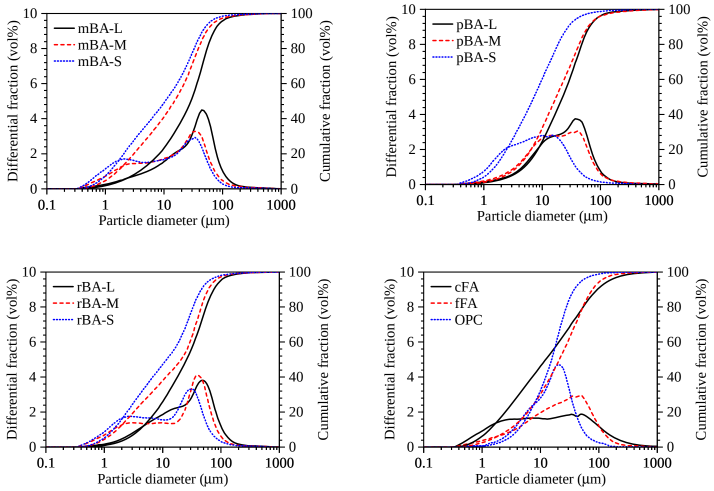


8

Eco-Efficient SCMs

BA/reclaimed coal ashes

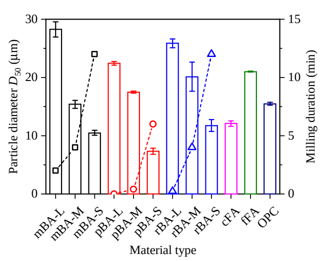
- ➢ Grinding to reduce particle size and increase fineness

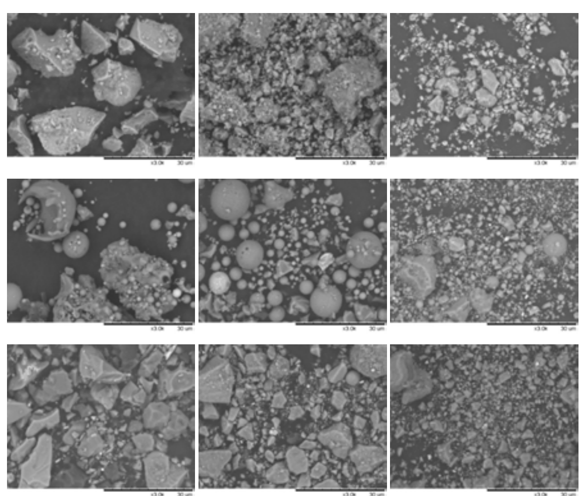


Eco-Efficient SCMs

BA/reclaimed coal ashes

- ➢ Grinding to reduce particle size and increase fineness

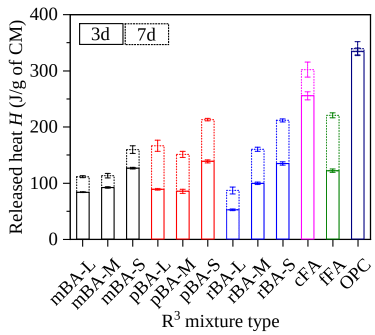


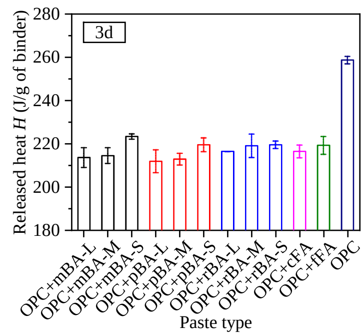


Eco-Efficient SCMs

BA/reclaimed coal ashes

- Reactivity, ASTM C1897, C1679

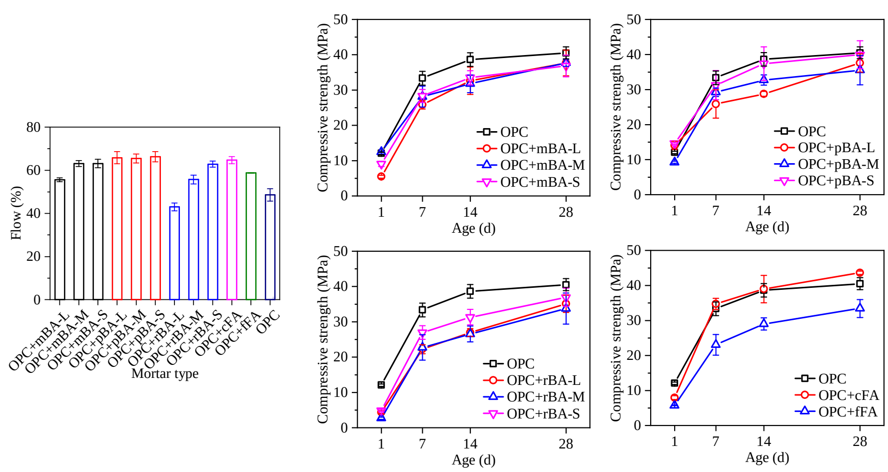




Eco-Efficient SCMs

BA/reclaimed coal ashes

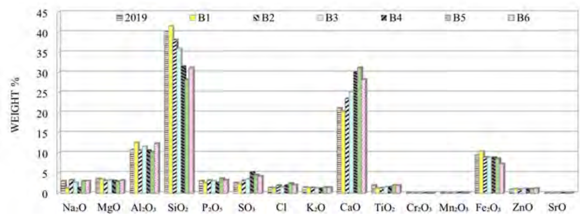
- Engineering performance

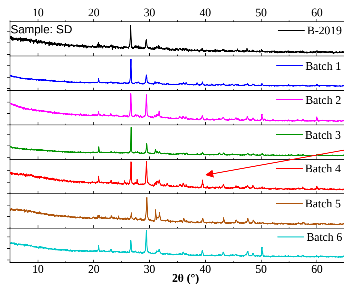


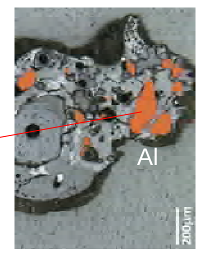
Eco-Efficient SCMs

MSWI bottom ash

➢ The most difficult to upcycle?





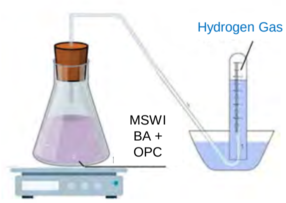


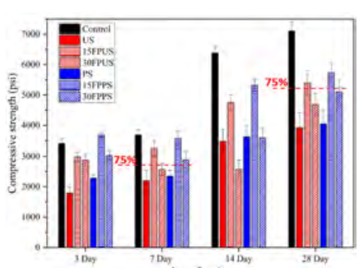
13

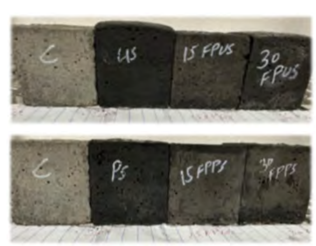
Eco-Efficient SCMs

MSWI bottom ash

➢ The most difficult to upcycle?





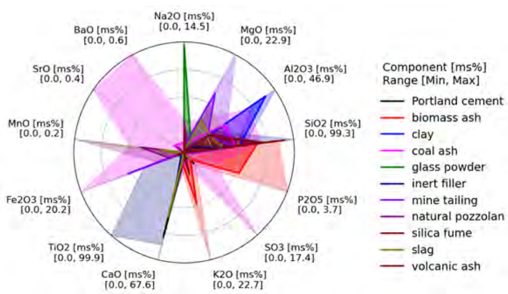


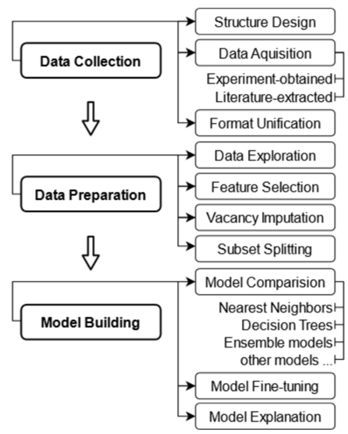
14

Eco-Efficient SCMs

Data Science/AI

- To address the compositional variability and enable multi-object optimization/design



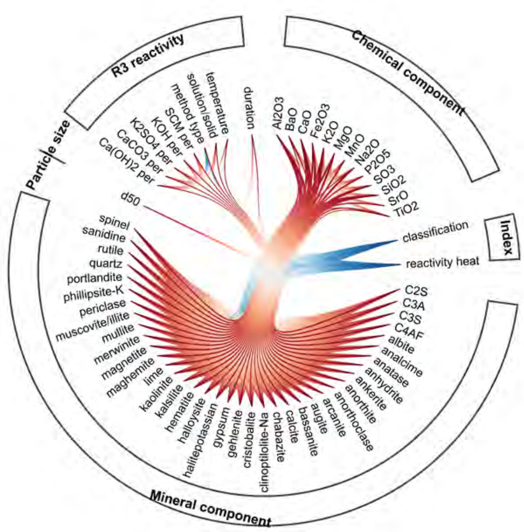


15

Eco-Efficient SCMs

Data Science/AI

- Database
  - **Features:**
    1) **Physical property:** particle size D_{50}
    2) **Chemical composition:** oxides like Al_2O_3
    3) **Mineralogical composition:** crystalline phases
    4) **Experimental configuration:** test conditions and duration
  - **Labels:**
    1) **Classification**
    2) **Cumulative reaction heat**

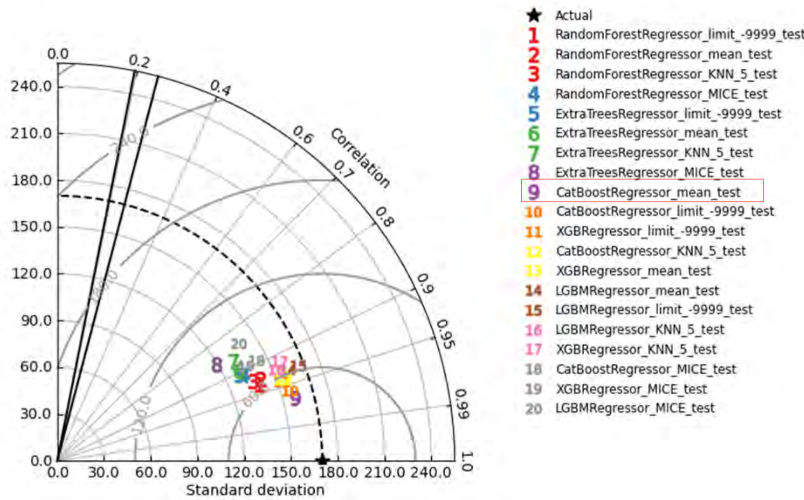


16

Eco-Efficient SCMs

Data Science/AI

➢ AI tools: **Tylor diagram** showing the performance of different AI tools



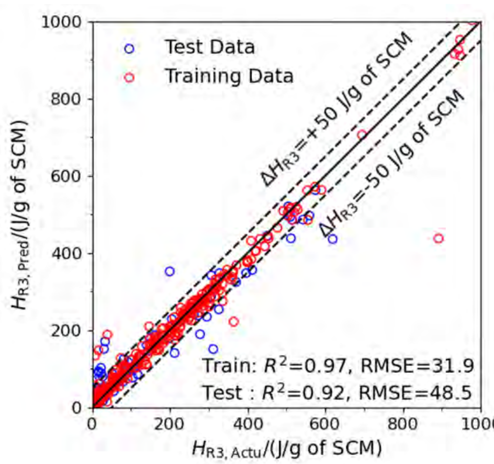
17

Eco-Efficient SCMs

Data Science/AI

➢ Performance prediction / process optimization

- **Procedures**
  1) **Algorithm comparison:** choose algorithms or models with best performances
  2) **Model construction:** ensemble model (CatBoost)
  3) **Model fine-tuning:** randomized search optimal values of hyperparameters
  4) **Model evaluation:** cross-validation and prediction scores



18

Eco-Efficient SCMs
Key Takeaways

- (Reclaimed) bottom ashes, if ground to a certain fineness, behave similarly to class C/F fly ashes in blended cement pastes;
- MSWI residues, if properly ground and pre-processed, can be used as alternative SCMs achieving >75% compressive strength (7- and 28-day) at no less than 20% substitution;
- Other solid wastes...
- AI is a great tool for performance prediction of solid waste-derived ASCMs, or optimization of processes upcycling solid wastes towards desired performance.

19

Outline

Eco-Efficient and Carbon-Negative
Supplementary Cementitious Materials (SCMs)
Derived from Solid Wastes

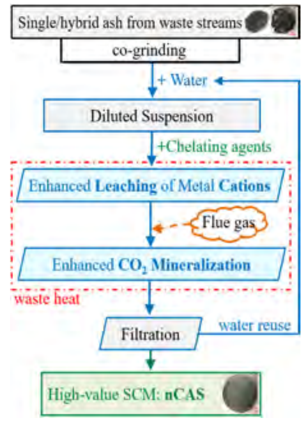
- **Introduction: Why?**
- **Eco-Efficient SCMs**
- **Carbon-Negative SCMs**
- **Concluding Remarks and Collaborations**

20

Carbon-Negative SCMs

What?

- Use CO2 (either captured CO2 or directly flue gases) to process ground **alkali aluminosilicate solid waste**, which produces SCMs named *nano-/micro-carbonates aluminosilicate* (**nCAS**).
- nCAS can substitute 50% or more clinker to produce blended cement or substitute cement in concrete, thus deeply decarbonize the cement/concrete industry.
- Does not compromise performance of cement/concrete.



Relevant Solid Wastes

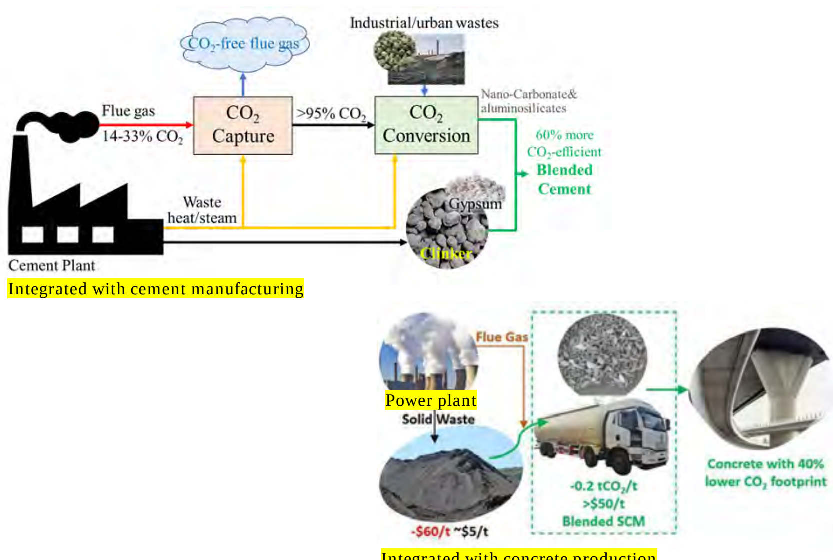
Alkali aluminosilicate wastes containing Ca, Mg, and leachable heavy metals (e.g., Pb, Zn, Cu, etc.):

- **Coal ashes** (including ponded and off-spec ashes)
- **MSWI** ashes
- Steel/copper/lead/nickel slags
- Concrete recycling dust
- ...

21

Carbon-Negative SCMs

Potential Deployment



22

Carbon-Negative SCMs
Value Proposition

To waste generators:

- Reduce carbon emissions (e.g., for coal-/natural gas-fired power plants)
- Turn negative-/low-value wastes/byproducts into high-value (>$50/t) commodity SCMs
  - Off-spec coal ash, > -$20/t;
  - MSWI ashes, -$20/t ~ -$100/t;
  - Steel slag, $0.05~$5/t.
- Tie the waste upcycling to a huge market – construction – which faces with a severe shortage of quality SCMs.

To cement and concrete makers:

- Cheaper raw materials and safer SCM supply chain
- Lower carbon footprint

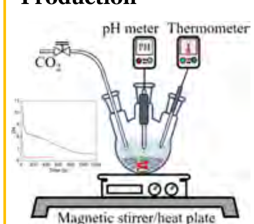
Contribution to the US and the world

- If fully deployed to address the demand of Biden's new infrastructure plan, it will form a $3.5-4.2 billion/year market with a potential CO2 reduction of more than 50Mt/year only in the US;
- The projected global CO2 reduction is >2 Gt/year.

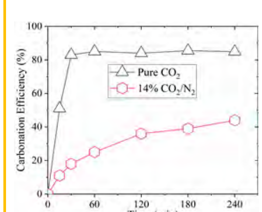
23

Carbon-Negative SCMs
Technology

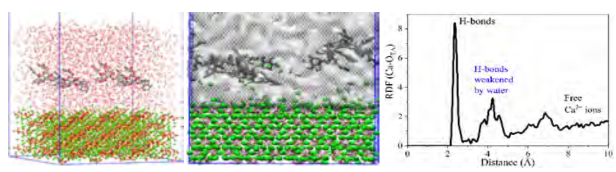
Production



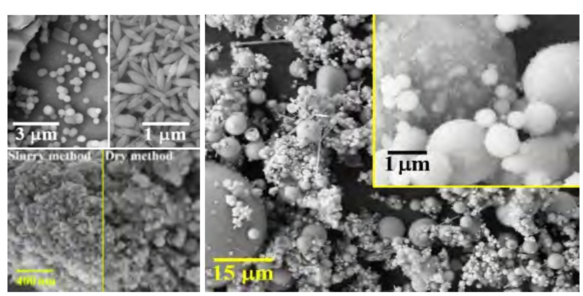
Slurry method



Carbonation efficiency



Enhanced leaching of Ca^{2+} from calcium aluminosilicate networks

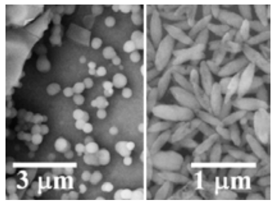


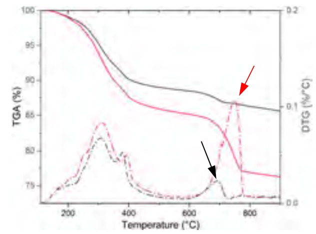
Carbonate nano-/submicron-particles formed following carbonation

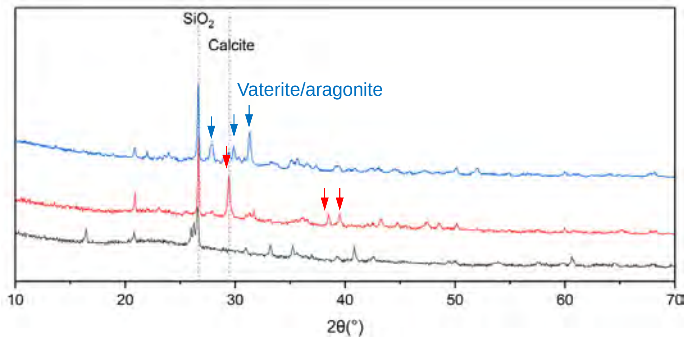
24

Carbon-Negative SCMs

Technology: Polymorphs



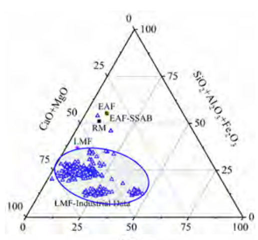


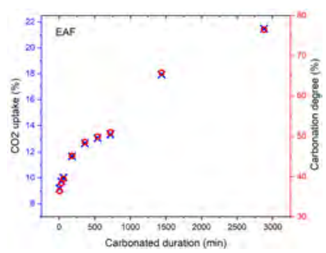


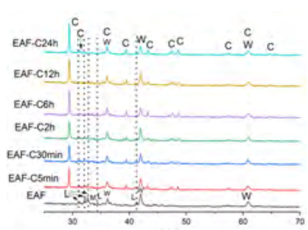
25

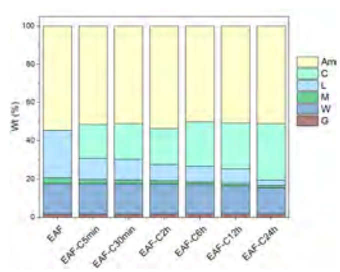
Carbon-Negative SCMs

Technology: Showcase, steel slag/EAF







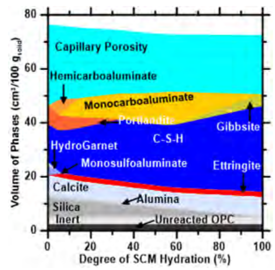


26

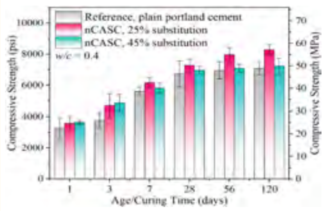
Carbon-Negative SCMs

Technology: Performance

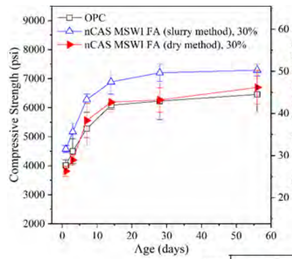
Interaction



Effect on compressive strength

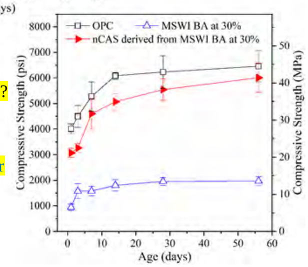


Low-quality feedstock?



MSWI FA:
Heavy metals?
High free-lime?
Other detrimental substances?

MSWI BA:
Low reactivity?
Metallic aluminum?
Other detrimental substances?
Mechanism unclear



27

Carbon-Negative SCMs

Key Takeaways

- Alkali aluminosilicate solid wastes can capture CO2 to produce carbon-negative SCMs (carbonate “fillers” + glassy aluminosilicate);
- Can potentially replace >50% of cement without performance compromise;
- Composition needs to be optimized toward the best performance/maximal substitution;
- AI will be helpful.

28

Outline

Eco-Efficient and Carbon-Negative
Supplementary Cementitious Materials (SCMs)
Derived from Solid Wastes

- **Introduction: Why?**
- **Eco-Efficient SCMs**
- **Carbon-Negative SCMs**
- **Concluding Remarks and Collaborations**

29

Concluding Remarks and Collaborations

- *Eco-efficient SCMs*
- *Carbon-negative SCMs*

Ongoing Work and Needs

- Addressing the compositional variation;
- Broadly characterizing the relevant solid wastes; (needing a lot of samples)
- Refining and optimizing processing conditions;
- Developing alternative carbonation pathways to mitigate techno-economic risks;

- Doing techno-economic analysis and life-cycle analysis;
- Seeking funding and industrial partners to scale up the production facility;
- Industrial insights?
- ...

30

Missouri University of Science and Technology

Thank You

FuCCI

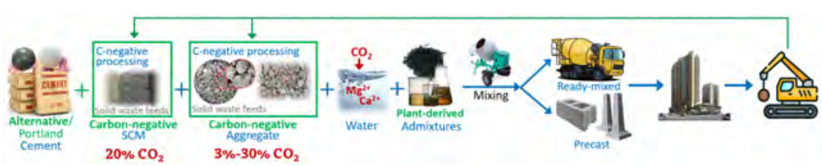
"Cement" the Future

Open for collaborations!

Contact:
Dr. Hongyan Ma
Email: mahon@mst.edu
Phone: 573-612-9568

31

An Innovation Ecosystem



Industrial Partners join us?

Email: mahon@mst.edu
Phone: 573-612-9568

32