

# The role of slags and other by-products within circular economy in the steel industry

- ▶ Sequestration potential of EAF C and ladle slags
- ▶ Mojca Lončnar, PhD

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*ESTEP Focus  
Group Circular  
Economy &  
FEhS-Institute*



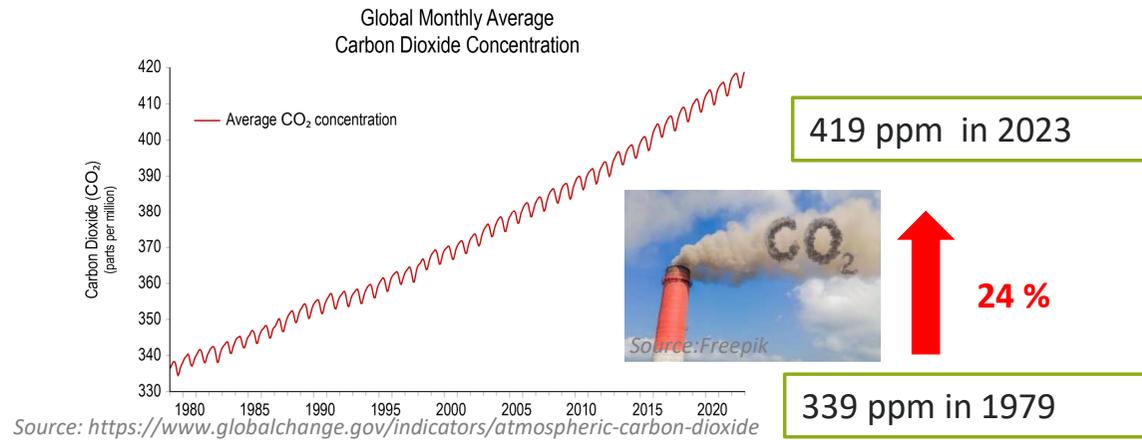
## Climate Change: Atmospheric Carbon Dioxide

Carbon Dioxide in the atmosphere is increasing.

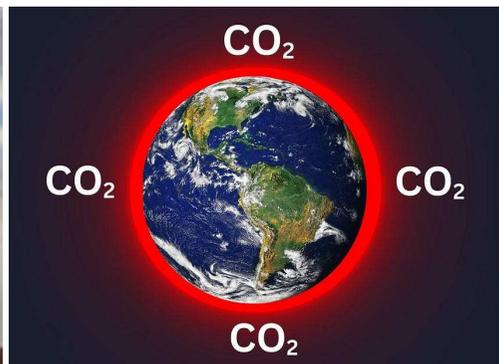
The concentration of CO<sub>2</sub> in the atmosphere has increased by more than 20 % over the past 45 years.

Human activities:

- Combustion of fossil fuels
- Deforestation



Source: Peter Gudella/Shutterstock.com



Source: <https://medium.com/>



Source: Andrii Tsynhariuk / Alamy Stock Photo

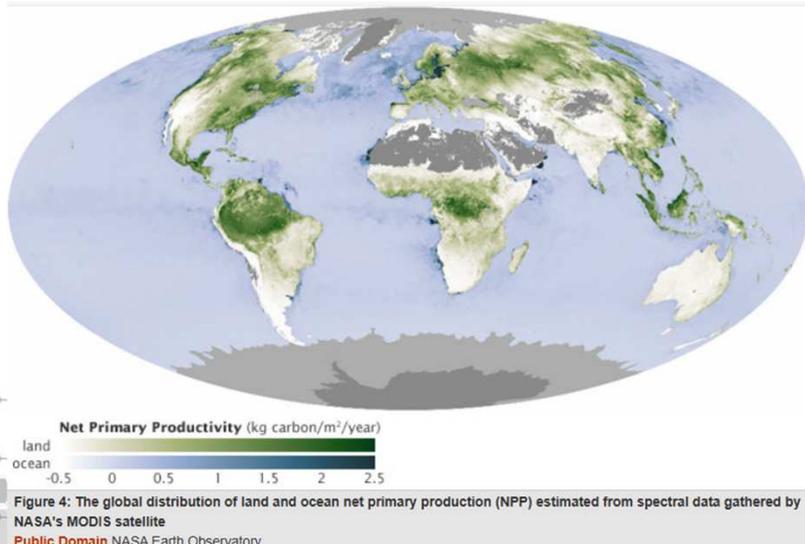
## Carbon dioxide (CO<sub>2</sub>) removal and storage

### Natural processes:

- Photosynthesis by plants

GPP from land, at 157 petagrams of carbon per year

- Carbon absorption by the oceans
- Geological processes

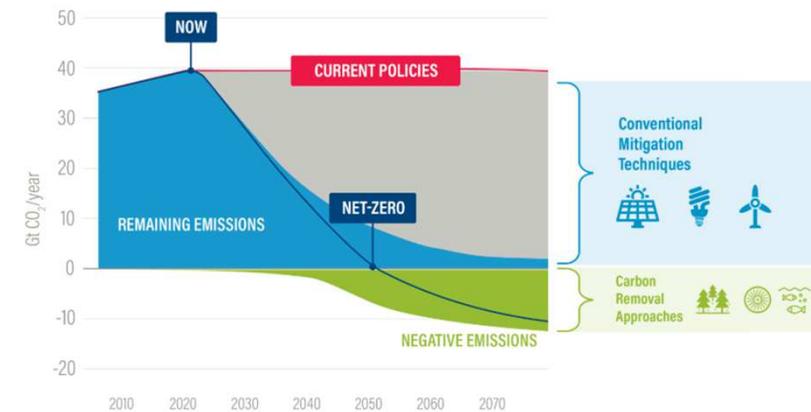


Source: <https://www.nature.com>; Terrestrial Primary Production: Fuel for Life

### Artificial techniques:

- Afforestation and reforestation
- Soil carbon sequestration
- Ocean fertilization
- Biomass Carbon Removal and Storage
- Direct Air Capture (DAC)
- Carbon mineralization

Staying below 1.5 Degrees Celsius of Global Temperature Rise

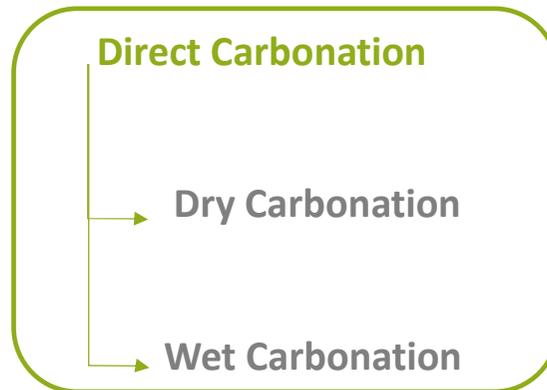
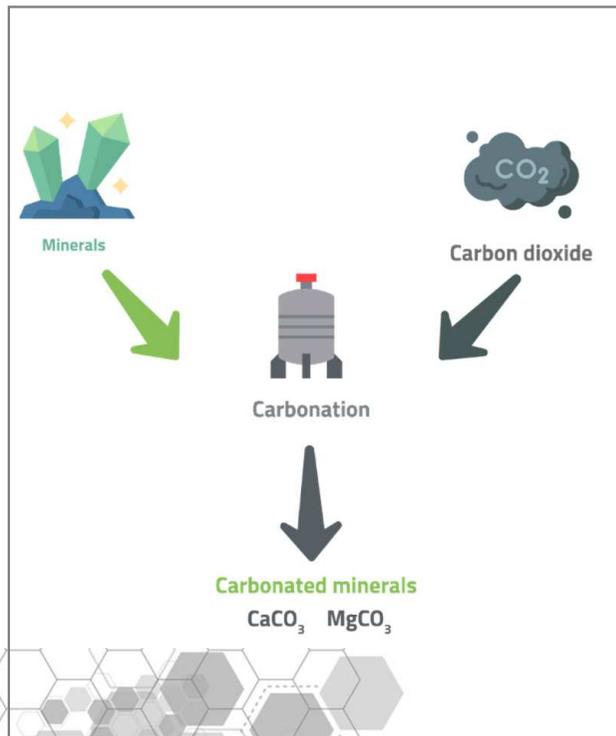


Notes: Abbreviation: GtCO<sub>2</sub>/yr = billions of metric tons of carbon dioxide per year. Source: Based on IPCC (2018) and CAT (2021).  
Source: <https://wri-indonesia.org/en/insights/6-ways-remove-carbon-pollution-sky>

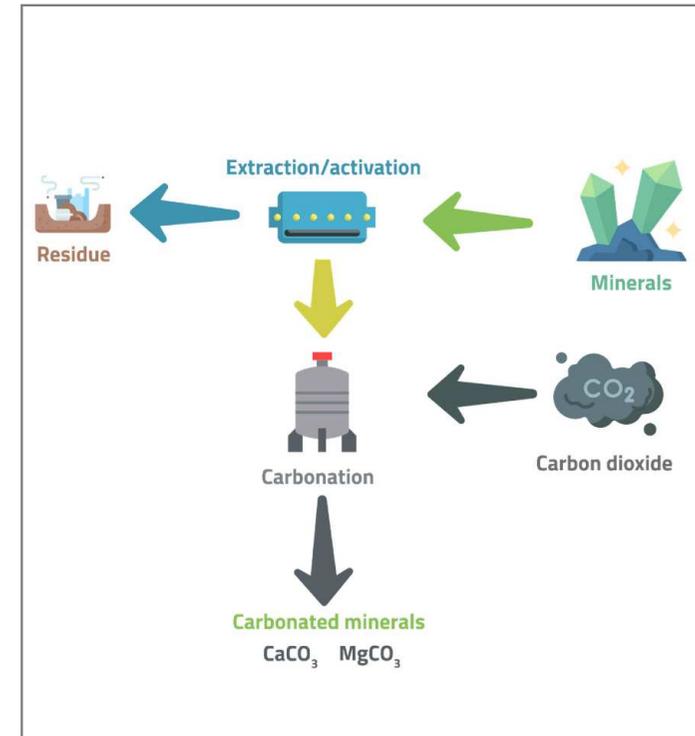
## Carbon mineralization

It involves the reaction of CO<sub>2</sub> with alkaline materials containing calcium (Ca) and magnesium (Mg)-rich (hydr)oxides and silicates, leading to the formation of solid carbonate products that are permanently stored.

### Principles of Direct Carbonation



### Principles of Indirect Carbonation

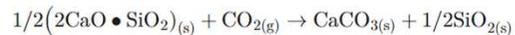
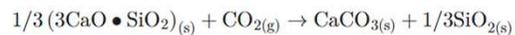
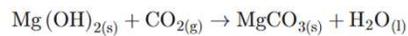
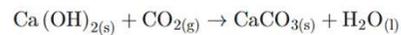
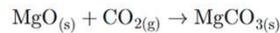
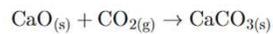
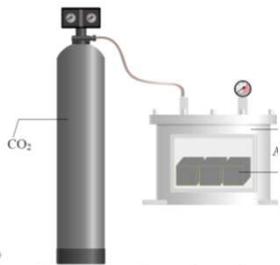


## Steel slags are among the most suitable candidates for Carbon Mineralization (CO<sub>2</sub> mineral sequestration)

- Wide availability (approx. 17.2 Mt of steel furnace slag were produced in Europe in 2022)
- Composition (Ca, Si, Fe, Al and Mg content) and mineralogy (silicate minerals, aluminosilicate minerals, f-CaO, f-MgO).

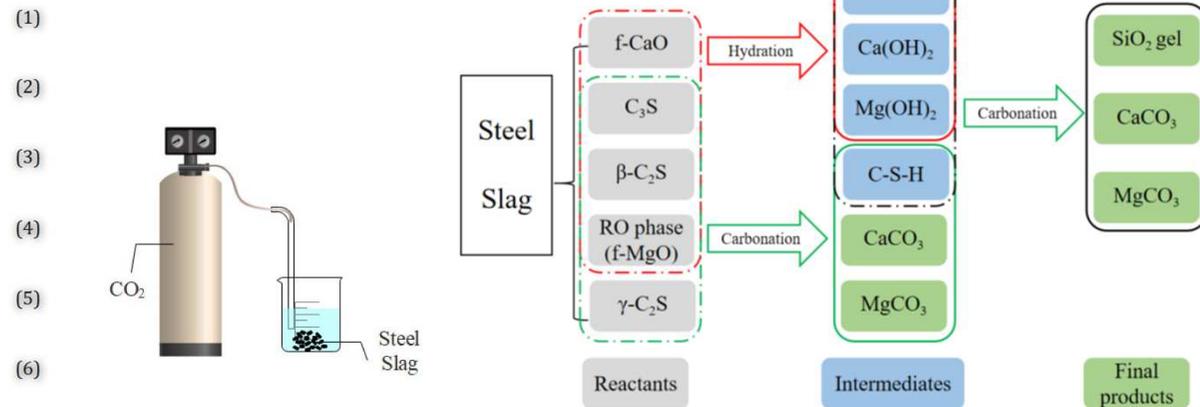
### Direct dry carbonation mimics natural weathering

- certain minerals (f-CaO, f-MgO, Ca(OH)<sub>2</sub>) ect) directly react with CO<sub>2</sub>.



### Direct wet carbonation is a complex three-phase reaction process

- hydration of f-CaO, f-MgO, β-C<sub>2</sub>S, C<sub>3</sub>S)
- those phases further react with CO<sub>2</sub> to produce CaCO<sub>3</sub>, MgCO<sub>3</sub> and silica-rich C-S-H gel
- on the other hand, CO<sub>2</sub> dissolves in water, forming H<sub>2</sub>CO<sub>3</sub>, which reacts with C<sub>3</sub>S and β-C<sub>2</sub>S



## Sequestration Potential of Electric Arc Furnace carbon (EAF C) Slags and Ladle Slags

- Tested material: steel slags from SIJ Group in Slovenia

The SIJ Group is a vertically integrated organization, consisting of five divisions and 35 companies worldwide

### SIJ Acroni, Slovenia



Stainless steel  
production plant

Location: Jesenice, Slovenia

Select products:

- stainless plates **SINOXX**<sup>\*\*\*</sup>
- special steel **SIDUR**<sup>\*\*\*</sup> **SIMAXX**<sup>\*\*\*</sup> **SIMOLD**<sup>\*\*\*</sup>
- electrical steel **SIWATT**<sup>\*\*\*</sup>
- structural plates **SIGUAL**<sup>\*\*\*</sup>



### SIJ Metal Ravne, Slovenia



Tool steel and  
special steel  
production plant

Location: Ravne na Koroškem, Slovenia

Select products:

- plastic moulding steel **SIMOLD**<sup>\*\*\*</sup>
- cold work tool steel **SIHARD**<sup>\*\*\*</sup>
- hot work tool steel **SITHERM**<sup>\*\*\*</sup>
- stainless steel **SINOXX**<sup>\*\*\*</sup>
- alloyed construction steel **SIGUAL**<sup>\*\*\*</sup>

The EAF technology uses electricity and oxygen instead of coal and natural gas, resulting in a 71 % reduction in CO2 emissions.

## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

- Aim of the Study: to evaluate sequestration potential of various types of steel slags

### — SIJ Acroni, Slovenia —



The chemical composition of slag samples in wt. %

Sample ID	LOI 950°C	CaO	SiO2	Fe2O3	MgO	MnO	Cr2O3
EAF C slag aggregate <sup>#</sup>	0.1	30	8	32	10	5	2
AOD-1*	/	52	24,9	2,4	11,1	0,17	0,29
AOD-2*	/	48,6	27,7	1,5	12	0,29	0,33
AOD-3*	/	49,5	25,7	1,8	11,2	0,23	0,31

<sup>#</sup> Characterized within GEORIS project

\*XRF results

\*AOD = Argon Oxygen Decarburization, AOD-1 = AOD refining slag, AOD-2 = AOD reduction slag; AOD-3 = mix AOD (refining and reduction) slag

#### Mineral composition

EAF C slag aggregate*	AOD-1	AOD-2	AOD-3
β-C2S belite	merwinite	merwinite	merwinite
ferrite	γ-C2S (Ca-olivine)	γ-C2S (Ca-olivine)	γ-C2S (Ca-olivine)
wuestite	β -C2S (belite)	β -C2S (belite)	β -C2S (belite)
magnetite	Na-C3A (Ca3Al2O6 ort)	Na-C3A (Ca3Al2O6 o	Na-C3A (Ca3Al2O6 ort)
periclase	Periclase	Periclase	Periclase
mayenite			
chromite			

### — SIJ Metal Ravne, Slovenia —



Wet chemistry results according to EN 196-2

Sample ID	950°C	CaO	SiO2	Fe2O3	MgO	MnO	Cr2O3
EAF C slag	5,7	21,6	15,9	20,8	10,2	>1.3*	>1.5*
ladle slag	0,0	52,8	17,2	1,03	7,9	0,1	0,13

\*ICP-MS analytical result could not be provided due to unusually high levels of interference from other elements.

#### Mineral composition

EAF C slag	ladle slag
brownmillerite	belite
magnetite	mayenite
gehlenite	dolomite
calcite	periclase
periclase	gehlenite
quartz	ferrite
wuestite	
belite	
alite	



\*AOD = Argon Oxygen Decarburization, AOD-1 = AOD refining slag, AOD-2 = AOD reduction slag; AOD-3 = mix AOD (refining and reduction) slag

## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

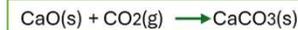
### Methodology for Evaluating the CO<sub>2</sub> Sequestration Capacity of Steel Slag (modified method proposed by Tominc and Ducman, 2023)

- **Particle size:** Below 125 μm.
- **Controlled conditions:** Chamber set at 40 ± 0.1°C, relative humidity (RH) of 80 ± 0.1%, and 20 ± 0.1 vol% CO<sub>2</sub>.
- **Carbonation monitoring:** Samples were initially weighed, and their weight was measured again after 1, 2, 3, and 5 days in the chamber.
- **Completion of carbonation:** When the weight difference between measurements reached 0.0 g, the samples were considered fully carbonated.
- **CO<sub>2</sub> content determination:** The CO<sub>2</sub> content (in wt-%) was assessed using thermogravimetric analysis (TGA) and calcimetry.
- **Sequestration capacity:** Based on calcimetric calculations, the sequestration capacity of the steel slags was determined.

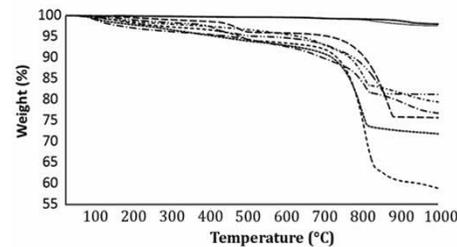
#### Steel slag



- sampling
- grinding, sieving
- accelerated carbonation



Characterization  
(calcimeter, TGA)



Determination of  
carbon  
sequestration  
potential

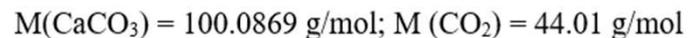
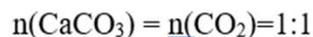
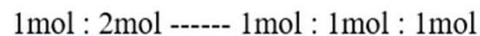
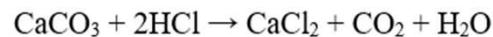


## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

**METHOD: The calculated CO<sub>2</sub> uptake was determined through calcimetric and TGA calculations**

### Calcimetry:

- A pressure calcimeter (OFITE Recording Calcimeter with DAQ, OFI Testing Equipment Inc., Houston, TX, USA) was used.
- **The carbonate content was determined by measuring the pressure of the released CO<sub>2</sub>, based on the reaction between the carbonate and acid, following ASTM D 4373.**



- Based on the calcimetric calculations, the sequestration capacity of different types of steel slags was determined.

### Thermogravimetric analysis (TGA):

- TGA was conducted using a TGA Q5000IR thermal analyzer (TA Instruments, New Castle, Delaware, USA), with a temperature range of 25 to 1000 °C at a heating rate of 10 K min<sup>-1</sup>.
- To prevent oxidation during the measurement, the sample chamber was filled with nitrogen (N<sub>2</sub>) at a flow rate of 25 mL min<sup>-1</sup>.
- **The CO<sub>2</sub> content (in wt%) was determined by the weight loss within the temperature range of the carbonate mineral's decomposition, based on dry mass at 105 °C.**
  - ✓ A weight loss below 150 °C was attributed to the evaporation of water in the slag.
  - ✓ The weight loss in the temperature range of ~420-800 °C was due to the decomposition of CaCO<sub>3</sub> into CaO and CO<sub>2</sub>.

## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

### RESULTS & DISCUSSION

Company	Sample ID	fresh / carbonated	TGA (weight losses-%)		TGA calculations			Calcimeter	Calcimetric calculations		CO <sub>2</sub> sequestration capacity (gCO <sub>2</sub> /kg <sub>slag</sub> )
			% H <sub>2</sub> O	% CO <sub>2</sub>	% dry matter	%CO <sub>2</sub> /dry matter	CO <sub>2</sub> uptake	% CaCO <sub>3</sub>	% CO <sub>2</sub>	CO <sub>2</sub> uptake	
SIJ ACRONI	EAF C slag aggregate	fresh	0,9	3,9	99,1	4,0	/	9,1	4,0	/	/
		carbonated	0,7	5,4	99,3	5,5	1,6	12,6	5,5	1,6	58,8
SIJ MetalRavne	EAF C slag	fresh	0,9	0,6	99,1	0,6	/	3,7	1,6	/	/
		carbonated	0,7	4,4	99,3	4,4	3,9	13,3	5,8	4,5	62,0
SIJ ACRONI	Argon Oxygen Decarburization (AOD) reduction slag	fresh	0,0	0,2	100,0	0,2	/	3,8	1,7	/	/
		carbonated	0,3	1,7	99,7	1,7	1,5	8,5	3,7	2,1	38,7
SIJ ACRONI	Argon Oxygen Decarburization (AOD) refining slag	fresh	0,0	0,1	100,0	0,1	/	3,5	1,5	/	/
		carbonated	0,2	1,5	99,8	1,5	1,4	7,4	3,3	1,8	33,7
SIJ ACRONI	Mix AOD (reduction and refining) slag	fresh	0,1	0,1	99,9	0,1	/	3,7	1,6	/	/
		carbonated	0,2	1,7	99,8	1,7	1,7	8,3	3,6	2,1	37,9
SIJ MetalRavne	ladle slag	fresh	0,1	0,2	99,9	0,2	/	4,7	2,0	/	/
		carbonated	0,2	2,0	99,8	2,0	1,8	8,9	3,9	2,0	40,9

$$CO_{2,uptake} (wt. \%) = \frac{(CO_{2,carbonated} (wt. \%) - CO_{2,initial} (wt. \%))}{(100 - CO_{2,carbonated} (wt. \%))} \times 100$$

$$CO_{2,capacity} (gCO_2 / kg_{ash}) = \frac{CO_{2,carbonated} (wt. \%)}{100 - CO_{2,carbonated} (wt. \%)} \times 1000$$

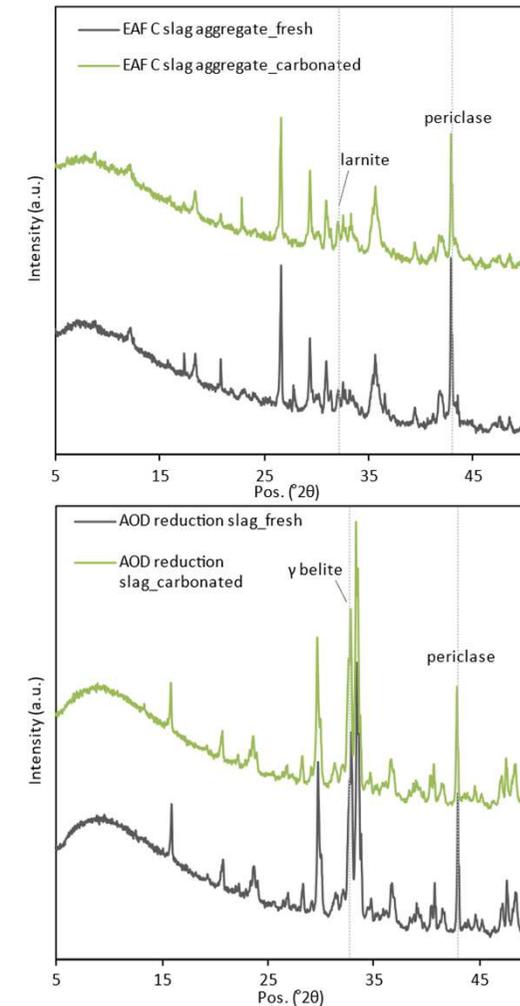
- The different types of steel slag exhibited varying sequestration potentials. The results indicated that EAF C slag is more reactive with CO<sub>2</sub> compared to ladle slags.
- EAF C slag can sequester up to 6 % of CO<sub>2</sub>, while ladle slags can sequester up to 4 % of CO<sub>2</sub>, which is slightly lower than the values reported in the literature.

## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

### DISCUSSION

- the selection of appropriate analytical methods to measure the CO<sub>2</sub> content in the samples is crucial, as different methods can lead to different results
- calcimetric calculations were used to assess the CO<sub>2</sub> sequestration capacity
- our results are slight below reported values for slags which reached a maximum CO<sub>2</sub> sequestration capacity of 62 gCO<sub>2</sub>/kg slag after dry carbonation treatment
- Quaghebeur et al., 2015, reported that carbonated SS sequester 150 g CO<sub>2</sub>/kg slag (pretreated SS slag (homogenization&mixing with water), particle size < 125 μm, reaction conditions: feed pressure of 2.0 MPa CO<sub>2</sub>, 80 °C)
- future work: to determine sequestration potential of slags using wet carbonation treatment

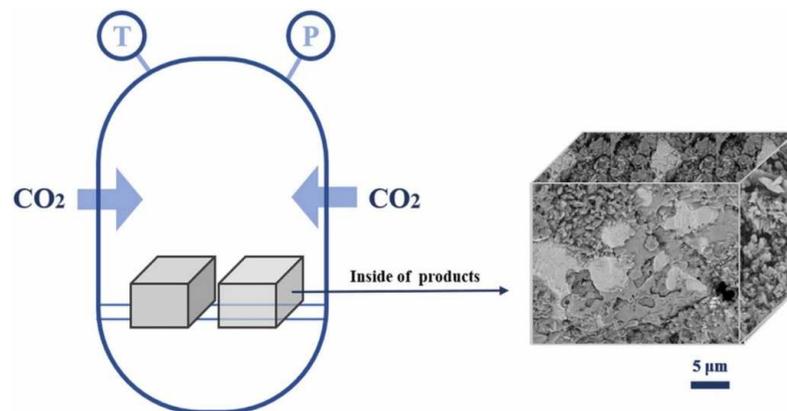
Reference: Quaghebeur et al., 2015. [doi.org/10.3389/fenrg.2015.00052](https://doi.org/10.3389/fenrg.2015.00052)



## Sequestration Potential of Electric Arc Furnace Carbon (EAF C) Slags and Ladle Slags

### CONCLUSION

- Mineral carbonation is a promising method for reducing the negative environmental impact by sequestering CO<sub>2</sub>.
- The mineralogical composition of the slag is one of the main factors influencing carbonation, as it affects the carbonation reactions.
- Developing standardized testing methods and regulations for carbon-based materials is essential for their widespread adoption.



Reference: Wang et. al, 2023. [doi.org/10.1016/j.mtcomm.2023.105827](https://doi.org/10.1016/j.mtcomm.2023.105827)



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We shift boundaries

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YOU.**



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